Energy Proceedings
Vol 29, 2022
ISSN 2004-2965

Sizing of long duration storage in a variable renewable power system#

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ABSTRACT

The sizing of long duration storage is one of the main challenges in the study of the feasibility of low-carbon power systems. In reviewing the literature, we identify that the consideration of technical and environmental constraints as well as uncertainty in production and consumption impact its sizing. We then determine that, with a classical unit commitment optimization, the choice of the simulation horizon, as well as the length of that horizon and the combination of years on which the study is carried out have a significant impact on the sizing of long duration storage. The reasons for this are the different long duration storage (LDS) discharge need profiles in different years and the sizing method used. We also found that the sequence of meteorological events significantly impacts the LDS sizing. Hence, our need for LDS considerably increases compared to the results proposed by the literature which in most cases doesn't consider those methodological aspects. This finding calls for the development of more robust methods for sizing long duration storage as well as further research on the LDS role in high penetration variable renewable energy (VRE) power systems.

Keywords: renewable power systems, energy storage, power systems modeling, long duration storage, security of supply.

NONMENCLATURE

Abbreviations	
LDS	Long duration storage
SoC	State of charge
VRE	Variable renewable energy

1. INTRODUCTION

Transforming our energy and power systems from fossil fuels to low-carbon solutions is a key part of the energy transition. The literature is rich with prospective scenarios for the development of variable renewables (mainly wind and solar) in the power system, exploring the challenges and solutions that emerge. Among these, Long Duration Storage (LDS) provides a solution to manage the large-scale variability of solar and wind production [1]. It has a role to play in most decarbonized power systems [2]: by charging during periods of surplus production and through its ability to store energy for long periods, LDS can cope with periods of low production or exceptional events to ensure security of supply. However, many challenges remain, both regarding the technology itself (the full charge-storage-discharge cycle is not yet industrially mature [1]) as well as integrating it with the rest of the power system [3],[4]. In addition, current methods for sizing long-duration storage do not appear to be mature enough, and its role does not appear to be adequately addressed, leading to potential under- or oversizing.

We seek to understand what criteria should be considered methodologically to properly understand the role of long-term storage and its sizing. To this end, we conduct exploratory work to identify the key drivers. First, we conduct a literature review to qualitatively understand the potential sources of under- or over-sizing of LDS. Then, we focus on two criteria that seem to be neglected in the literature: The pluriannual variation of VRE generation and consumption, and the length of the period over which the simulation is performed. To this end, we use a simple theoretical use case with 8 years of data, using only VRE production and short- and long-term storage. We find that the need for LDS varies significantly when considering these two factors, but also that the combination of years affects it. The reasons for this are the VRE inter- and multi-year variation, but also the sizing criterium - which significantly affects the multi-year energy displacement - and the simulation myopia.

Hence, the novelty of this research lies in the quantification of different model parameter's impact on the LDS sizing, highlighting monthly, annual and pluriannual dynamics in the VRE and consumption variability as well as it's dependency to the sizing criteria. For example, we find that the LDS state of charge of a given n year is dependent to the discharge need in the n+2 or n+3 year. Doing so, we go further than most of papers dealing with LDS in VRE power systems by suggesting that the need for LDS might be significantly higher to balance power system on the long run.

Thereby, the contribution of this paper is to highlight the issues associated with sizing LDS and batteries in full VRE power systems. This is implemented in a simple use case in which a central actor has perfect foresight.

2. BIBLIOGRAPHIC ANALYSIS

2.1 Method

We compiled a corpus of articles from the literature, sourced from journals such as *Journal of Energy Storage, Renewable and Sustainable Energy Reviews, Renewable Energy, Joule, Energy Conversion and Management, Nature Energy* but also a few PhD thesis and institutional reports published since 2010 dealing with 100% variable renewable power (VRE) systems issues. Then, we developed an analysis framework which assigns a score to each of these studies based on several criteria. Each of these criteria – described below – can be found in the literature, independently of each other, and are identified by the different authors as having an influence on the role of the long duration storage. Grouped together, those criteria allow us to highlight studies judged to be methodologically complete on the representation of LDS.

The literature is extensive about power systems with high variable renewable penetration. Hence, we focus on studies that present a unit commitment problem, where the penetration of wind and solar renewables is above 80% and that provide sufficient details (production capacity installed, storage description, production and consumption data, etc.) to be exploited. This first screening of 100 studies allows us to select 38 of them [2,6-12,14-44] which are used to fill the analysis framework provided below.

Our analysis framework is divided into 23 criteria:

(1) <u>Description of the LDS.</u> The purpose of the LDS, the discharge and charge strategies and the interaction strategy with the rest of the energy and storage system are scrutinized:

(a) Is a distinction made between the energy/power ratio and the operating time without recharging?
(b) Is a distinction made between LDS and batteries in terms of demand response?
(c) Is response time or ramping considered?
(d) Is minimum uptime or downtime considered?
(e) Is efficiency considered?
(f) Is a degradation factor for storage considered?
(g) Is the discharge rate considered?
(h) Are the land, environmental or material footprints considered?
(i) Is the charging power described?
(j) Is the discharge power described and differentiated from the charge power?
(k) Is a strategy for operating the storage system described?
(l) Are grid constraints discussed?
(m) Are the SoCs (State of Charge) presented?

(2) <u>Plurality of demand and generation data and consideration of meteorological and contingencies:</u>

(a) Is future demand analyzed or discussed?
(b) Are weather related demand contingencies identified?
(c) Is the peak sizing of production discussed?
(d) Is a sensitivity analysis conducted on the technological orientations of the demand?
(e) Are weather-related production contingencies identified?
(f) Is balancing simulated over several years?
(g) Are the impacts of climate change considered?

(3) <u>Sizing and security of supply:</u>

(a) Are the risks of underestimating storage capacities discussed?
(b) Is a safety margin or reserve discussed?
(c) Are the risks of failure discussed?

2.2 Results

The main conclusions of the framework analysis are:

(1) The technical constraints of storage facilities do not seem to be generally considered in the literature, although these elements have physical realities beyond the charge, discharge, and efficiency (which are broadly explored) and use cases are rarely expressed. Optimization is essentially based on economic criteria and does not consider the technical and environmental dimension of the problem. The services that can be provided by the different types of storage facilities are rarely discussed.

(2) Risk management as well as human, technological and meteorological uncertainties are poorly described in a literature that is dominated by deterministic studies over limited number of years, but which do not capture the weather and demand variability.

(3) A large majority of studies simulate on a single year and do not analyze the impact of variability in

production and consumption over several years, although more and more recent studies tend to do so [5,6,7]. Indeed, studying a power system over only one year underestimates the need for long duration storage although the underestimation factor is not known [8].

(4) Security of supply is poorly addressed: 15% of analyzed studies mention it as a source of underestimation of LDS need but only a few addresses it in detail. However, in an uncertain environment and to ensure security of supply, energy displacement requirements may be considerably higher, as well as costs since the literature shows a higher sensitivity to energy displacement than to power requirements [9].

(5) The use of inappropriate tools for the intended objective: according to the studied methodologies, to capture the role of the LDS, a modelling tool should have a multi-annual vision at an hourly time step in a continuous manner (simulation over consecutive years) and consider the uncertainty in production and consumption. The latter is mainly due to meteorological factors as unpredictable events can occur. In current power systems such events occur mostly during high demand period (such as very cold winter as in Texas in 2020-2021 or during the last summers in California) but in 100% VRE power system, the attention could shift towards low wind events, which are largely unpredictable and should occur more often and in a more intense way due to climate change [46]. Three categories of tools are identified: stochastic, deterministic, and capacity expansion ones. Stochastic tools use many production and consumption data and hence capture the uncertainty in production and consumption but the two distinct tools that were identified do so only over short periods (typically a year) and therefore do not capture the impact of the variability of net demand on a multi-year scale and the associated risks and opportunities. The rationale for simulating over a short period of time is not detailed, but it may be because simulating over many consecutive years is not necessary in current power systems as the main issue is power balancing and the sizing timesteps are at the consumption peak, often in winter. With 100% VRE power systems, an energy balancing issue rises with poorly known implications. Moreover, as stochastic tools are largely used by institutional actors who have access to data and significant computing power, this doesn't come from a lack of resources.

Similarly, deterministic tools using data from a small number of years fail to capture the plurality of different years that exist. Unlike the former set of tools, this could come from a lack of data and computing power. Moreover, some studies such as [10] use deterministic models and consecutive weather years but replicating the consumption data from only one year, hence failing to match appropriate consumption and production data which are correlated since weather dependent.

Finally, capacity expansion tools often apply clustering methods where typical days are identified, which does not allow for proper load tracking of long duration storages on the one hand, and for capturing the variability of RE over the simulation horizon on the other. Some deterministic and capacity expansion studies use over-sizing factors which multiply the production power capacity resulting from the simulation to account for uncertainty, but none was found to do so for storage capacity. Moreover, there is no certainty that the usage of such factor would result in a correct sizing for a given power system. Thus, insofar as no model is omniscient and each one meets a precise objective, it seems that no available model or methodology is adequate to study the place of long duration storage, which requires several cross-cutting issues.

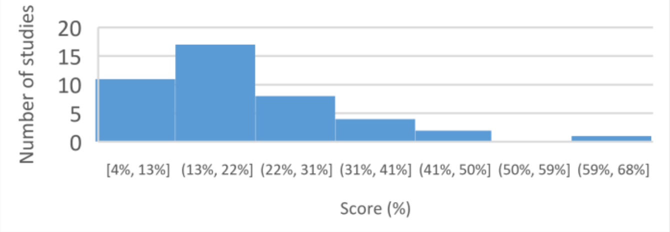


Fig. 1 - Distribution of studies according to their consideration of criteria influencing the design of LDS

The distribution of scores (defined as the percentage of criteria – where every criterium has the same weight since we don't know their ranking toward LDS sizing – considered by a study: a ~35% score means 8 identified criteria were considered in each study) is plotted (Fig. 1). The median is at 20% and the maximum score is close to 70%.

2.3. Discussion

Although the literature review is not exhaustive and its analysis subject to potential misunderstandings as every aspect of each model is not described in each article, it does allow us to formulate several areas for improvement to correctly understand the place of long duration storage. First, it seems necessary to consider the technical and environmental constraints of storage facilities, both in the modelling and in the discussion of the results. For this purpose, use cases should be designed and evaluated. Moreover, the consideration of uncertainty in consumption and production, through the discussion of technological choices, meteorological hazards, climate change impact in a stochastic process with simulations over long periods should be conducted to correctly assess the issues of security of supply and the role that storage and long duration storage can play in it.

Although identified as possibly impacting the LDS sizing, the quantitative impact of considering these elements in the design of LDS has not been determined and underestimation factors for each of these criteria is not known. Thus, ranking them is difficult and it calls for further research.

3. ANALYSIS OF THE SENSITIVITY OF THE LONG DURATION STORAGE TO THE SIMULATION YEAR

Among the criteria that may lead to an underestimation of the LDS sizing, we choose to focus on the choice of the simulation year and the duration of the horizon on which the simulation is conducted. [8] already explored this topic by concluding that when simulating a deterministic model over consecutive years the LDS sizing increases, but we aim to explicit the two main reasons: the combinatorics of meteorological events and the sizing method of the power system. Hence, our objective is not to size LDS systems nor the power system but to explore the degree to which those methodological aspects are critical in a 100% VRE power system.

3.1 Method

To explore the impact of the simulation year and the number of consecutive years used, we build a theoretical example. We use data from Eco2Mix from 2012 to 2019 [13] for electricity demand as well as wind and solar load factors. The only means of generation are variable renewable energy sources (wind and solar) and we optimize with a unit commitment tool the operation of the storage system on an economic criterion, curtailment, and default. The simulation is made with an hourly time step on a single node with no interconnection. The penetration of solar in the power system is fixed at 25% of energy production which represents an LDS energy sizing optimum according to [6]. The storage system is made of 24 hours batteries with an efficiency of 85% representing all the existing flexibilities on a weekly scale and an unspecified long duration storage with an efficiency of 40% (80% applied at the charge, 50% applied at the discharge). Whereas the mathematical model and equations of the unit commitment tool are like many studies [6,7,10], we have a different approach for data and methodology.

For each simulation we calculate a capacity generation portfolio that allows the power system to meet the totality of the demand and limiting curtailment to 0.5% (for computational reasons) of the total energy produced. Allowing a higher curtailment would reduce the need for long duration energy storage but it would yield a more complex problem to analyze: one more variable (curtailment) would need to be optimized and its impact will need to be considered when analyzing the results. Since our goal is not to size the power system nor to optimize its costs, we prefer this sizing criteria in which it is easier to understand the variables. Furthermore, the power charge and discharge of the storage systems (batteries and LDS) will be oversized as this is not the issue of interest.

The outputs of the model are the VRE production and the charge, discharge, and energy capacity for each hour of the simulated horizon.

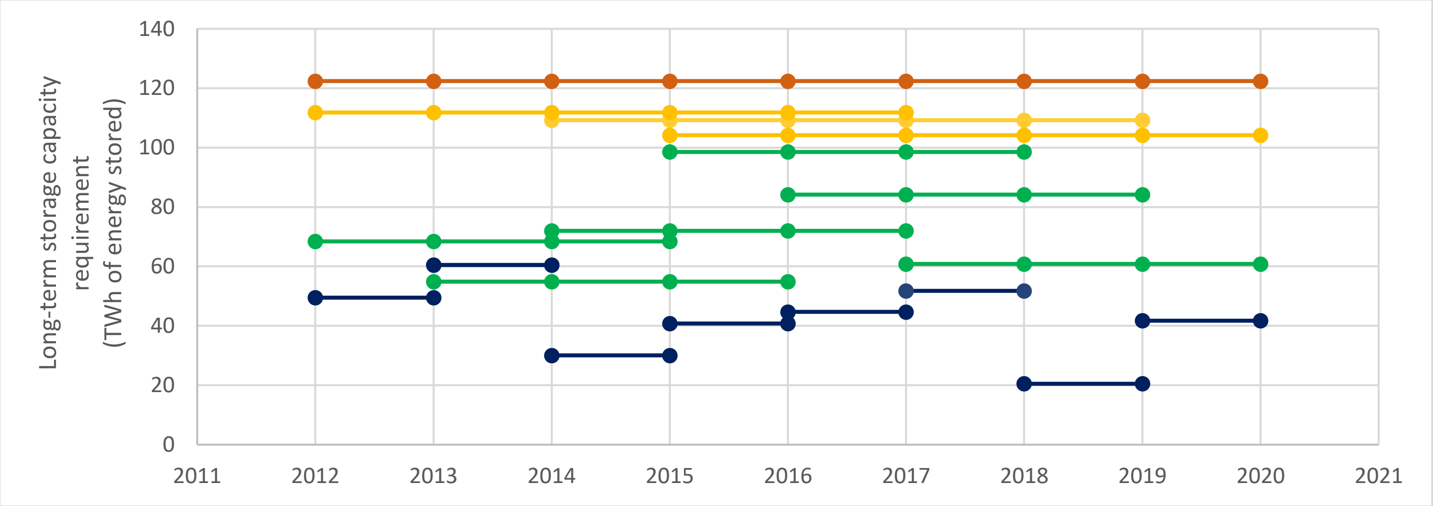


Fig. 2 - Long duration storage requirement (LDS-energy-TWh) by simulation horizon and horizon length. In red the 8-year simulation, in yellow the 5-year simulation, in green the 3-year simulation, in blue the 1-year simulation

3.2 Results and analysis

We run several simulations over one, three, five and eight consecutive years between 2012 and 2019. The results for the energy sizing of the LDS are presented in Fig. 2. This graph represents the maximum quantity of energy stored in the LDS under its efficiency assumptions and that is needed to enforce energy balancing. The aggregate capacity production is represented in Fig. 7 for each simulation with a PV penetration of about 25%.

3.2.1 <u>Long duration storage requirement according to simulation year and simulation duration</u>

We observe that the energy storage capacity requirements vary considerably along the horizon of simulation (which year(s)) and along the horizon length (how many consecutive years). We find that when a simulation is carried out over 3, 5 and 8 years respectively, the average storage requirement increases by 60%, 155% and 187% (Table 1) and within the same group of horizon lengths, the storage requirement varies by up to 50% with respect to its mean.

Simulation horizon length	Maximum (TWh)	Minimum (TWh)	Mean (TWh)
1 year	60	20	42
3 years	98	54	73
5 years	111	104	108
8 years	122	122	122

Table 1 - Mean, maximum and minimum of storage requirement as for the simulation horizon length under LDS efficiency assumptions

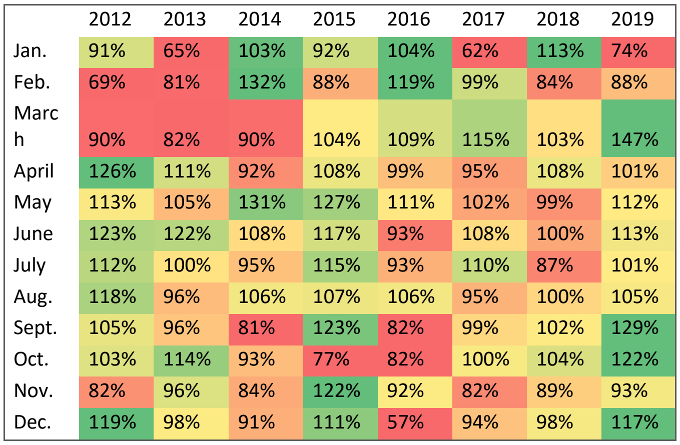
3.2.2 <u>Elements justifying the observed difference in storage needs</u>

Several elements justify the discrepancy observed between the needs for long duration storage, between the years but also between horizon simulation lengths.

3.2.2.1 Difference within a same group of horizon length simulation:

The need for long duration storage for simulation over the same number of years varies (Fig. 1, table 1) and is mainly due to one factor: the profile of the discharge needed – which varies due to the variability of VRE production – implies different discharge pattern distributions and thus storage needs.

Looking at the LDS states of charge (SoC) for the single-year simulations (Fig. 3) – SoC are represented in LDS energy TWh and not electrical TWh just all others SoC in this paper unless mentioned otherwise –, we observe that that the SoC, despite having common patterns, are quite different: while LDS cycles about once in a year and the discharge need is concentrated in winter months, the discharge profile is not always the same over the year, hence a different need for storage. During some years, the production is smoothened throughout the year (like in 2014 and 2018) but during others, low wind production events can occur, mainly in winter and increase the storage need (like in 2016-2017).



	2012	2013	2014	2015	2016	2017	2018	2019
Jan.	91%	65%	103%	92%	104%	62%	113%	74%
Feb.	69%	81%	132%	88%	119%	99%	84%	88%
March	90%	82%	90%	104%	109%	115%	103%	147%
April	126%	111%	92%	108%	99%	95%	108%	101%
May	113%	105%	131%	127%	111%	102%	99%	112%
June	123%	122%	108%	117%	93%	108%	100%	113%
July	112%	100%	95%	115%	93%	110%	87%	101%
Aug.	118%	96%	106%	107%	106%	95%	100%	105%
Sept.	105%	96%	81%	123%	82%	99%	102%	129%
Oct.	103%	114%	93%	77%	82%	100%	104%	122%
Nov.	82%	96%	84%	122%	92%	82%	89%	93%
Dec.	119%	98%	91%	111%	57%	94%	98%	117%

Table 2 - Monthly production over the monthly consumption - the color scheme is generated over a set of same months.

How to read: in September 2014, 81% of the monthly consumption was covered by the monthly production: 19% was needed from the LDS

This can also be observed when analyzing the monthly production normalized by the monthly consumption (Table 2). On this figure, the color scheme (which is calculated for each set of 8 months from 2012 to 2019) represents the variation of the monthly production over the monthly consumption regarding other respective months from other years. We observe that the VRE production patterns varies significantly and there are large discrepancies within a same group of months, hence the distribution of LDS demand is different.

Therefore, the temporal distribution of the need to discharge the long duration storage during a simulation period impacts the amount of the storage needed and due to its variation, the need for LDS increases or decreases according to the data with which the simulation is performed. This observation can also be made for the 3- and 5-years simulations.

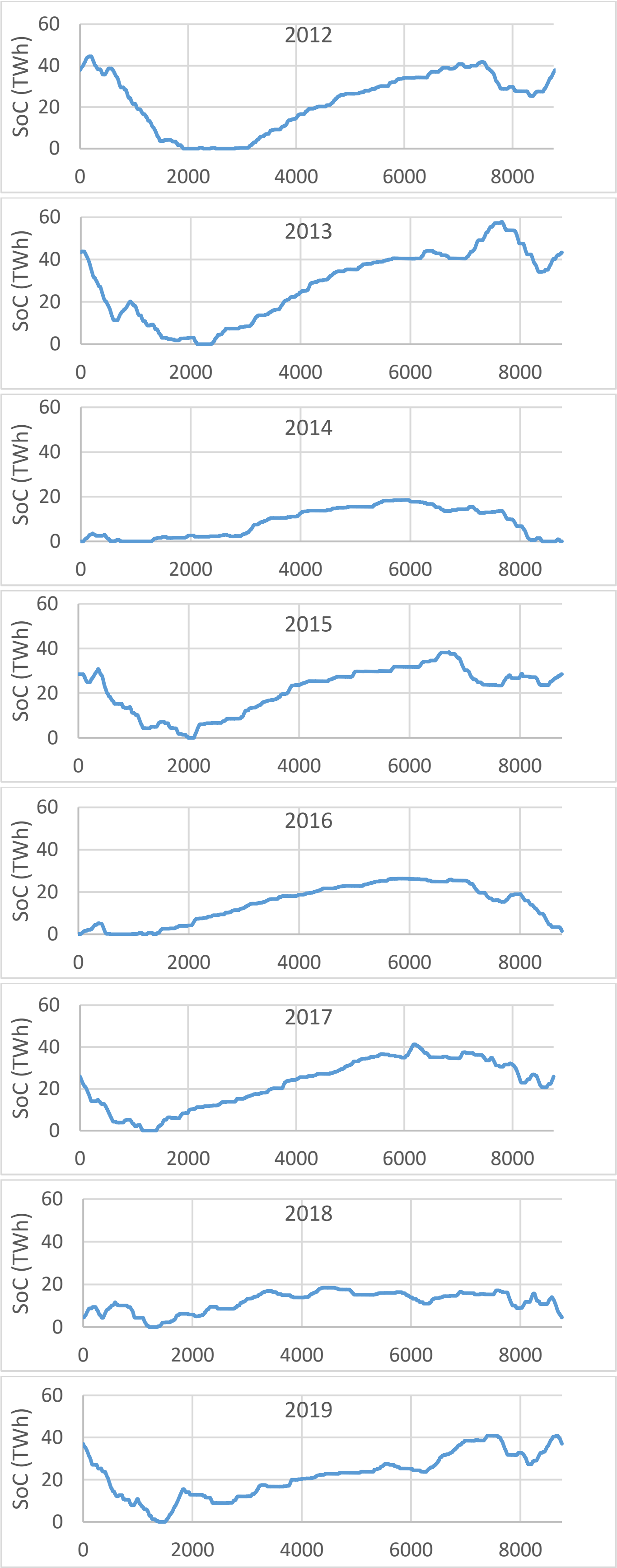


Fig. 3 - State of charge (LDS-energy-TWh) of LDS by simulation year

3.2.2.2 Difference between different horizon length simulations

We observe an increase in the need for long duration storage when increasing the horizon simulation length. This is mainly due to two reasons which cause the optimization to move energy over a longer time span. First, the myopia of the simulation prevents us to seize the previous and subsequent events and plan accordingly. Secondly, the combination and sequence of events over a longer time span increase the energy displacement need.

Let us explore these two factors. Firstly, the myopia of the simulations leads to the inability to predict the need for storage in the period following the end of the simulation. This leads to the discontinuity of SoC between simulations, like in the 2016 simulation (Fig. 3) where the SoC is near zero at the end of the year even if the SoC is needed to be high (~20 TWh) at the beginning of the 2017 year. This myopia leads to results depending solely on the net demand patterns during the simulation period. Reconstructing the state of charge over a long period from simulations from shorter periods by ensuring its continuity between years gives a good approximation but still presents a margin of error of about 20% (Fig. 4).

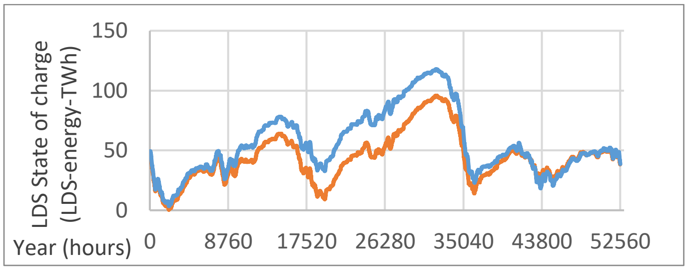


Fig. 4 - Comparison between the state of charge (LDS-energy-TWh) reconstructed from short simulations (in orange) and the state of charge calculated over the whole period (in blue)

This gap is due to the difference of production capacity portfolio over the different simulations (Fig. 6) and is intrinsic to the methodology. For each simulation, all other things are not equal as the sizing criterium set the curtailment variable to zero to liberate the optimization problem from this issue. To achieve this and because the wind and solar load factors differs each year, the capacity production is different from each simulation, being calculated to exactly meet the demand throughout a simulation without any energy loss. Therefore, the charge and discharge pattern differ even for a same year but in different time length simulations. For example, for the 2014-2016 simulation the wind and solar total production capacity was at 261.5 GW but for the 2012-2019 it was 272 GW. Hence, the need for LDS discharge during November 2014 was 2.5 TWh in the former simulation but 1.3 TWh in the latter (for a total demand of 40.4 TWh). Therefore, the discharge needs change as does the global state of charge, hence the observed difference in Fig. 4.

The second factor concerns the need for energy displacement over a certain combination of weather and demand data even on a multi-annual scale: at no curtailment, the annual net demand reaches up to 25 TWh (Fig. 5), i.e., nearly 6% of consumption (450 TWh). To ensure this pluriannual displacement, the need for storage increases.

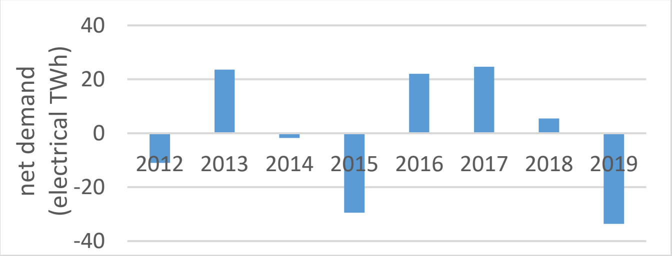


Fig. 5 - yearly net demand (electrical TWh) with zero curtailment

However, the combination of yearly net demands also influences the result: 2016 and 2017 are two years with positive net demands (respectively 22 and 24 electrical TWh), due to lower wind generation in the winter 2016-2017. This means that the system must be able to store around 46 electrical TWh from other years in anticipation of this sizing event (Fig. 7) and because of the curtailment condition, the charge is to be done over a long period of time. Hence, we observe a discharge of about 100 LDS-energy-TWh in the winter 2016-2017. In addition, the following years do not allow the LDS to be recharged and a significant need for LDS (40 LDS-energy-TWh) during the winter of 2018-2019 pushes the need for LDS upwards

Therefore, we have identified two causes for the increase in storage requirements as the simulation time increases. Firstly, the myopia of the model leads to a misunderstanding of future needs and past events. It is possible to partially compensate for this myopia by reconstructing the state of charge, but since the hypotheses for the power generation capacity for each simulation are not the same (due to the choice of curtailment as a sizing criterion), this reconstruction is limited and represents a source of underestimation of LDS requirement. Moreover, simulating over a longer horizon makes it possible to take into account a greater succession of events, which increases the need for long duration storage: in addition to sizing events, it is also the combination of events and its sequence that is central to the understanding of the behavior and therefore the sizing of LDS.

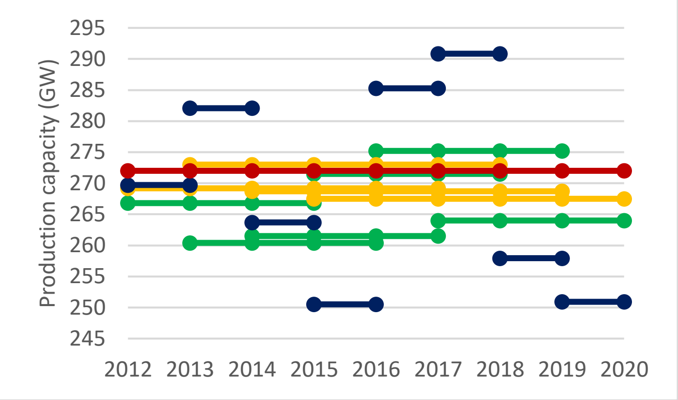


Fig. 6 - Total installed capacity (GW) to meet demand under no curtailment, according to simulation year and simulation duration. In red the 8-year simulation, in yellow the 5-year simulation, in green the 3-year simulation, in blue the 1-year simulation

3.2.2.3 *Summary.*

We find several explanations to the variability of LDS needs when simulating over different horizon and different horizon length. First, because of the VRE load factor variability but also, its profile, the temporal distribution of LDS discharge needs change and hence the SoC and the total need change also. Moreover, when simulating over longer horizon, the need for LDS increases. This is because of two biases: first, the myopia of the model prevents the model from foreseeing the previous and subsequent events, which considerably increases the LDS needs. Secondly, because we chose no curtailment as the sizing criterium, the net demand (defined as the demand minus the VRE generation, here with no curtailment) over certain years is particularly high and the system needs more energy displacement and hence more energy storage.

3.2.3 *Discussion*

The choice of the simulation horizon and its length have a significant impact on the need for energy transfer and thus long duration storage requirements, which is dependent on high discharge need events in anticipation of which the storage system is recharged. This poses a major challenge insofar as we observe a double dependency of the security of supply on production (and consumption to a lesser extent) uncertainty: here the need to discharge the LDS appears mainly in winter during events with low wind production [2] but the capacity to recharge it is dependent on the production preceding these same events.

Fig. 7 - State of charge (LDS-energy-TWh) between 2012 and 2019 for a simulation over 8 years

Thus – and this can be seen by observing the net demands (Fig. 5) and the state of charge (Fig. 7) – it is likely that the order of the simulated events also impacts the energy need for long duration storage to the first order. Moreover, long-term wind and solar load factors remain difficult to estimate, and this difficulty is increased by the impacts of climate change: simulating past years without considering the succession of possible events and especially extreme event may not be sufficient to guarantee security of supply based on the LDS.

We foresee that the very simple examples presented in this paper could be modified to include a larger number of more representative renewable production as well as demand profiles in line with future evolutions. Furthermore, to correctly size the LDS we expect that we should formulate many use cases and combine the years to find the most unfavorable combination of events. The latter being an extreme case, moving towards a 100% renewable system will significantly increase the security of supply costs. Another solution would be to rely on conventional thermal means to cope with extreme events [2,7].

The first use case to study the sizing of LDS was to consider an isolated power system without curtailment, which presents limitations. It is a theoretical example chosen with limited variables which allows us to understand the main factors at play. Adding layers to the problem will probably decrease the need for LDS but the main methodological conclusions remain. For example, allowing curtailment [11], interconnections to smoothen renewable generation between countries [12], allowing decarbonized controllable power generations [1],[2] will decrease the need for energy transfers and LDS.

4. CONCLUSIONS

The role of long duration storage in decarbonized power systems remains to be clarified in the literature despite a growing interest, and the challenges remain numerous. By reviewing the literature, we find that most of the studies dealing with 100% VRE power systems perform analysis from a classical technical-economic perspective, but without analyzing the technical, environmental, and temporal feasibility and implications and without addressing certain critical modelling aspects, which are essential for decarbonized power systems : poor consideration of technical and environmental constraints of LDS, uncertainty in renewable generation and consumption, and incomplete analysis of the role of LDS in security of supply. Then, to clarify the main issues related to LDS sizing, we analyze the impact of using different horizons (i.e., years) as well as different horizon simulation lengths (i.e., multiple year simulations). We conclude that the choice of the simulation data is essential but that even more, it is necessary to simulate over several years and several combinations of years to capture the variation of the renewable production on a multi-year scale as well as outliers. Hence, it becomes necessary to study power systems with a large number of different data set with consideration to extreme events and extreme series of events through a stochastic process that will allow us to size and to grasp the role of the long duration storage.

ACKNOWLEDGEMENT

This work was carried out as part of a PhD program funded by Electricité de France (EDF) and Mines Paris-PSL

under a CIFRE agreement approved by the French national association for research and technology (ANRT).

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