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HYBRID RENEWABLE ENERGY SUPPLY SYSTEM - STORAGE REQUIREMENTS CONSIDERING SEASONAL VARIATION OF PV OUTPUT

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Abstract

The transition toward sustainable and decentralized energy systems has accelerated the deployment of hybrid renewable energy supply systems (HRESS) in remote and off-grid areas worldwide. Hybrid systems that combine photovoltaic (PV) and wind energy technologies are particularly attractive because they exploit complementary renewable resources, reduce dependence on fossil fuels, and improve energy security for isolated users. Although the literature contains numerous technical studies on hybrid renewable energy systems, detailed analyses of annual storage requirements that explicitly account for seasonal variations in renewable generation remain limited. The main objective of this paper is to address this gap by proposing an analytical method for determining the annual energy storage capacity required to ensure a continuous power supply to an isolated consumer while accounting for seasonal variations in PV output. We illustrate the proposed method through a case study involving a 2–3 ha vineyard with a small guesthouse located in a mountainous region of Romania.

Key words: *Hybrid Renewable Energy System, seasonal photovoltaic (PV) energy storage, sizing method of storage.*

INTRODUCTION

Hybrid Renewable Energy Systems (HRES), particularly those combining photovoltaic (PV) and wind energy generation, have been the subject of extensive research due to their potential to improve the reliability and sustainability of power supply in remote and off-grid locations. Several comprehensive reviews highlight that the integration of multiple renewable sources significantly enhances energy availability and reduces the dependency on conventional fuels, making hybrid configurations well-suited for isolated demand scenarios (Ahmad et al., 2024). Hybridization helps to mitigate the intermittency inherent in solar and wind resources by exploiting their complementary behaviour over daily and seasonal cycles, thus improving overall system performance and reliability (Hassan et al., 2023).

A critical aspect of HRES design is the sizing and optimization of both generation and storage components. Reviews on PV-wind-based hybrid systems report a wide range of deterministic and stochastic methods used to size system components, including energy production units and storage elements, based on historical climate data and user load profiles (Anoune et al., 2018). Many studies emphasize that appropriate sizing directly influences system reliability, cost-effectiveness, and the ability to meet energy demand throughout the year. However, they also point out that most sizing approaches tend to focus on capacity and reliability indices without deeply addressing the long-term or seasonal storage needs aligned with annual variability in renewable generation (Kafando et al., 2024).

Energy storage plays a central role in balancing supply and demand in hybrid systems. Storage systems such as batteries, hydrogen storage, or hybrid storage configurations are critical for accommodating fluctuations in renewable generation and sustaining continuous power availability during low resource periods. Systematic reviews in the field underscore that efficient energy storage integration and energy management strategies are essential to offset the intermittency of PV and wind resources and to improve system performance over extended temporal scales (Ma et al., 2015). Research also

highlights that hybrid storage solutions (e.g., battery-supercapacitor combinations) and advanced energy management systems can enhance storage utilization and extend equipment life while providing better operational flexibility (Kafando et al., 2024).
Despite the inclusion of storage sizing in many studies' optimization frameworks, a principled, analytical analysis of annual or seasonal storage requirements remains infrequent.
Most existing approaches focus on short-term sizing (daily or monthly) and rely on optimization tools such as HOMER or artificial intelligence-based techniques for short-term energy balance and reliability criteria (Ahmad et al., 2024). While these frameworks are useful for determining optimal component sizing under given climatic conditions, they often do not explicitly model annual storage autonomy that accounts for significant seasonal mismatches between renewable supply and demand.
Furthermore, research on the complementarity of solar and wind resources suggests that combining these sources can inherently reduce the magnitude of storage needed by smoothing variability. Studies employing metrics such as stability coefficients and capacity credits demonstrate that optimal PV–wind configurations provide more uniform generation profiles than single source systems, potentially lowering the storage burden required for year-round operation (Badea et al., 2019). Nevertheless, these studies generally focus on large-scale or grid-connected applications rather than isolated, remote systems with stringent autonomy requirements.
In summary, the recent literature (Hassan et al., 2023) underscores the advantages of hybrid PV–wind systems in enhancing renewable energy reliability, the necessity of integrating storage for autonomous operation (Dagdougui et al., 2012) and the variety of sizing and optimization methodologies available (Anoune et al., 2018).
Yet a gap remains in explicitly characterizing annual storage requirements that fully capture the seasonal dynamics of renewable resources.
This gap motivates the analytical method proposed in the present paper, which aims to quantify the storage capacity needed to ensure continuous energy supply for isolated users across an annual cycle, considering seasonal variation of the PV source.

MATERIALS AND METHODS

Conceptual physical model of a HRES

In this paper, a hybrid energy supply system will be an analysed, considering a conceptual physical model that contains the al00main components of the system: the photovoltaic electricity generator, end users of electricity, and the energy storage subsystem, as well as the connections necessary to ensure its functionality. The HYBRID system offers a partially or fully autonomous energy supply that relies solely on renewable energy sources, specifically the photovoltaic (PV) source in this case.
Figure 1 shows a diagram of such a hybrid autonomous electricity supply system.
As energy end users, there can be, for example, small tourist complexes or vineyards of 2-3 ha with a small guesthouse, located in isolated areas.

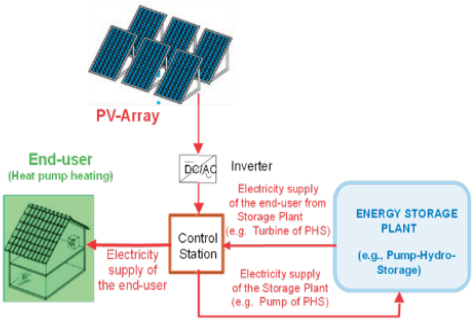


Figure 1. Conceptual physical model of a Hybrid Renewable Energy Systems (HRES) (Simão & Ramos, 2020)

The most important component of the system is the energy storage system (e.g. a Pump-hydro-storage) which ensures the seasonal energy balance between the required energy load of the end-user and the variable PV energy due to the solar radiation variability. Red lines with arrows show the flow of electrical energy between system components.

Required energy supply for end-user

The type of user determines the required energy demand that the hybrid photovoltaic storage system must meet.
End users such as tourist establishments or households use energy for lighting and electrical appliances, space heating and hot water, space

cooling, cooking, and other end uses. In Figure 2 we can follow the average distribution of household energy in the EU (EUROSTAT, 2026).

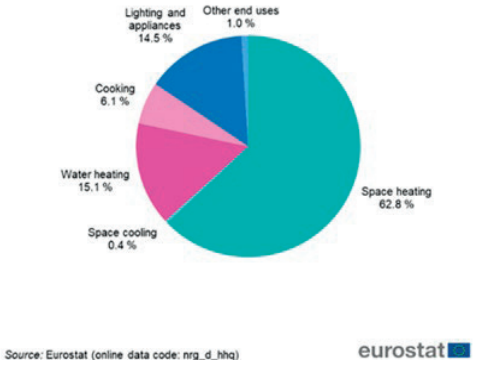


Figure 2. Averaged energy sharing in a household in EU (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households)

It can be seen in Figure 2 that, in a household, approximately 20% represents the direct consumption of electricity, and the remaining 80% is consumed mainly for heating and the preparation of domestic hot water.

From the European statistical data (EUROSTAT, 2026) follows that the specific total energy consumption in households per capita and year (e_{ECH}) is approximately:

e_{ECH} =6800 kWh/cap/a in EU and e_{ECH} =53200 kWh/cap/a in Romania. (Anoune et al., 2018)

Knowing the specific energy consumption, the total energy consumption for N people can be calculated:

$$E_{L/a} = N \cdot e_{ECH} \text{ in kWh/a} \quad (1)$$

For another type of end user, like guesthouse or vineyard of 2-3 ha with a small guesthouse, the required energy can be estimated using data from Malvoni & Cponcedo (2017), INSSE/Eurostat (2020-2025), OIV (2025) or REHVA. Such a user will be considered an example in the next paragraph - *The PV component*.

From the annual energy load $E_{l/a}$ (kWh/a) the annual average power demand can be determined $P_{l/a}$ (kW):

$$P_{l/a} = E_{l/a}/8760 \text{ in kW} \quad (2)$$

It is worth noting that energy consumption for heating, representing approximately 70-80% of a household's total energy consumption, can be substantially reduced (by approximately 50-75%) by using a heat pump, which operates on the electricity produced by PV. Thus, the entire energy consumption can be covered from the green electric current produced by PV

The analysis of heat pump efficiency based on the so-called Coefficient of Performance (COP) (i.e., the generated heating energy (kWh) divided the electricity consumed to generate heat (kWh) can be followed in detail in (WOLF, 2026).

The PV component

The PV-array component (Figure 1) is used to supply the consumer and, as appropriate, the storage system, respectively. Photovoltaic (PV) energy is a renewable energy source that does not produce emissions or pollutants while being a cost-effective energy source available everywhere (Quaschning, 2010; Badea et al., 2019).

The main disadvantage of a photovoltaic energy source (PV), in addition to its benefits, is the fluctuation in electricity output caused by the day and night cycle of solar radiation and seasonal variations, which result in higher output during the summer months and lower output in the winter months, as depicted in Figure 3.

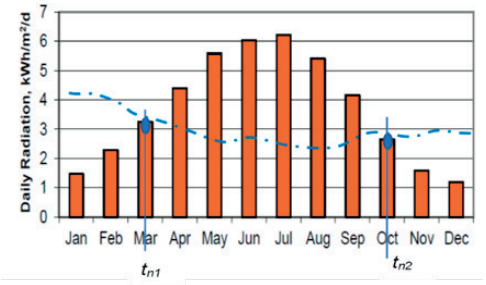


Figure 3. Example to schematic diagrams showing the annual distribution of monthly average solar radiation (https://www.researchgate.net/figure/Monthly-average-daily-solar-radiation_fig2_346271383)

For comparison, the required energy load (blue line) was also depicted. This juxtaposition is important for understanding the necessity of storing solar energy during times when solar radiation (i.e., PV-generated electricity) exceeds the required load ($t_{n1}<t_i<t_{n2}$) and for returning stored energy to meet demand during periods of

low solar radiation (e.g., the winter months: $t_i<t_{n1}$ and $t_i> t_{n2}$).

The annual output energy $E_{PV/a}$ generated by PV panel can be determined from the annual solar radiation ESR/a considering the *PR*-Performance Ratio (about 0,70-0,75) and the performance coefficient of PV panel $\eta \cong 0{,}18$-$0{,}25$ (Quaschning, 2010); https://www.solar.com/learn/solar-panel-efficiency/; https://strom-profis.net/produkt/ja-solar-jam72s20-455-mr-455-wp-solarmodul-bfr/).

An average value can be estimated as:

$$E_{PV/a}=\eta \cdot PR \cdot E_{SR/a}=\eta \cdot E_{PVP/a}\cong 0{,}145 E_{PVP/a} \quad (3)$$

For a given location, the solar radiation $E_{SR/a}$ is given in databases like NASA POWER and Global Solar Atlas.

For the design and analysis of the efficiency of a photovoltaic system (PV array), it is beneficial to develop a mathematical model that describes the influence of seasonal variations in solar radiation, a topic that has been less researched in the specialized literature.

In this context, it is noteworthy that the shape of the solar radiation distribution curve (Figure 3) is close to a sinusoidal one, which suggests the possibility using a mathematical representation based on trigonometric functions.

Based on these observations, the following trigonometric function is proposed to calculate the annual distribution of the average monthly power $P_{PV}(ti)$ (i.e. the monthly energy in kwh/month generated by the PV plant):

$$P_{PV}(t_i) = A\,(1-B\cos(\pi t_i)/6) \quad (4)$$

- A and B are specific parameters of the solar energy distribution diagram (e.g. Figure 3).
- In this context, ti represents the month number i of the year (for example, for January, $t_i=t_1=1$; for February, $t_i=t_2=2$; and for December, $t_i=t_{12}=T=12$).

To determine the parameter A, observe that by integrating equation (4) over a period of one year (Ta=12 month) the integral of the left-hand term represents the annual PV energy $E_{PV/a}$. On the other hand, $E_{PV/a}$ can be expressed using the annual average P_{PV0} of the monthly average powers P_{PV} (ti) as $E_{PV/a}=12\ P_{PV0}$.

Since the integral over the time interval Ta of the function *cos (πti)/6*) is zero, it follows that the integral of the right-hand side of equation (4) has the value 12A. Based on these results, the value of the parameter *A* is equal to P_{PV0}, meaning $A = P_{PV0}$.

To determine the parameter B, equation (4) will be applied for two characteristic points of the distribution diagram (Figure 3): the maximum monthly average power (P_{PVmax}) in the months June-July (i.e. $t_i=6$), respectively the minimum monthly average power (P_{PVmin}) in the months January and December (i.e., $t_i=0$ and $t_i=12$)

$$B = \frac{P_{PVmax}-P_{PVmin}}{P_{PVmax}+P_{PVmin}} \quad (5)$$

It is noted that the parameter B represents the maximum deviation of the maximum monthly mean power, P_{PVmax}. For this reason, B continues to be designated as σ.

Based on the above considerations and results, the mathematical model of the seasonal variation of the monthly average photovoltaic power (4) can be written in the form

$$P_{PV}(t_i) = P_{PV0}\left(1-\sigma_S \cos\frac{\pi t_i}{6}\right) \quad (6)$$

This proposed mathematical model will be further used (in paragraph entitled *Calculation method of the required energy storage to balance seasonal variation of PV*) to determine the PV energy storage required to balance seasonal variations of solar radiation.

Calculation method of the required energy storage to balance seasonal variation of PV

We can establish the characteristic operating intervals of the PV energy supply system using the representation from Figure 3, where the times marking t_{n1} and t_{n2} indicate the intersection points of both curves' load and photovoltaic (PV) energy production.

During the intervals $t < t_{n1}$ and $t > t_{n2}$ (i.e., the winter months) when the consumption requirement is higher than the PV-generated energy, the energy supply must be provided from the energy storage system (Figure 1) (i.e. turbine operation in the case of PHS). In the interval $[t_{n1} – t_{n2}]$ (i.e. during the months with higher solar radiation) the PV-generated energy is higher than the required energy by the consumer; the excess energy can be stored (i.e. pump operation in the case of PHS pump operation).

Denoting with $P_{L(t)}$ the power demand and with $P_{PV(t)}$ the photovoltaic power at the current

month t, the required *annual energy stored capacity* $E_{S/a}$ can be expressed as

$$E_{S/a} = \int_0^{t_{n1}} [P_L(\tau) - P_{PV}(\tau)]d\tau + \int_{t_{n2}}^{T} [P_L(\tau) - P_{PV}(\tau)]d\tau \quad (7)$$

Relation (7) can be rearranged using the proposed analytical model of the solar power (6) and a series of mathematical transformations, obtaining the following form:

$$E_{S/a} = 2\int_0^{t_{n1}} \left[P_L(\tau) - P_{PV0}\left(1 - \sigma_S cos\frac{\pi\tau}{6}\right)\right] d\tau \quad (8)$$

In the mathematical developments to obtain relation (8) the following simplifications were considered: the function *cos πτ/6 h*as approximately the same values in the time intervals [0, t_{n1}]and [t_{n2}, T] (Figure 3).
The photovoltaic energy ($E_{PVE/a}$), which exceeds the energy demand during the time interval t_{n1}-t_{n2}, can also be expressed in a similar integral form.

$$E_{PVE/a} = \int_{t_{n1}}^{t_{n2}} [P_{PV}(\tau) - P_L(\tau)]d\tau \quad (9)$$

respectively, using (6)

$$E_{PVE/a} = \int_{t_{n1}}^{t_{n2}} \left[P_{PV0}\left(1 - \sigma_S cos\frac{\pi\tau}{6}\right) - P_L(\tau)\right] d\tau \quad (10)$$

To analyse different HESS electricity supply options, a parameter can be introduced and defined as the ratio between the annual produced photovoltaic (PV) energy and the load that defines the degree of energy autonomy:

$$\lambda = \frac{E_{PV/a}}{E_{L/a}} = \frac{P_{PV0}}{P_{L0}} \quad (11)$$

For feasibility studies it is sufficient to consider a simplified case of a constant average power demand i.e.,

$$P_L(t) = P_{L0} = \frac{E_L/a}{12} \quad (12)$$

Using the parameter λ and (12) the equation (8) of the required annual storage can be rearranged by obtaining the following form:

$$E_{S/a} = \frac{E_{L/a}}{6}\int_0^{t_{n1}} \left[1 - \lambda\left(1 - \sigma_S cos\frac{\pi\tau}{6}\right)\right] d\tau \quad (13)$$

Integration yields the following equation for required annual storage:

$$E_{S/a} = E_{L/a}\left[(1-\lambda)\frac{t_{n1}}{6} + \lambda\frac{\sigma_S}{\pi} sin\frac{\pi t_{n1}}{6}\right] \quad (14)$$

Similarly, (10) can be written in the following form:

$$E_{PVE/a} = \frac{E_{L/a}}{12}\int_{t_{n1}}^{t_{n2}} \left[\lambda\left(1 - \sigma_S cos\frac{\pi\tau}{6}\right) - 1\right] d\tau \quad (15)$$

Performing the integration, we obtain

$$E_{PVE/a} = E_{L/a}\left[(\lambda - 1)\frac{t_{n2} - t_{n1}}{12} - \lambda\frac{\sigma_S}{2\pi}(sin\frac{\pi t_{n2}}{6} - sin\frac{\pi t_{n1}}{6})\right] \quad (16)$$

The values of t_{ni} (i=1,2) are the abscissas of the intersection points of the load curve P_L with the seasonal P_{PV} variation curve (Figure 3). Equations (13) and (6) yield:

$$t_{n1} = \frac{6}{\pi}\cos^{-1}(\frac{\lambda - 1}{\lambda\sigma_S}) \quad (17)$$

Equation (14) allows the calculation of the required annual storage $E_{S/a}$, given the annual consumption $E_{L/a}$ and the parameter λ, which defines the usage scenario for the photovoltaic (PV) energy supply in the planned HESS.
For an energy autonomous HESS, the annual photovoltaic energy production ($E_{PV/a}$) should be greater than or at least equal to the annual load ($E_{L/a}$), i.e. $\lambda \geq 1$. For the security of a standalone energy supply with a HESS, a λ value of 1.25 or even 1.5 is recommended (Quaschning, 2010).
For the simplified case when considering usual values for t_{n1} and t_{n2}, namely t_{n1} =3 and t_{n2}=9, the calculation equation (14) of the storage capacity per year ($E_{S/a}$) becomes the simplified form:

$$E_{S/a} = E_{L/a}\frac{\sigma_S}{\pi} \quad (18)$$

We remind you also that currently, the maximum deviation of the monthly solar radiation, has values between 0.5 and 0.6
The method and the calculation formulas presented above can be used to determine the required storage capacity of HESS, which ensures the annual energy balancing between the photovoltaic (PV) energy source and

consumption, considering the seasonal variation of photovoltaic (PV) energy.

Storage systems, Pump-Hydro-Storage

Luo et al. (2015) present a comprehensive overview and analysis of the current development of various types of technologies in electrical energy storage (EES).

Batteries and Pump-Hydro-Storage systems (PHS) are the most used storage systems (Kousksou et al., 2014).

Batteries are commonly employed as storage in stand-alone renewable energy systems have well known limitations (Hassan et al., 2023).

Regarding the economics of this technology, pumped hydro energy storage seems more economical than batteries as well for standalone applications (Ma et al., 2015) and has relatively low payback periods.

These aspects are the reason why we in our paper choose pumped hydro storage (PHS) as storage example. PHS is a storage system that uses excess PV electricity to pump water from a lower reservoir to an upper reservoir to store energy, and conversely, the water is released from the upper reservoir to the lower reservoir, assuring the energy supply of user at lower or missing solar radiation (Figure 4).

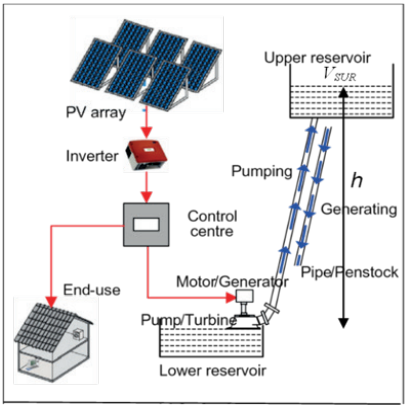


Figure 4. Scheme a PV electricity supply system with Pump-Hydro-Storage (Simão & Ramos, 2020)

If there are geographical conditions for PHS implementation, a hybrid system represented in Figure 4 can provide a reliable and cost-effective solution for providing electricity in remote areas. Additionally, such a hybrid energy supply system reduces substantially the environmental pollution (Rastler, 2010).

The two most significant parameter for the design of a PHS are the volume of the upper and lower reservoirs, which are the same value ($V_{UR/LR}$) and the turbine/pump head (h) (Figure 4) For a concrete study, the head of the turbine/pump (h) must be determined based on local topographic.

Therefore, for operating and sizing the PHS, only the volume of the upper reservoir ($V_{UR/LR}$) must be carried out.

The required input power for the pump $P_P(t)$ can be expressed as:

$$P_P(t) = \frac{1}{\eta_P} \rho g h \cdot q_P(t) \quad (19)$$

ρ is the density of water (1000 kg/m3),
g is the gravity acceleration and
η_P is the overall pumping efficiency
h is the pump head

The output power from the turbine $P_T(t)$ can be expressed as

$$P_T(t) = \eta_T \rho g h \cdot q_T(t) \quad (20)$$

η_T is the overall efficiency of the turbine;
$q_{T(t)}$ is the flow rate of the turbine
h is the turbine head

The other parameters have the same meaning as in the formula (19). In the case of standalone supply, the option of annual compensation is required for the security of a user's correct and safe energy supply in a remote area throughout the year.

The required annual energy storage $E_{S/a}$ can be determined using (14) or, in the simplified case, (18). Knowing $E_{S/a}$ we can calculate the volume of the upper/lower reservoir $V_{UR/LR}$. For this purpose, we note that, integrating the relationship (20) in relation to time (over one year), the left term is the energy stored $E_{S/a}$, and in the right member, the turbine flow q_T integrated represents the volume to be calculated V_{UR}.

So, the required water volume in the upper reservoir for energy storage in case of annual energy balance of the PV-PHS energy supply system, i.e., the volume of the upper reservoir V_{UR}, can be expressed as

$$V_{UR} = \frac{E_{S/a}}{\eta_T \rho g h} \quad (21)$$

RESULTS AND DISCUSSIONS

This section presents and illustrates the application of the calculation methods presented in the preceding sections for an end user in a remote area with an annual electricity consumption of $E_{L/a}$ 25,000 kWh. This consumption would correspond to an end user like a vineyard of 2-3 hectares with a small guesthouse of 4-5 rooms powered by photovoltaic panels and a heat pump (Malvoni & Cponcedo, 2017; INSSE/EUROSTAT, 2020-2025).

Here is the rationale for the considered electricity consumption of 25,000 kWh:

- Guesthouse (approx. 150-200 m²): a well-insulated building with 5 rooms consumes approximately 10,000-12,000 kWh/year for heating and hot water (using a modern air-to-water heat pump).
- Household consumption (lighting, kitchen, electronics): Approx. 4,000-5,000 kWh/year. These rationales are based on data from REHVA.
- Winery (Technology): for 2 hectares of vineyards (production of approximately 10,000–14,000 litters), the processes of must cooling, controlled fermentation, and stabilization require concentrated, but not enormous, energy consumption estimated at 8,000–10,000 kWh/year. This estimation is based on data from (OIV, 2025). Thus, the total estimated consumption is 22,000-27,000 kWh/year.

To ensure that this annual load is covered, a minimum annual photovoltaic energy production of $E_{PV/a}$ which is achieved using PV modules. In our example, a mountainous region of Romania, the annual solar irradiance can be estimated using the data in Figure 5 at a value of =1241 kWh/m^2. If we select JA Solar JAM72S20 455/MR 455 Wp PV modules with an efficiency of η = 20.05% and a module area Ap = 2.2 m² (https://www.enfsolar.com/pv/panel-datasheet/crystalline/46963) the PV potential of one solar module is:

$$E_{PV/p} = \eta \cdot A_P \, E_{PV/m^2} \cong 550 \, kWh/p \quad (22)$$

Thus, the required number of solar modules (NP) to be installed for a photovoltaic (PV) energy production of EPV/a (e.g. EPV/a =25,000) is:

$$N_P = \frac{E_{PV/a}}{E_{PV/p}} = \frac{25000}{550} \cong 45 \, modules \quad (23)$$

Furthermore, the next component of HESS will be analysed, namely the storage. As presented in the introduction and in paragraph - *Calculation method of the required energy storage to balance seasonal variation of PV*, the storage component of the HESS (Figure 3) is crucial to balancing the fluctuations of the renewable energy generation (PV) to ensure a secure and stable energy supply throughout the year. Knowing the annual load of $E_{L/a}$ =25,000 kWh/a, different scenarios for HESS can be analysed using the parameter λ defined as the ratio between the annual photovoltaic (PV) energy production ($E_{PV/a}$) and the annual load ($E_{L/a}$).

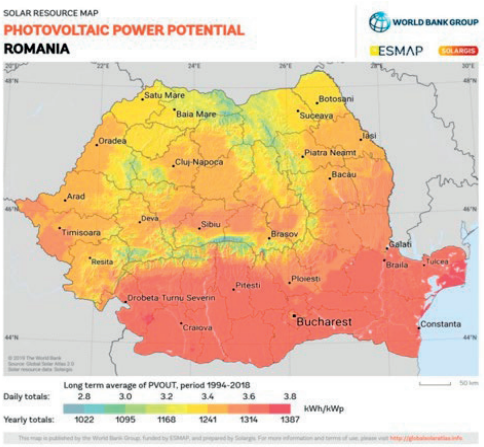


Figure 5. Solar energy resource map of Romania ((https://solargis.com/maps-and-gis-data/download/romania)

As reference case, we consider that discussed above in which the energy consumption $E_{L/a}$ corresponds to the generated photovoltaic energy $E_{PV/a}$ and thus from (11) λ=1. Any other value of λ corresponds to an energy supply scenario as follows:

- λ <1, when the annual photovoltaic energy production is less than energy consumption: $E_{PV/a}<E_{L/a}$
- λ>1, when the annual photovoltaic energy production exceeds the annual energy consumption: $E_{PV/a}>E_{L/a}$

The first case (λ<1) corresponds to partially energy autonomous scenarios of HESS i.e., when only a part of the energy supply ensured

from the PV source. To cover the difference between consumption $E_{L/a}$ and $E_{PV/a}$, it is necessary to use an additional energy source.
The second case ($\lambda>1$) corresponds to a scenario of energy autonomy for HESS, meaning that the entire energy supply is provided by photovoltaic systems integrated with appropriate storage solutions.
It should be noted that for the security of energy autonomy with a HESS, a λ value of 1.25 or even 1.5 is recommended (Quersching, 2010).
Based on these considerations, it is relevant to discuss three further scenarios of HESS in addition to the reference case ($\lambda=1$). Two of these scenarios correspond to cases of secure energy supply with HESS, where λ has values of 1.25 and 1.5, respectively.
One of scenarios corresponds to the case when only a part (e.g. about 75%) of the energy supply comes from PV source (i.e. λ =0,75). For the remaining 25% other sources are needed, such as electricity from power grid.
Using the proposed method and calculation formulas presented in the paragraph -*Required energy supply for end-user,* Table 1 shows the results for the end user – a tourist facility that consists of a 2-hectare vineyard with a small guesthouse in a mountainous region of Romania – with an annual consumption of $E_{L/a}$ = 25,000 kWh/a. Four scenarios were considered: λ = 0.75; λ = 1.00; λ = 1.25; λ = 1.50.

Table 1. Required energy supply for tourist facility

λ	0.75	**1.00**	1.25	1.50
$E_{PV/a}$ [kWh/a]	16,670	**25,000**	31,250	37,500
NPV [-]	30	**45**	57	68
t_{n1} [month]	4.4	**3**	2.21	1.6
$E_{S/a}$ [kWh/a]	-	**4,000**	2,250	1,125
$E_{PV/a}$-$E_{L/a}$ [kWh/a]	-8,330	**0.00**	+6,250*	+12,500*
V_{UR} [m^3]	-	**81,550**	127,422*	254,844*

For each scenario, the following values are calculated:

- the annual energy production of the PV system ($E_{PV/a}$, equation (9))
- the number of PV modules (N_P)
- the required annual storage to compensate for seasonal fluctuations of PV production ($E_{S/a}$), equation (12))
- the energy difference between the annually produced photovoltaic (PV) energy ($E_{PV/a}$) and the annually required consumption ($E_{L/a}$)
- the required storage volume V_{UR} of the upper/lower reservoir when using a pump hydro storage system (paragraph - *Storage systems, Pump-Hydro-Storage*, equation (21)).

The additional energy ($E_{PV/a}$ - $E_{L/a}$) generated in the scenarios with λ =1.25 and λ =1.5 (row 3 in the Table 1), which exceeds the effective annual energy consumption (25,000 kWh) marked with an asterisk (*) in Table 1, serves to ensure the consumer's security of supply. This generated photovoltaic (PV) energy is lost if it is not used by other consumers, fed into the grid (if available), or stored.
The last rows of Table 1 show the required storage volume for a pumped-storage hydroelectric plant.
It is evident that the additional water volume required to store the extra energy generated is very high: over 50% for variant λ =1.25 and over 200% for variant λ =1.5. Therefore, a techno-economic analysis is necessary to assess the viability of such storage.

CONCLUSIONS

This paper presented a novel analytical approach to determining the annual energy storage requirements for Hybrid Renewable Energy Supply Systems (HRESS), specifically addressing the challenges posed by seasonal PV output variations. By employing a trigonometric mathematical model to describe the sinusoidal distribution of annual solar radiation, this study bridged a critical gap in existing literature, which often overlooks long-term seasonal dynamics in favour of short-term technical optimizations.
The application of the proposed method to a case study - a vineyard and guesthouse in mountainous Romania - provided several key insights:
Analytical Precision: The introduction of the energy autonomy parameter (λ) proved to be a robust metric for sizing HRESS. The mathematical derivation of the required annual

storage via the intersection points of load and generation curves allows for a precise quantification of storage needs without the necessity for computationally expensive hour-by-hour simulations.

Impact of Autarky Levels: The results demonstrate that while a reference case theoretically covers annual demand, it necessitates maximum storage capacity to bridge seasonal deficits. Increasing the PV capacity to security levels of or above significantly enhances energy security but results in substantial surplus energy. This highlights a critical design trade-off: over-dimensioning the PV array can reduce the relative storage burden but requires effective ategies for utilizing excess energy, such as grid-feeding or secondary thermal loads.

Storage Feasibility: The study quantified that for a typical 25,000 kWh/a consumer, the seasonal storage requirements are substantial. For isolated systems, the results suggest that Pumped Hydro Storage (PHS) or advanced long-term battery solutions are indispensable, as conventional short-term storage cannot compensate for the sinusoidal "winter gap" identified in the model.

In conclusion, the proposed analytical equations provide a valuable tool for engineers and policymakers in the early feasibility stages of decentralized energy projects. Future research should extend this trigonometric model to include stochastic weather fluctuations and the complementary integration of wind energy to further optimize the parameter λ and reduce the physical footprint of the required storage systems.

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