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Do we really need a seasonal energy storage? Results for photovoltaic technology in an unfavourable scenario

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ABSTRACT

Energy storage systems play a crucial role in the transition to renewable energy. Short-term storage (STS), e.g., batteries, has a capacity of a few hours, meant to compensate the energy deficit due to day-night cycle or short-term fluctuations. Long-term storage (LTS), e.g., renewable fuels, can compensate seasonal variations. The importance of STS is undisputed; the need for LTS is much more debated. Here we compare two photovoltaic systems, one (A) endowed only with STS, and another (B) equipped also with unlimited LTS, in a scenario unfavourable to (A) because of high seasonal variability of irradiation and high heating load in winter. We show that (A) requires only a moderate oversize of the peak power (about 20%) w.r.t. (B) when both systems are sized to supply 85% of the whole electrifiable load, which includes domestic heating and transport. Therefore, the current lack of clear routes towards grid-scale LTS should not be considered as a reason to delay the transition to renewables.

1. Introduction

The recent price drop of technologies for renewable energy, especially wind turbines and photovoltaic systems, and the undergoing electrification of transport make an economy based on nearly-100% renewable energy a realistic perspective. The main energy sources that are expected to play a dominant role in the near future are wind energy (WE), solar photovoltaic energy (PV) and hydroelectric energy (HE). Among these technologies, HE has a long history and is already widely exploited. Energy production from wind and photovoltaic, on the other hand, is expected to increase, due to: (i) competitive cost, and (ii) the overwhelming abundance of primary resources, particularly sunlight. Despite requiring different technologies, both WE and PV directly produce electric power, whose amount is related to the instantaneous availability of the primary source; they are usually indicated as VRE (Variable Renewable Energy). Therefore, an energy storage solution is needed if these technologies are meant to produce a large fraction of the required energy supply.

Storage systems can be classified with some approximation in short-time storage (STS in the following) and long-time storage (LTS) depending on whether they are devised in order to compensate short-time fluctuations (e.g., day-night cycles) or seasonal variations. Feasible STS solutions are currently available (e.g., electrical batteries), but there are no clear routes to achieve a grid-scale LTS capacity in a short-term perspective. In view of a nearly complete transition to renewable energy, the importance of STS is undisputed; however, the need for LTS is more questionable. The debate plays an essential role in the development of a strategy for transition to renewables. The choice of immediate massive investments on WE and PV can be short-sighted if LTS is required for the transition. On the other hand, given the urgency of reducing greenhouse gas emissions, the choice of delaying installation of production capacity in order to concentrate on research and development of LTS can be catastrophically ill-advised if LTS turns out not to be so crucial after all.

Despite the large amount of accurate studies found in the literature that address the problem of evaluating storage requirements, e.g., see [1–20], no firm conclusions have been achieved, with contrasting results stemming from the large variety of optimization criteria, specific scenarios, targets, admissible power sources and load requirements (electricity only or overall). Papers [1,7] show that 80% of the electric-only load can be obtained with 1-day storage, considering Texas and the whole US, respectively; but [2,3] and the same [7] show that a more ambitious target of 100% renewable supply requires a huge storage size (about 20% of the annual load). It is stated in [4] that no economic justification can be found for LTS, admitting in the energy mix non-renewable

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Nomenclature

Abbreviations

COP	Coefficient of performance
DFI	Diffuse irradiation
DNI	Direct normal irradiation
HE	Hydroelectric energy
LTS	Long-term storage
PV	Photovoltaic
STS	Short-term storage
VRE	Variable renewable energy
WE	Wind energy

Symbols

A_{pv}	Total area of the panels in the solar field
$E_{pv}(j)$	PV output at step j
E_m	Missing energy
F_t	Fraction of electrifiable load supplied by PV
g	Gravity acceleration
$I(j)$	Solar radiation incident on the panel surface
j	Simulation step
$L(j)$	Load at step j
T	Temperature
T_{ref}	Reference temperature for PV efficiency
T_{sky}	Effective radiative temperature of the sky
Δt	Time step for the simulation
W_{peak}	Peak power of PV field
η	PV efficiency
η_0	PV efficiency at T_{ref}
β	Temperature coefficient for PV efficiency
θ	PV panel inclination
ρ	Solar panel reflectivity
Nu	Nusselt number
Ra	Rayleigh number
Pr	Prandtl number

sources with the aim of reducing carbon emission up to 70%. The authors of [13] focus on the reduction of CO_2 emission of 80% w.r.t. 1990 level, including H_2 production in the analysis and concluding that a significant storage is required in order to obtain a reduction of more than 80%. According to [14], a target of producing up to 70% of electric energy with a solar/wind mix in the ERCOT electric system of Texas requires a 10–15 day storage; [15] compares LTS and STS concluding that LTS are required even for not-so-ambitious VRE penetration (up to 60%). However, [18,20] draw opposite conclusions. Generally speaking, in [9] a short synthesis of previous works points out that the estimation of the required storage size for a penetration of VRE above 80% varies of two orders of magnitude across the literature. The studies are usually very specific and seem to be heavily influenced by the cost of the various systems at the time of publication; moreover, targets often penalize the oversizing of plants, even though oversizing has been shown to be advantageous w.r.t. the realization of large storage systems [21].

In this paper we seek to draw some general conclusions by comparing performances of LTS and STS for PV systems. We compare two generating systems, one (A) endowed with a limited capacity STS (a few hours of peak production) and one (B) with the same STS plus unlimited LTS, assuming plausible storage efficiencies for the two storage types. The two systems must supply a high fraction (ranging from 60% to 90%) of the overall (electrifiable) energy requirement of a community, and the required oversizing of (A) w.r.t. (B) is computed. Instead of studying a specific real-life example, we build a scenario that – within plausibility range – is deliberately unfavourable to system (A). We perform a parametric study of the oversizing as a function of the required energy supply. The computed oversizing can be regarded as an estimate of the maximum oversizing needed in order to avoid LTS, for a given energy production goal, and it is independent of current prices of specific technologies. As a consequence, it is a good indicator of the real usefulness of devising a grid-scale LTS.

2. Storage systems

The most obvious difference between STS and LTS is storage capacity: STS should have a capacity of the order of a few hours of production, whereas the capacity of LTS should correspond to a significant fraction of the annual production. Another important factor to consider is energy loss over time: for instance, a storage system that loses 2% of the stored energy per day is surely acceptable for STS, but not for LTS, since the energy accumulated, e.g., in summer will be almost completely lost well before winter. The acceptable energy loss rate of a storage system is related to the system's storage time scale, as a long storage time can only be attained when energy loss is nearly negligible.

A capacity / storage time graph showing most of the technologies currently under scrutiny for energy storage is shown in [22]. Concerning LTS, it can be seen that the combined storage time / capacity requirements rule out most known storage systems, except for two: gravity storage and electrochemical production of stable fuels. Gravity storage is ordinarily used in large-scale hydroelectric systems, but its expansion potential is quite limited: hydroelectric resources are already intensively exploited, at least if only large-basin facilities are considered. Moreover, the realization of large hydroelectric basins has a considerable environmental impact. The available basins can surely be exploited, as far as possible, to contribute to storage, but the available capacity is not likely to supply a significant seasonal storage except in some countries. Other gravity technologies (e.g., using solid blocks pulled along rails or similar systems, [22]) have been investigated, but no economically feasible solutions have been proposed on a sufficiently large scale.

The production of easily storable, stable fuels, among which hydrogen (obtainable from electrolysis) is surely the most sought for, would be the definitive solution. However, the technology for producing hydrogen, storing it safely and re-converting it to electricity on-demand is currently far less mature than WE or PV technology. Costs are high, and the overall efficiency of the cycle is estimated in the range 34–44%, according to [23].

As already mentioned, the technology is far more developed for STS. The main option is surely represented by electrochemical batteries. Note that, when considering large-scale static storage, the compactness of batteries is not a crucial requirement: options are not limited to compact lithium-ion (Li-ion) batteries (as in transport applications), but they are much more varied. As an example, an old, reliable and cheap technology such as acid-lead batteries could be adequate, provided that it supports a sufficient number of day-night cycles. Note however that recent literature [24] compares them unfavourably to Li-based batteries even for large-scale static storage. $LiFePO_4$ batteries are especially promising due to their safety, high cyclability, and the absence of polluting or difficult-to-supply materials (such as cobalt for Co-based Li-ion batteries).

Moreover, a major contribution to daily storage is expected to come in the next future from "second-life" car batteries, i.e., old batteries with reduced capacity that are no longer fit for transport applications, but still have many remaining years of useful life as static accumulators for electric production plants.

An alternative is represented by thermal storage, sometimes called Carnot batteries. The study of thermal storage is typically aimed at usage in plants that produce heat as a first step, such as nuclear or thermal solar plants. However, thermal storage has also been proposed as a cheaper large-scale alternative to electrical batteries [25]. Two main working principles can be applied. The first, very straightforward, is the heating of the storage material by means of electric resistances; the second is the use of electricity to feed a thermodynamic cycle (e.g., using a reversible heat pump). In this second case, a perfectly reversible cycle would lead to a 100% efficiency, while in the first case the efficiency of the cycle is limited by Carnot efficiency. According to [25], real efficiencies are typically below 70% for standard Carnot batteries: lower than the efficiency of electrochemical batteries, but higher than the efficiency of hydrogen-based storage systems.

Other possibilities (compressed air, flywheels, capacitors, superconducting magnets, liquefied air, redox flow batteries) have been proposed and are actively studied, but some are clearly unsuitable for grid-scale storage (flywheels, capacitors) and others are in development stage.

So, given the currently available technologies, the possible need for seasonal storage would be the main obstacle on the road towards renewable energy.

3. The scenario under study

The simulation of systems (A) and (B) requires the time sequence of the available energy source and of the required load. We choose to consider PV-only systems for achieving the target fraction of renewable energy supply, using as primary source the sun irradiation in the south of Sicily, Italy. Average daily radiation for each month is shown in Fig. 1. Note that this scenario is unfavourable to system (A), for the following reasons:

- Ignoring hydroelectric production means ignoring the contribution of a renewable source that is tunable and already endowed with seasonal storage;
- Moreover, ignoring the existence of hydroelectric basins means that they cannot be used for long-term storage of electric production in excess from other sources, whereas in a real-life scenario System (A) could rely on the limited LTS provided by already-existing pumped HE;
- Ignoring wind energy, in a temperate country, means ignoring a compensating seasonal factor for PV electric production, since wind is usually more abundant in winter and sun in summer;
- The seasonal variation of irradiation is strong: in the scenario under consideration, the average irradiation in December is 51% lower than in July.

Given this energy source, we build an hourly time sequence for the energy load considering three contributions:

- the electrical consumption of Italy,
- the energy required by transportation, in the hypothesis of a total electrification except for aviation and navigation,
- the energy required for non-industrial heating, in the hypothesis of a total electrification via heat pumps.

The average daily load is shown in Fig. 2, normalized for a community of 10000 people. Details on the construction of time sequences are given in Section 4.

This load amounts to 87% of the overall national energy requirement; the remaining 13% is used by aviation, navigation, agriculture and fishing, and industry (non-electric) [26,27]. We adopted the conservative view that these sectors are not easily electrifiable, even if this assumption might not be completely correct for the industrial sector. Note the presence of a strong heating load concentrated in winter, when the energy source is less abundant.

Even if Italian data are used, due their easy availability to the authors, this scenario is very far from actual Italian conditions, which would be more favourable to system (A): Italy has a well-developed HE sector (producing about 15% of the electric energy [26]) and a significant storage capacity through pumped HE. WE has a significant potential too, with a strong seasonal compensating effect. The proposed simulation is not meant to represent accurately a specific real-life energy system: it rather aims at building a simple scenario that is at the same time plausible, but also challenging for system (A). Since we are studying a 100% PV system, plausibility implies that the annual load profile is demanding but not extremely so: the Italian case is a good example. Of course, this load would be supplied choosing the best available location for PV plants (for Italy, a good location is southern Sicily). Therefore in this scenario we have a plausible PV-only supply with seasonally mismatched load and irradiation. Of course one could worsen the situation by using the energy requirements or the irradiation of a northern and colder country, but in this case it would be implausible to assume a PV-only energy supply, as WE would be dominant, with a better source-load correspondence.

To summarize, if LTS did indeed play a crucial role in ensuring the feasibility of a high PV penetration in energy production, we would expect to recognize this phenomenon very clearly from the comparison of systems (A) and (B).

Let us describe in more detail the systems (A) and (B). Both systems adopt fixed PV panels.

- System (A): a system equipped with STS with 80% storage efficiency, and 1% daily energy loss. Four cases are studied, with capacities of 2, 3, 4 and 6 h of peak production.
- System (B): a system equipped with the same STS as (A), plus unlimited LTS with 45% efficiency, and no daily loss.

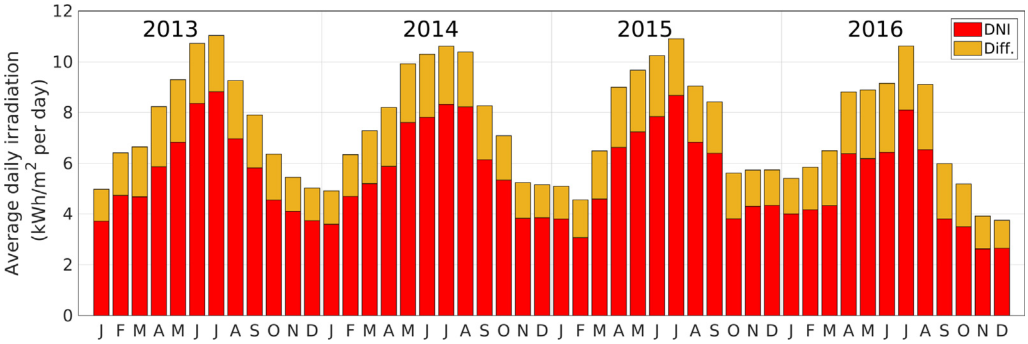


Fig. 1. Average daily irradiation (DNI and diffuse).

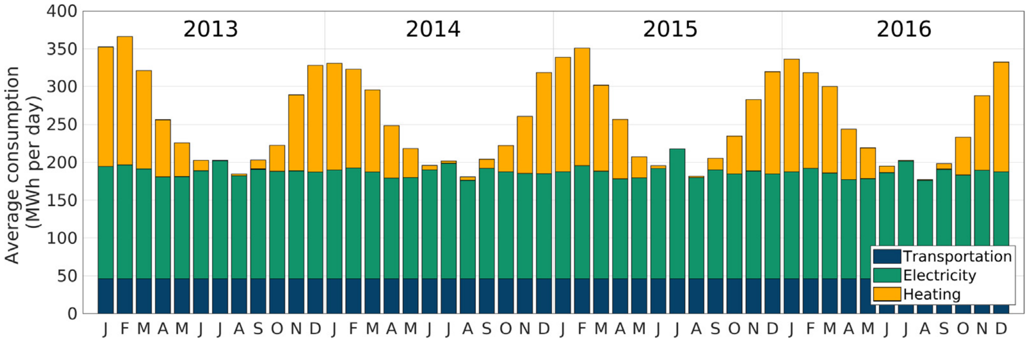


Fig. 2. Average daily energy consumption, rescaled for a community of 10000 people.

The two storage systems are clearly modeled on electrochemical batteries for STS, and renewable fuel production for LTS, since these two systems are most likely to provide new installed capacity for STS and LTS in the future. Note that the hypotheses on STS are quite conservative, as 1% daily loss is high for a battery, and an 80% efficiency is not exceptional. On the other hand, the hypotheses on LTS are rather optimistic: 45% efficiency for the whole electricity → fuel → electricity cycle is better than what can be currently realized, and no daily loss is assumed. This is, of course, a deliberate choice.

The PV panels face South and their inclination is optimized in order to minimize the required panel area, while achieving at least a target fraction F_t of the total electrifiable load. For (A), a non-storable production excess is expected in summer, and it is wasted.

The simulation of the system is performed over 4 years (2013–2016). The energy production of the PV panels is computed as follows: at each time step, the total incident radiation on the panel surface is determined, and the computed total incident radiation is then multiplied by the efficiency of the panels, which is supposed to be dependent on the temperature of the panel. Details on the model are given in Section 4. The obtained electric power is then sent to the load; if there is a production excess, the excess is sent to the STS; if the STS is full, in (A) the further excess is lost, in (B) it is sent to the LTS. When the directly produced electric energy is not enough, the STS will supply the missing part; if the STS is empty, in (B) the LTS is activated. When the available storage systems are empty and there is a production deficit, energy must be supplied by other sources (e.g., a fossil backup). The systems are sized to limit the fraction of missing energy to at most $(1 - F_t)$, thus obtaining the fraction F_t of the energy supply from solar source. The target fraction F_t ranges from 60% to 90%.

4. Input data and methodology

4.1. Input data

The simulation of the system is performed taking as input the time sequences over 4 years (2013 – 2016) with a resolution of an hour, both for sun irradiation (direct and diffuse) and for the required electric load.

Time sequences of solar irradiation in the chosen location (near the town of Pachino, Sicily) and ambient temperature – the latter required in order to compute the efficiency of the PV panels – are obtained from [28]. The three components of the electric load sequence are:

(a) The actual electric load of Italy, obtained from [29]: hourly data from 2013 to 2016. This sequence includes all of the actual electric consumption, including the electricity used for transport – which is therefore not included in (b) – and the electric energy used for heating/ cooling, hence not included in (c).

(b) The non-electric energy currently required for transportation, in the hypothesis of a full conversion of land transportation to electricity, leaving aside aviation and navigation. The overall energy load due to transportation is obtained from [26] for the year 2019; the part of consumption that is already electric (trains and urban transport) is excluded, being already accounted for in (a). For the simulation, it is assumed that the ratio (transport load)/ (electric load) takes the same value for the period 2013–2016. Once the overall energy consumption for transportation is obtained, the estimated fraction for aviation and navigation [27] is subtracted. The equivalent electric load is obtained by assuming the average efficiency of a thermal engine to be 0.2, and that of an electrical engine to be 0.75. Since there is no strong seasonality for transportation energy consumption, and since there is a certain flexibility in the charging process of electric vehicles, it is assumed that the additional electric load due to transportation is uniformly distributed, adding to (a) a constant electric load that sums up to the estimated overall transport consumption.

(c) The non-electric energy currently required for non-industrial heating. The overall required energy is estimated the same way as (b) [26], excluding the consumption already provided by electricity. The equivalent required electric energy is estimated assuming to use heat pumps with coefficient of performance (COP) equal to 3. Unlike transportation energy, heating clearly shows a marked seasonality, so a plausible heating sequence was built by considering the four main climatic regions in which Italy is conventionally divided (ignoring local rules on heating season): a representative temperature time sequence of each of the four zone is estimated as the temperature of its most populous city (Milan, Rome, Naples and Palermo) obtained from [28]; for each zone, a heating load distributed proportionally to the difference – when positive – between a conventional temperature of 20 °C and the ambient temperature is assumed; the four load sequences are averaged, weighing them w.r.t. the population of each zone (respectively, 46.8%, 25.8%, 21.9% and 5.5% of the whole population); the obtained load is then rescaled so that it sums up to the overall required electric energy.

The sum of (a), (b) and (c) is the required electric load. In the final balance, (a) represents 55.5% of the whole electric energy consumption, (b) the 18.0%, (c) the 26.5%.

In this scenario, we do not consider to be easily electrifiable, beside aviation and navigation, also the non-electric consumption of agriculture, fishing and of the whole industrial sector. This is a conservative assumption, since it is likely that a large part of the energy for industrial processes could be easily supplied by electricity. However, there are sectors, such as siderurgy or mining, whose complete electrification could be problematic, and it is difficult to estimate the fraction of easily electrifiable load from the available aggregate data. So, we excluded the whole industrial non-electric consumption from the computation. The final electric energy supply corresponds, under these hypotheses, to 87.05% of the overall energy requirements, but this percentage could likely be well above 90% if the electrifiable industrial consumption is taken into account.

4.2. PV modules

The production of the PV panels is computed at each simulation timestep by obtaining the total incident radiation on the panel surface, from the radiation sequences. The direct radiation (DNI) is corrected for the cosine factor: the sun position is computed using algorithm n. 3 in [30] (max. error < 0.01 deg; includes parallax correction to sun elevation and refraction effect), and the cosine of the incidence angle on the panels is obtained. The contribution of diffuse radiation (DFI) is considered to be isotropic, hence independent of the sun position. The computed total incident radiation is then multiplied by the efficiency η of the PV panel, which is supposed to be dependent on the temperature of the panel according to [31]:

$$\eta = \eta_0[1 + \beta(T - T_{ref})] \tag{1}$$

where η_0 is the nominal efficiency at temperature T_{ref}. We assume $T_{ref} = 25$ °C, $\beta = 0.0041, \eta_0 = 0.15$. So, the nominal efficiency of the panels is 15% at 25 °C. PV peak power is computed as the production at nominal efficiency under 1000 W/m^2 on the surface: so, 1 m^2 of PV modules corresponds to 150 W of peak power. The peak power and the total area of panels are, in fact, equivalent parameters in that they provide the same information.

The panel temperature is computed adopting a simple model already described in [32]. The temperature is computed assuming:

- natural convection from both sides as described in [33], §8.4: the correlation between Nusselt number (Nu), Rayleigh number (Ra) and Prandtl number (Pr) for both faces of the panel is given by the two formulas

$$\begin{aligned} \mathrm{Nu}_1 &= 0.68 + 0.67\mathrm{Ra}^{1/4}\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{-4/9}, \\ \mathrm{Nu}_2 &= 0.14\mathrm{Ra}^{1/3}\left(\frac{1+0.0107\mathrm{Pr}}{1+0.01\mathrm{Pr}}\right). \end{aligned} \tag{2}$$

  Nu_1 is used for the rear face of the panel, while for the front face the maximum between Nu_1 and Nu_2 should be used. In the computation of Ra, the gravity acceleration g must be replaced by $g\cos\theta$, where θ is the panel inclination;
- radiative emission towards the sky, which is assumed to have an effective radiative temperature T_{sky} of 284.7 K [34];
- radiative emission towards the ground, which is assumed to be at atmospheric temperature.

A thermal resistivity of 10^{-4} Km^2/W is assumed between the cell and the rear of the panel, as well as an emissivity of 0.95 on both faces. An optical reflectance $\rho = 0.08$ is assumed for the PV panel surface. The size of the PV array is not taken into consideration for computing the PV efficiency.

4.3. Simulation procedure

The simulation is performed using MATLAB. A program was written in order to perform a step-by-step simulation, which reads as input data the source and the load sequences discussed in SubSection 4.1. In order to smoothen the time simulation, the input time sequences are pre-processed in order to change the time-step Δt to 1/10 h instead of 1 h, adding points by linear interpolation. The simulation parameters are the peak power W_{peak} of the PV field (or, equivalently, the area A_{pv} of the panels) and the inclination of the panels. For each time step j the production $E_{pv}(j)$ of the PV field is computed, applying the model described in SubSection 4.2: temperature and efficiency of the panel are found by solving recursively the equation for the thermal balance, with a thermal flux on the cell surface given by $I(j)(1 - \rho - \eta)$. $I(j)$ is the radiation on the panel surface, computed as in SubSection 4.2. Recursion is required since η is temperature-dependent (1), hence the thermal flux – required to compute temperatures – is temperature-dependent. At the end of the recursion, the resulting η is used to compute $E_{pv}(j) = A_{pv}I(j)\eta\Delta t$. Then, $E_{pv}(j)$ is compared with the energy load $L(j)$ required in the time step. If $E_{pv}(j)$ is larger than the load $L(j)$, the excess of production is sent to the STS; if the STS is full, in (A) the further excess is lost, in (B) it is sent to the LTS. Stored energy is multiplied by a factor 0.8 when it enters the STS, and by 0.45 when it enters LTS, in order to account for storage efficiency. If $E_{pv}(j)$ is smaller than $L(j)$, the STS supplies the missing energy. If STS is empty, in (A) the missing energy is added to the overall missing energy E_m; in (B) the LTS can supply the missing part, and only when the LTS is also empty the missing energy is added to the overall missing energy E_m. At the end of each time step, the energy in the STS is reduced by a fraction corresponding to a daily loss of 1%. The flowchart of a simulation step for both systems is shown in Fig. 3.

Starting the simulation with empty storages might be penalizing for LTS, as the first winter months of the first year would not benefit from the energy possibly stored in the preceding year. For this reason, a 5-years-long simulation is run, adding before the time sequences a copy of the year 2013 and considering only the 4 following years for the energy balance. So, the true simulation starts with the storages at plausible levels.

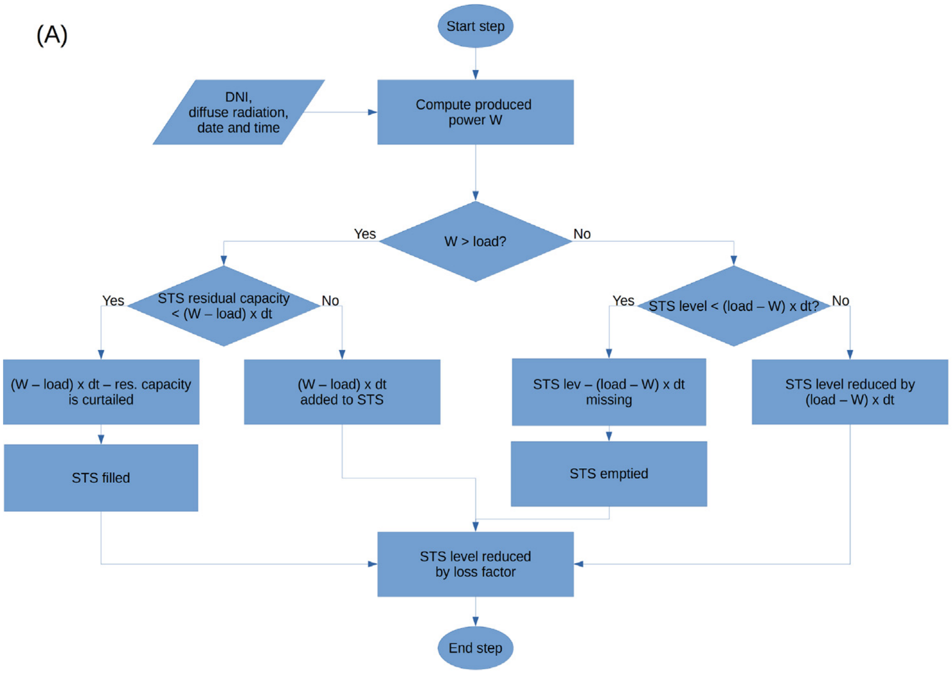
The step-by-step simulation is the basic computational block. It requires as input parameters W_{peak} (or A_{pv}) and the inclination of the panels. These are not free parameters: the only free parameter is F_t, while the inclination of the panels must be optimized in order to achieve the desired F_t with W_{peak} as small as possible. The optimization proceeds in two steps. Given a value for F_t and for the inclination of the PV panels, the simulation is repeated at different W_{peak} values in order to find the W_{peak} that is required to supply the fraction F_t of the whole electrifiable load. The whole procedure is then repeated at different inclinations in order to find the optimal inclination, i.e., the inclination that minimizes W_{peak} for the given target F_t. The optimal inclination for (A) will be larger than the optimal inclination for (B), since in (A) the winter collection of radiation must be enhanced. The oversizing of (A) vs (B) for the given target F_t is given by the ratio of the peak powers of the systems with optimal inclinations.

5. Results and discussion

5.1. Results

For convenience, results are normalized for a community of 10000 people. Of course, results can be rescaled to any size.

Fig. 4 (i) shows the peak power for both systems (A) and (B) necessary to achieve the target fraction F_t of the load, and Fig. 4 (ii) shows the wasted energy, i.e., the PV output that goes unused or that is lost due to less-than-100% efficiency of the storage. The wasted energy is given as a percentage of the overall PV output of the solar field. Fig. 4 (iii) shows the overall efficiency of the panels, defined as the ratio (dispatched energy)/ (overall incident radiation); it takes into account the efficiency of the PV panels, the



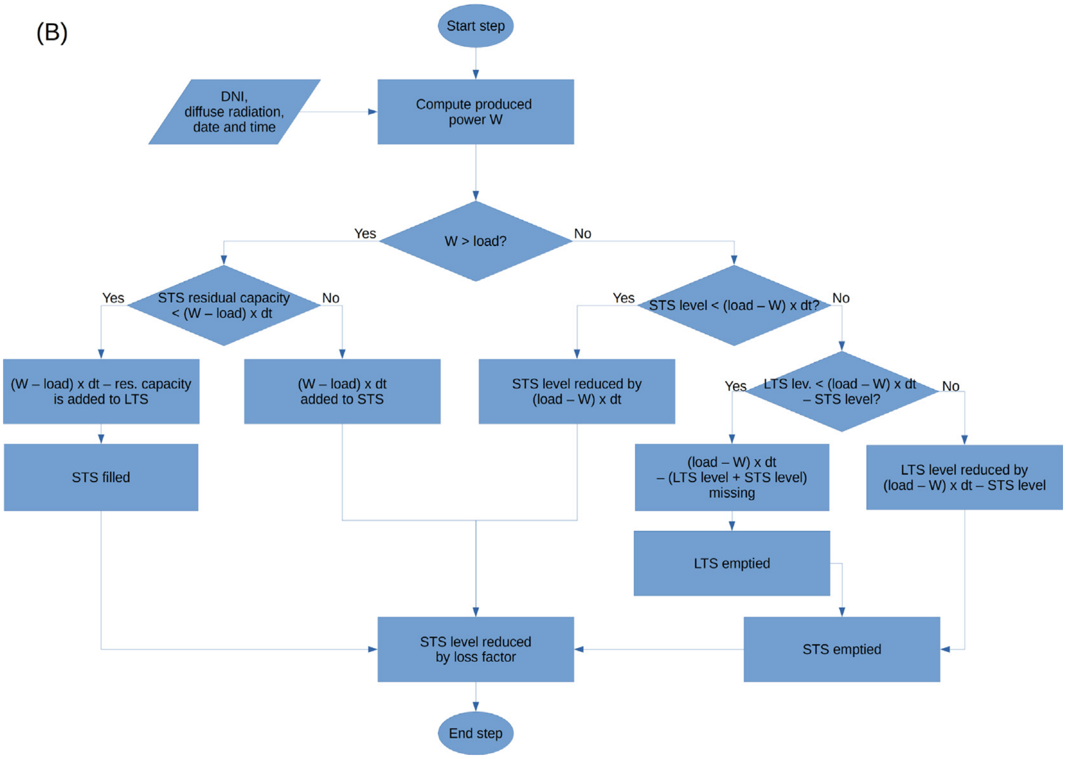


Fig. 3. Flowcharts of a simulation time step Δt, for system (A) (above) and (B) (below).

wasted energy and the efficiency of the storage systems. Fig. 4 (iv) concerns system (B) only, and it shows the maximum of the stored energy in the LTS reached over the four years. This data yields an estimate of the LTS capacity required in order to achieve F_t and is therefore useful to assess the feasibility of the LTS. Note that results concerning system (B) with an STS in the range 3–6 h are very close, for all the displayed quantities.

As mentioned above, the main purpose of this work is to draw a comparison between systems (A) and (B). The key findings are highlighted in Fig. 5, which shows the oversizing of (A) vs (B) required to meet the same F_t, for the 4 different STS capacities under consideration. One can see that for a storage capacity of 3 h or more the oversizing remains quite moderate up to high F_t values. As an example, 85% of the electrifiable load can be supplied

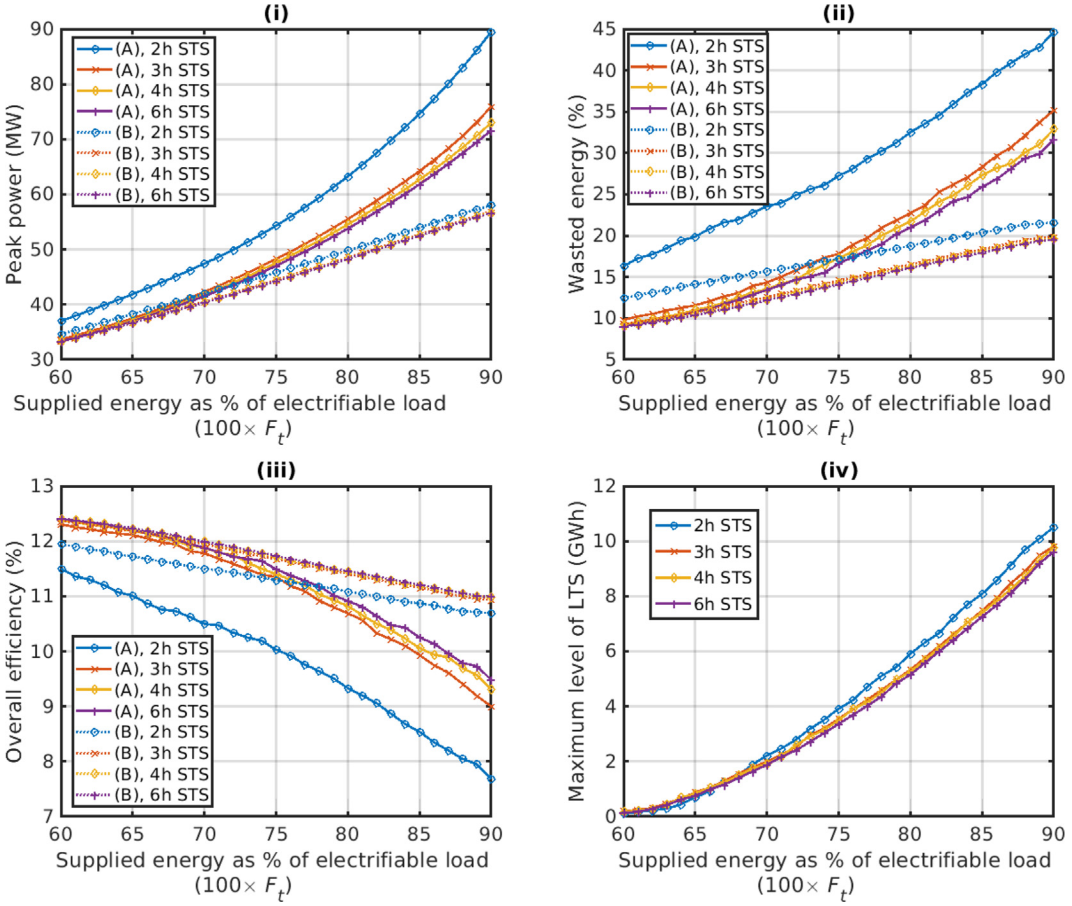


Fig. 4. Results of the simulations: (i) peak power of the systems, (ii) wasted energy as percentage of the overall PV output, (iii) overall efficiency (ratio dispatched energy / irradiation on panels), (iv) maximum level reached by LTS for system (B). Results for system (B) in the range 3–6 h of STS are almost indistinguishable.

with an oversizing close to 20%. For less ambitious goals ($F_t < 0.75$) the oversizing becomes lower than 10%.

The marked improvement when going from 2 h to 3 h of storage is in contrast with the comparatively small improvement from 3 h to 6 h. This behaviour is related to the presence of two dominant cycles for the storage: the night/day cycle and the seasonal cycle. A strong improvement can be expected when the STS reaches a level where it covers the day/night cycle; this is likely to happen between 2 h and 3 h of peak production. On the other hand, a less marked improvement is expected when increasing the storage further.

As a reference case, we choose the system with $F_t = 0.85$ and a STS capacity of 3 h. Such a system allows to reach a rather ambitious target (corresponding roughly to 75% of the *overall* energy load) with an acceptable oversizing. Details of this system are shown in Table 1.

The oversizing can be read from the ratio between the PV peak powers of the two systems, and is equal to 21.80% for the case considered in Table 1.

Fig. 6 shows the time evolution of the cumulative missing energy (which sums up to 15% of the load for both systems) and of the LTS level for System (B), for the reference case. The LTS, when present, exhibits a charging phase between April and September, and a discharge phase between October and December. The target $F_t = 0.85$ allows for the use of non-renewable energy in the first months of the year, amounting to less than 15% of the required load. The dynamics is not so different from the system without LTS, as can be seen by the evolution of the cumulative missing energy: the increase for system (A) takes place a couple of months earlier and it is more gradual. Recall however that (A) is more than 20% larger than (B). Such a dynamics cannot be avoided in system (A), whereas in (B) it could be re-modulated allowing for a better distribution of the energy accumulated in the LTS and a less-peaked use of non-renewable sources.

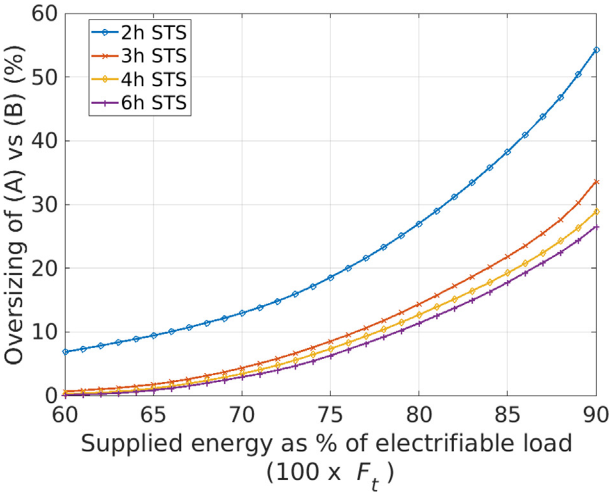


Fig. 5. Oversizing of System (A) w.r.t. (B) vs the percentage of electrifiable load supplied by PV ($100\times F_t$), for different STS capacities.

Table 1
Results for Systems (A) and (B) with STS capacity of 3 h, $F_t = 0.85$.

	PV peak power (MW)	Inclination (deg)	Overall PV output (GWh)	Dispatched output (GWh)	Overall efficiency (%)	Wasted energy (%)
System (A)	64.24	58	443.24	317.57	9.92	28.35
System (B)	52.74	36	388.92	317.57	11.15	18.35

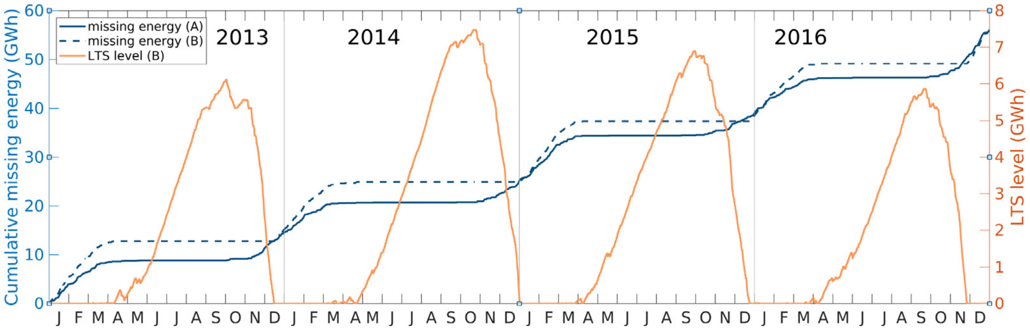


Fig. 6. Time evolution of the cumulative missing energy for (A) and (B), and of the LTS level for (B), for STS capacity of 3 h, $F_t = 0.85$.

5.2. Discussion

A PV-only system in a location with a large seasonal variation on irradiation and demanding heating requirements can supply 85% of the electrifiable load (corresponding to nearly 75% of the overall energy requirements, under conservative hypotheses) by adopting only a 3-h STS, with an oversizing of about 20% w.r.t. a system with unlimited LTS. Such oversizing is clearly feasible and surely – at present – economically advantageous w.r.t. the design and implementation of a grid-scale LTS system. In real scenarios, considering the contribution from all renewable energy sources and the available – even if limited – LTS capacity from HE, this oversizing will presumably be much lower for a given F_t; or the same oversizing could lead to a higher F_t.

A 85% threshold is an ambitious goal, and its achievement in reasonable time is certainly a worthy result even in absence of a strategy to supply the remaining 15% through renewable sources. So, the comparison between the two systems suggests that the role of LTS for achieving high penetration of VRE is not crucial, and that there is no reason to delay the transition to renewables while waiting for the development of, e.g., stable solar fuels. Given the urgency of an environmental emergency such as climate change, massive deployment of PV endowed with STS should be started without further hesitation in favourable locations. Meanwhile, electrification of transport, heating and all the electrifiable energy load (including a large part of the industrial non-electric current load) should be pursued. While reaching 100% of VRE with STS only is not a realistic task (a simulation with $F_t = 0.99$ indicates that the required curtailment would be about 65% of the production), the remaining fraction could be in large part covered by HE, leaving to fossil fuels a marginal contribution.

The main drawback in this scenario is that a tunable backup should be present anyway in order to guarantee the continuity of electric supply, since it is clear that STS cannot compensate low radiation (or wind) lasting more than a few days. Given the presence of STS, the needed power for the backup system would be comparable to the daily average load, rather than the peak load, since STS can be used to accumulate the energy produced by the backup as well. This requirement should not be a problem in a short-term perspective, since the already-installed fossil-powered plants can be used for such emergencies. Over the long term, this role will be fulfilled by economically viable LTS systems, whose development remains one of the fundamental tasks in energy research. In particular, it is widely recognized that developing stable, storable and inexpensive renewable fuels would be the definitive solution, with overwhelming advantages in terms of energy management. Moreover, such fuels would provide a solution for the non-electrifiable load. However, while this goal is being pursued, renewable sources can supply a large part of the needed energy only with STS. There is no justified concern of wasting resources with a massive investment in installed capacity: indeed, the installations are not specific to an STS-only plant (except perhaps for the inclination of the panels, which can be easily changed) and can also be used to charge an LTS, when it will be available.

It should also be stressed that the analysis is tailored to the current energy demand, without any demand-side optimizations changes to match the supply; but in the near future it is likely that actions will be taken to change the demand profile, as hypothesized e.g. in [18]. Better thermal insulation of buildings, redistribution of working hours for energy-intensive activities, use of EV batteries as supplementary storage (encouraging charge when VRE production is high) are demand-side measures that can give a further contribution to VRE penetration.

6. Conclusions

The main goal of the present work is to draw a general comparison between STS and LTS in a PV system and to evaluate the need for LTS in order to achieve high penetration of VRE in energy production. The comparison was carried on by computing the oversizing of an STS-only plant vs a plant endowed with unlimited LTS, both of them producing the same fraction of the overall electrifiable energy load, including transport and domestic heating. Results show that, up to a large fraction of the energy load (up to 90%), an STS-only production facility with a feasible capacity (3 h of peak production) can supply the same energy as the LTS plant with a moderate oversizing of the solar field (less than a third). There is no strong improvement when increasing the STS to more than 3 h of peak production. In particular, an oversizing of about 20% is enough to supply 85% of the whole electrifiable load (roughly corresponding to 75% of the overall energy load) with a 3 h STS. Therefore, LTS does not appear to play a crucial role in penetration of VRE up to a large fraction of the load, at least for PV systems. As a consequence, transition to renewables can be pursued over the short term through massive deployment of VRE endowed with STS.

The analysis does not take into account the contribution of wind energy (with a seasonal compensating factor), nor the contribution of HE, both for energy production and for storage purposes. Moreover, no hypotheses on demand-side measures (remodulation of the load, better thermal insulation) were made. When considering all these factors, it is to be expected that energy from fossil fuels can be reduced to a marginal contribution, mostly limited to exceptional weather conditions. Note however that this backup role can be taken by the already-installed fossil-based power plants, up to the end of their planned lifespan. The main role of future LTS (whose development remains a fundamental goal in energy research) will be to eliminate the need for a full-scale fossil backup system.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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