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) to supply 85% of the whole electrifiable load. Therefore, the current lack of clear routes towards grid-scale LTS should not be considered as a reason to delay the transition to renewables.

The recent price drop of technologies for renewable energy, especially wind and photovoltaic, 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.

Expected variations of the sources can be classified in short-time variations (e.g., day-night cycle, or short time fluctuations) and seasonal variations. Correspondingly, storage systems must meet different requirements on available power, capacity and energy losses, depending on whether they are devised in order to compensate short-time variations (short-time storage, STS in the following), or to compensate seasonal variations (long-time storage, LTS in the following). In particular, requirements on capacity and on daily energy loss are more stringent for LTS.

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). 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. These 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 close to worst-case for 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 the *maximum* oversizing needed in order to avoid LTS, for a given energy production goal, and it is independent of current prices and specific technologies. As a consequence, it is a good indicator of the real usefulness of devising a grid-scale LTS.

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 Fig. 2 of [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]. Moreover, a hydrogen-based energy policy conceals an additional management risk: when hydrogen is established as the main secondary source to produce electricity, the possibility of obtaining it using a far cheaper route (from hydrocarbons) can lead, for instance in times of economical crisis, to accept that a significant fraction of the energy supply could be obtained from hydrocarbons, possibly with some amount of CO_2 sequestration, therefore delaying the transition to renewables indefinitely.

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 Li 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. LiFePO4 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 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.

The scenario under study

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

1. Ignoring hydroelectric production means ignoring a renewable source that is tunable and already endowed with seasonal storage;
2. 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;
3. 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;
4. The seasonal variation of irradiation is strong: in the scenario under consideration, the average irradiation in December is 51% lower than in July.

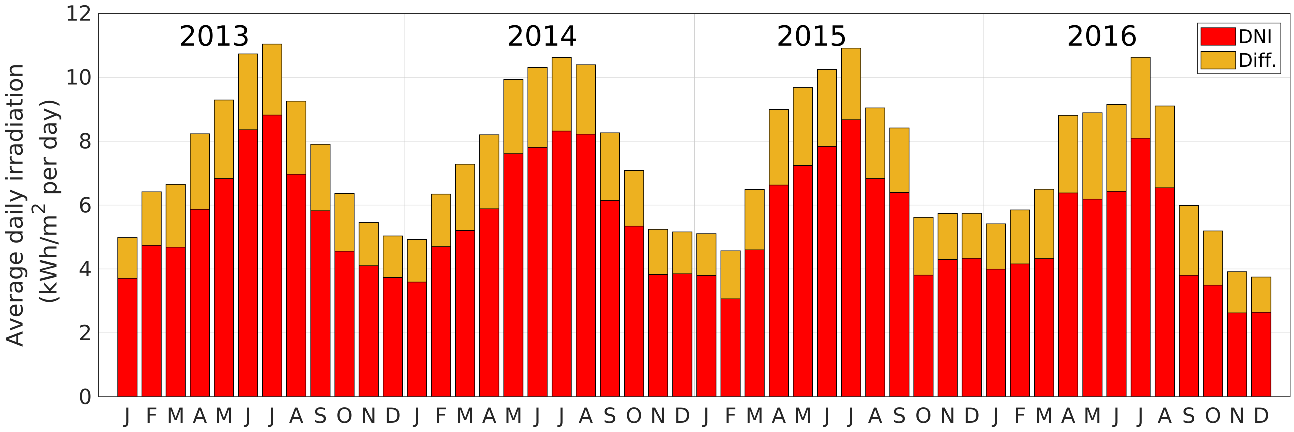

Figure 1: Average daily irradiation (DNI and diffuse).

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

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

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

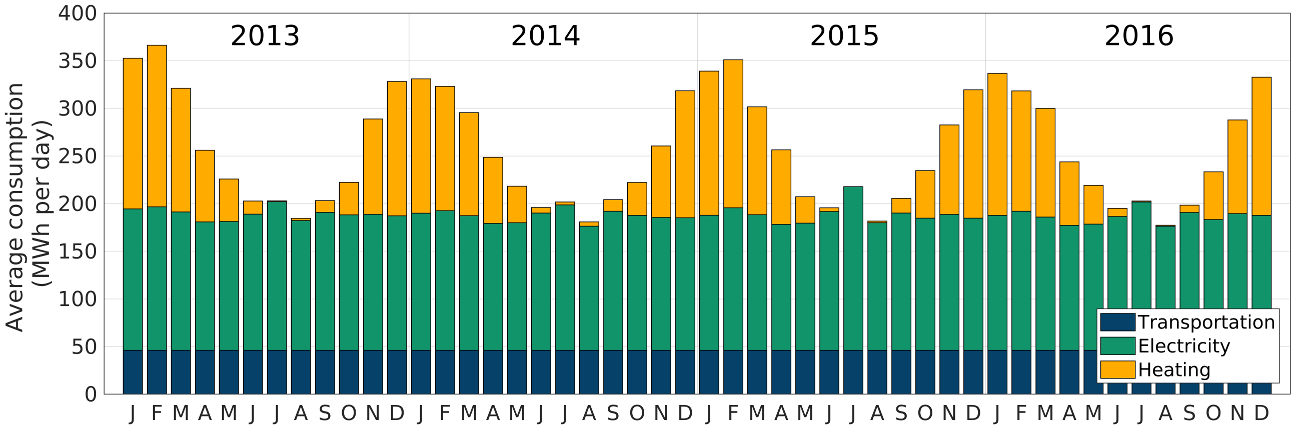

Figure 2: Average daily energy consumption, rescaled for a community of 10000 people.

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.

The choice of the load is also highly unfavourable to system (A), for the presence of a strong heating load that is, of course, 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 much 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, but to build a scenario that can be considered as a worst-case for system (A), while remaining in the range of plausible systems. 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.

On the whole, for the purpose of comparing the two systems, we think that in this scenario the needs for a LTS would be felt as strongly as reasonably possible, and the difference in performance between (A) and (B) is expected to be emphasized. So, the computed oversizing is a good indication of the maximum oversizing one could expect for a PV system.

A comparison will be performed between (A) and (B), with both systems adopting 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 hours of peak production.

System (B): a system equipped with the same STS as (A), plus unlimited LTS with 45% efficiency, and no daily loss.

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 Methods.

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%.

Results

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

Figure 3 show 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 with an oversizing close to 20%. For less ambitious goals ($F_t < 0.75$) the oversizing becomes lower than 10%.

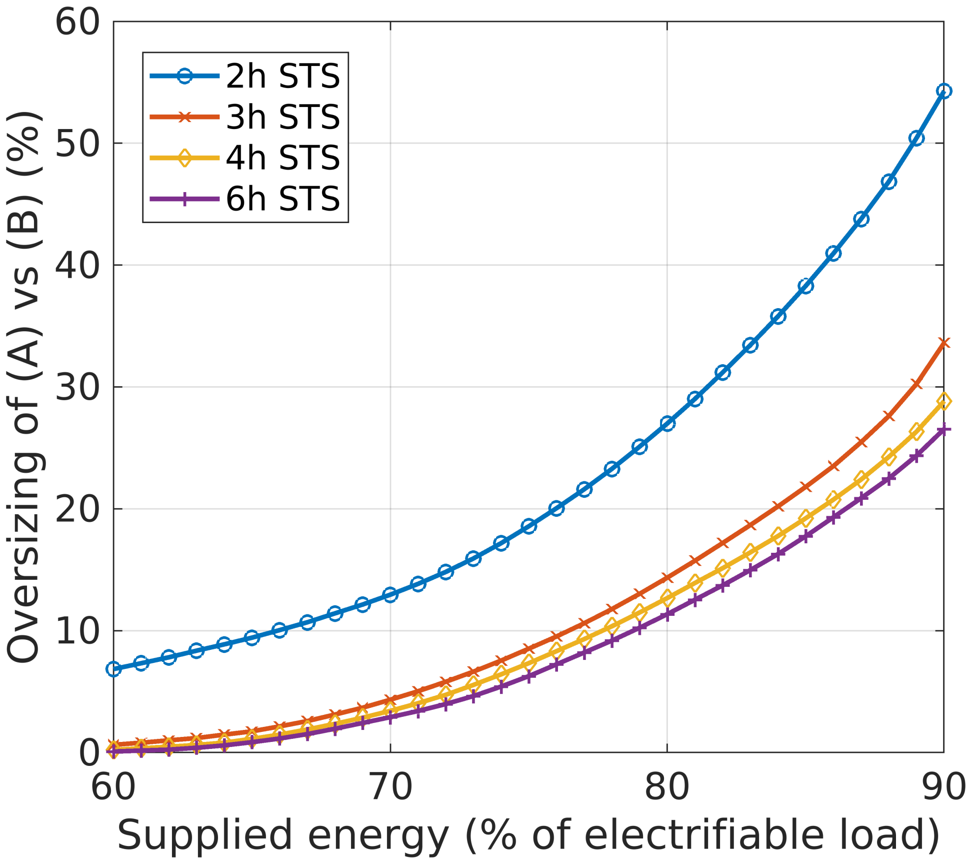

Figure 3: Oversizing of System (A) *w.r.t.* (B) *vs the fraction of electrifiable load supplied by PV, for different STS capacities.*

As a reference case, we choose the system with F_t = 0.85 and a STS capacity of 3 h. Details of this system are shown in Table 1.

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

	PV peak power (MW)	Panel inclination (deg)	Overall PV output (GWh)	Dispatched energy (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

The overall efficiency is the ratio (dispatched energy) / (overall incident radiation); it takes into account the efficiency of the PV panels, the wasted energy and the efficiency of the storage systems. The wasted energy is the PV output that goes unused or that is lost due to less-than-100% efficiency of the storage; it is given as a percentage of the overall PV output.

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.

Figure 4 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.

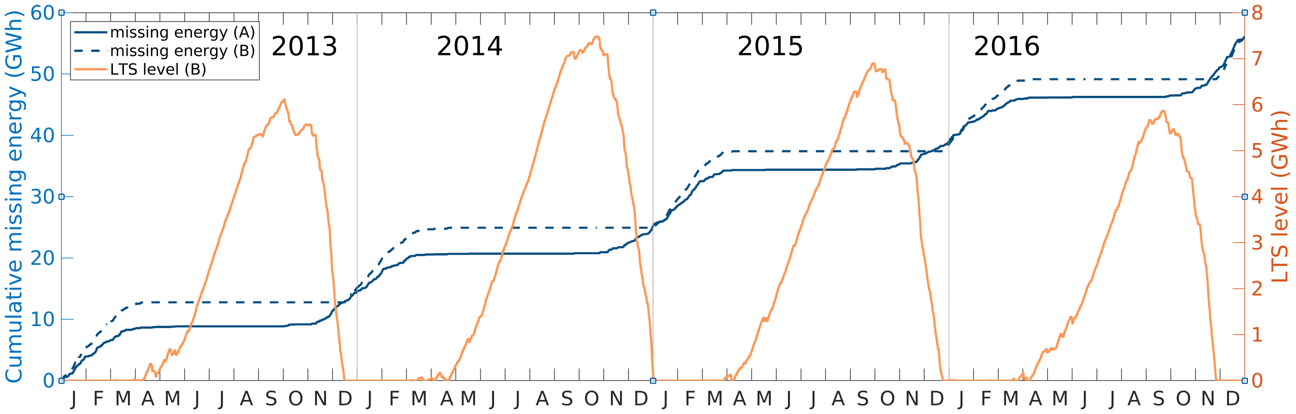

Figure 4: time evolution of the cumulative missing energy for (A) *and* (B), *and of the LTS level for* (B), *for STS capacity of 3 h,* $F_t = 0.85$.

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-hour 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.

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 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.

Of course, this does not mean that research on renewable fuels or other forms of seasonal storage is devoid of value: 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.

Methods

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 (https://re.jrc.ec.europa.eu/pvg_tools/en/).

The electric load sequence is the sum of three different components:

a) The actual electric load of Italy, obtained from (https://www.terna.it/it/sistema-elettrico/dispacciamento/dati-esercizio): hourly data from 2013 to 2016;

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. 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]. The equivalent required electric energy is estimated assuming to use heat pumps with COP = 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 (https://re.jrc.ec.europa.eu/pvg_tools/en/); 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.

PV modules

The production of the PV panels is computed at each 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 [28]. The contribution of diffuse radiation (DFI) is considered to be 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 [29]:

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

where η_0 is the nominal efficiency at temperature T_{ref}. We assume T_{ref} = 25 °C, β = 0.0041, η_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 panel temperature is estimated adopting a simple model already described in [30], which considers thermal irradiation and natural convection from the panels, using correlation for heat exchange taken from [31], Section 8.4.

Simulation procedure

In order to smoothen the time simulation, the input time sequences are pre-processed in order to change the time-step to 1/10 h instead of 1 h, adding points by linear interpolation. Given the peak power W_{peak} of the PV field (or, equivalently, the area 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. If $E_{pv}(j)$ is larger than the load $L(j)$ required for the time step, 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. 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%.

Since starting the simulation with empty storages can 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, 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.

Given a value for F_t and for the panels inclination, the simulation is repeated in order to find the W_{peak} that is required to supply the fraction F_t of the whole electrifiable load; W_{peak} is found by bisection. 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.

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