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An overview of large-scale stationary electricity storage plants in Europe: Current status and new developments

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ABSTRACT

Pumped hydro energy storage (PHS) currently is the only electricity grid storage technology with substantial deployment throughout the world, representing over 99% of storage capacity, but other storage technologies such as batteries are increasingly finding application. In Europe, the implementation of storage systems is expected to increase because of the integration of intermittent, nondispatchable renewable energy sources. Nevertheless, there is no overview available of the power *and* energy ratings of large-scale stationary storage at the supranational level. In the absence of officially collected statistics on energy capacity, publicly available information is collected from storage owners, freely accessible databases, scientific articles, reports, brochures and government websites. The status of PHS and other large-scale storage technologies in the EU-28 countries, supplemented by Norway and Switzerland, is presented. First, this paper defines a measure of energy storage capacity, to allow comparison of pumped hydro storage plants with other storage technologies. Next, a set of technical parameters of current large-scale storage plants is presented, as well as an overview of planned storage projects. The estimate of PHS power ratings in the EU-28 exceeds previous estimates, with a total of 160 plants and 45.283 GW rated power in turbine mode and a full cycle storage capacity of 602 GWh. When adding Norway and Switzerland, a total of 188 operational PHS plants is shown with 1313 GWh. The data is used to obtain EU-wide discharge curves and national indicators of utilization and significance.

Contents

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1. Introduction

Renewable power generation in Europe increased significantly during the past decade, and is expected to increase further as under Directive 2009/28/EC, in which renewable energy will have to hold a 20% share in the final European energy demand by 2020. The target for electricity generation is 34.3% of total electricity demand provided by renewable energy sources [1]. In order for Europe to meet its ambitious climate and energy policy targets, investments in additional electricity storage facilities are currently discussed to facilitate the large-scale integration of renewable energy sources [2].

The primary technology of electricity storage world-wide and Europe is pumped hydro storage (PHS), with over 99% of the installed capacity [3]. Nevertheless, some other electricity storage technologies are deployed, including compressed air energy storage (CAES), battery energy storage systems (BESS), power-to-gas (P2G) and flywheels. Recent publications discuss the techno-economic parameters of a wide range of such electricity storage technologies [4–6]. In 2013 10 of the identified projects of common interest of the European Commission include PHS; one considers BESS in Italy; another includes CAES in Larne, United Kingdom [7].

Recent overviews of current European PHS plants and new developments are given in [8–10]. A large variation in statistics regarding PHS is reported in [10]. Eurostat [11] keeps statistics on installed PHS power, but not on energy storage capacity [12]. Report [12] has a partial list of PHS plants in Germany, France, Spain and Luxembourg, including energy storage capacity. Report [13] provides an almost complete overview of pumped hydro in Germany, including energy storage capacity. For other countries, energy storage capacity is challenging to obtain. Often power ratings of PHS in turbine mode can be assembled from generation portfolio overviews of generators or grid operators [14–17]. Through a member survey, Eurelectric [18] assembled a list of national PHS power *and* energy ratings. However, some EU-28 countries known to have significant PHS capabilities that are missing, e.g. Italy. Due to the lack of information on the plant level and the lack of a definition of energy storage capacity, the information provided can only be used to a limited extent.

Nevertheless, there is a clear need for such information in the context of security of supply and the increasing uptake of renewable generation technologies. In the long-term, increasing intermittent generation requires significant energy storage capacities to bridge the gap between generation and consumption, on timescales ranging from days to seasons. For instance, [19] notes that a fully solar-based generation system for the UK would require an energy storage capacity equivalent to 80 'Dinorwigs' to bridge merely one winter night, where the Dinorwig PHS plant is the largest one operational in the UK today. Obviously, for seasonal storage, the storage capacity requirements grow further and may become impractical to accommodate for. In this context it is sometimes suggested that mountainous countries such as Switzerland and Norway may use their topographical advantages to serve as a battery for neighboring countries [12]. In order to grasp the future efforts necessary, it is imperative to have a good understanding of storage resources available today.

Supranational research projects, statistics and reports provide insufficient information to assemble an overview on the European level. Furthermore, a variety of databases can be used. EASE has a database with a number of storage plants in Europe [20] (including thermal, chemical and electrochemical storage). In addition, the US DOE maintains a global energy storage database [21]. Finally, the global energy observatory collects a list of PHS plants [22]. For some plants, details can be found at Enipedia [23]. Nevertheless, project data in these databases is incomplete, primarily lacking data of reservoir volumes and energy storage capacity.

Next, [8–10] discuss new projects, but only PHS technology. Deliverables of the European StoRE project discuss storage developments in Spain, Germany, Denmark, Greece, Austria and Ireland [24]. An overview of storage research projects of any technology in Europe is provided in [25]. However, this report includes almost exclusively publicly funded storage projects. A variety of projects of different technologies is discussed in [26].

The contribution of this paper is the presentation of an overview of stationary large-scale electricity storage plants, in terms of both power *and* energy ratings, at the plant and country level for the EU-28 countries plus Norway and Switzerland. It is not possible to guarantee that this overview is entirely complete. The use of these databases [20–23] is avoided, unless no other source is available. Scientific articles are preferred to reports, to brochures, to websites. Information provided by owners/operators is preferred to third party sources. Nevertheless, for some plants information remains incomplete. Furthermore, the data collected may contain inaccuracies. Readers are specifically invited to contact the authors if they can provide higher-accuracy data.

First, Section 2 defines energy storage capacity and other parameters, allowing for a comparison of PHS plants and other storage systems. Section 3 proposes a dataset of current European PHS plants by country, accompanied by information of other large-scale stationary storage systems. Section 4 analyzes the PHS data using additional statistics. Finally, Section 5 concludes this review article.

2. Definition and method

2.1. General definition

The storage of electricity represents a combination of three functions [27]: firstly consuming electricity, secondly accumulating the energy in some form, and finally generating electricity again. A simplified, linear definition is given to facilitate data collection. Only storage systems that consume nonnegligible amounts of electric power $P_c(t) > 0$ during charging and generate nonnegligible amounts of electric power again during discharging $P_d(t) > 0$ are considered. Furthermore, it is assumed that the storage system is operated with $P_d(t) \cdot P_c(t) = 0$ to determine the energy storage capacity. This means that the electricity consumption phase and the electricity generation phase are strictly separated. The rated power during charging P_c^{nom} and discharging P_d^{nom} are specified by the designer of the storage system, therefore the energy consumed E_c^{nom} and generated E_d^{nom} can be measured easily over a full electricity storage cycle at rated power:

$$E_c^{nom} = P_c^{nom} \cdot \Delta t_c, \tag{1}$$

$$E_d^{nom} = P_d^{nom} \cdot \Delta t_d. \tag{2}$$

Only part of the consumed electric energy is converted to energy stored in the buffer during charging and only part of the stored energy is converted back into electric energy during discharging. Furthermore, over time, the buffered energy may increase and decrease independent of the grid (exogenous), e.g. in PHS plants due to natural inflow or evaporation and in diabatic CAES due to natural gas combustion and heat losses. In reality it may be difficult to accurately distinguish the different mechanisms for exogenous change, e.g. in case evaporation and natural inflow of water in a PHS occur at the same time, the water level in the reservoir does not necessarily change. To determine a measure for storage capacity

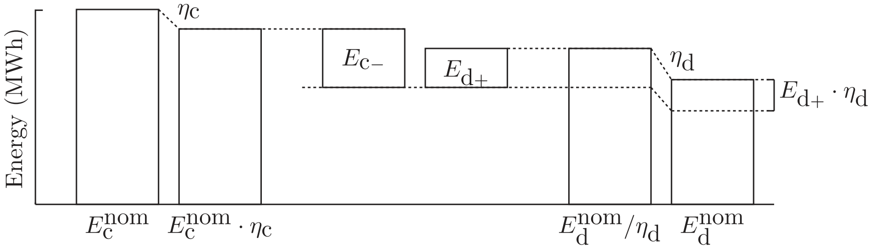

Fig. 1. Energy storage capacity definition over a cycle.

Table 1
New storage developments in Europe (> 1 MW).

Country	*Number of projects*	Project	P_d^{nom}(MW)
AT	11	Ebensee 150 MW, Kaunertal 400 MW, Koralm 940 MW, Kuhtai II 130 MW, Limberg III 480 MW, Molln 300 MW, Obervermuntwerk II 360 MW (T) 320 MW (P), Reißek II 430 MW, Rellswerk 12 MW (T) 15 MW (P), Tauernmoos 130 MW, Riedl 300 MW	3632
BE	2	Coo III 600 MW, iLand offshore PHS 550 MW	1150
BG	1	Chaira lower reservoir upgrade	–
EE	1	Muuga 500 MW	500
FR	3	Lac Noir upgrade, Le Cheylas variable frequency upgrade, Revin refurbishment	–
DE	12	Adele CAES 90 MW, Atdorf 1400 MW, Blautal 60 MW, Forbach 200 MW, Heimbach 400–600 MW, Juchber/Walchensee 700 MW, Nethe 390 MW, Rurh spoil tip complex 200 MW, Schmalwasser 400 MW, Schweich 300 MW, Simmerath 640 MW, Waldeck II plus 300 MW	5080–5280
GR	1	Amfilochia 587 MW	587
HU	1	[33] 560 MW	560
IE	3	Glinsk 480–1200 MW, Kippagh Lough 70 MW, Knockagreenan 70 MW	620–1340
IT	11	Campolattaro 572 MW (T) 630 MW (P), Sambuco 960 MW, Somplago 115 MW, Val D'Ambra II 70 MW, Verzasca 300 MW, Cavaglia II 105 MW, NaS BESS 35 MW [34] as part of [7], ABB Li-ion BESS 2 MW, Saft Li-ion BESS 1 MW, FIAMM NaNiCl BESS, 1.2 MW 39 MWh water electrolysis	2161.2
LT	1	Kruonis fifth turbine addition +225 MW (T) +200 MW (P)	225
LU	1	Vianden refurbishment	–
PL	1	Mloty 750 MW	750
PT	12	Alto Tamega complex 1200 MW includes Gouvaes– Padroselos – Alto Tamega-Diavoes, Baixo Sabor 170 MW, Carvao-Ribeira 555 MW, Foz Tua 251–324 MW, Frades II 192MW, Fridao 238–256 MW, Alvito 136–225 MW, Girabolhos 430 MW, Paradela II 318 MW, Salamonde II 204 MW, Venda Nova III 736 MW, Younicos BESS 2.5 MW	4432.5–4612.5
RO	3	Gozna Semenic 200–500 MW, Izbiceni reservoir, Tarnita – Laputesti 1000 MW	1200–1500
SI	1	Kozjak 400 MW	400
ES	8	Aguayo II 1014 MW (T) 1244 MW (P), Belesar III 210 MW, Conchas-salas 400 MW, El Hierro 11.3 MW (T) 6 MW (P), Jabalcon 550 MW, Moralets II 400 MW, Peares III 150 MW, Santa Cristina 750 MW	3485.3
GB	6	Balmacaan 300–600 MW, Coire Glas 300–600 MW, Glyn Rhonwy 99.9 MW, Sloy 60 MW, Larne CAES, Leighton Buzzard substation BESS 6 MW 10 MWh	765.9–1365.9
$\sum$28	79		25 548.9–27 548.9
NO	5	Tonstad III 1400 MW, Holen 700 MW, Kvilldall 1400 MW, Tinnsjo 700 MW, Tysso 700 MW	4900
CH	7	Bernina (Lago Bianco) 1000 MW, Grimsel III 600 MW, Linthal 1000 MW, Nant De Drance 900 MW, Verzasca 300 MW, Veytaux upgrade 240 MW (T) 256 MW (P), Tierfehd (Nestil) upgrade 1000 MW	5040
$\sum$30	91		35 488.9.6–37 488.9

and efficiency, it is assumed that the storage system is operated with electricity generation starting immediately after the storage buffer is filled. Therefore, only the exogenous net flows during charging and discharging must be compensated for. Therefore, E_{c-} and E_{d+} can be derived to only consider the exogenous changes which are noncoinciding. E_{d+} is the net generated electric power which is provided exogenously during discharging and E_{c-} is the net consumed electric power which is wasted during charging:

$$\Delta E = E_c^{nom} \cdot \eta_c - E_d^{nom}/\eta_d + E_{c-} - E_{d+} \tag{3}$$

where ΔE denotes the change in energy content of the storage buffer between time steps, with $\Delta E = 0$ over a storage cycle. For an electricity storage cycle, the relationship between E_c, E_d, E_{c-}, and E_{d+} is depicted in Fig. 1. The relationship between electricity input and output therefore is

$$E_d^{nom} = \eta_{rt} E_c^{nom} + \eta_d \cdot E_{d+}, \tag{4}$$

where the electricity storage roundtrip efficiency η_{rt} is also

$$\eta_{rt} = \eta_c \cdot \eta_d \left(1 - \frac{E_{c-}}{\eta_c \cdot E_c^{nom}}\right) \tag{5}$$

This efficiency reflects the part of electricity generated that is causally related to the earlier electricity consumption E_c. A measure of the electric energy storage capacity is in this work considered at the generation side:

$$E_{stor} = \eta_{rt} \cdot E_c^{nom}, \tag{6}$$

but other measures can be envisioned. This is the amount of electric energy generation that can be guaranteed when the maximum amount of electricity is stored. The amount of electric energy that can be guaranteed to be consumed when no electricity is stored is then E_{stor}/η_{rt}. At rated charge and discharge power, a pure, full electricity storage cycle takes at least an amount of time:

$$\Delta t_{cycle} = E_{stor}/(P_c^{nom} \cdot \eta_{rt}) + (E_{stor} + E_{d+}\eta_d)/P_d^{nom}. \tag{7}$$

The storage utilization u_{stor} (h/a) is defined as how much time is spent operating to provide electricity storage service – as opposed to operating as a net generator or consumer:

$$u_{stor} = n_c \cdot \Delta t_{cycle}, \tag{8}$$

with n_c being the annual number of electricity storage cycles (1/a).

2.2. BESS

A variety of battery types and chemistries exist. Historically, mainly Pb-acid have been used, with the focus now shifting to NaS and Li-ion. Charging and discharging a battery at the same time is not feasible. The battery energy content is at all times limited by the rated battery capacity. Losses occur in battery converters, auxiliaries and in the batteries during charging, discharging and self-discharge. In general, it is challenging to separate the battery losses incurred during charging from those incurred during discharging. The usable storage capacity at rated discharge power E_d^{nom} is sometimes substantially lower than the rated energy storage capacity. Given low self-discharge $E_{c-} \approx 0$ and $E_{d+} = 0$, $\eta_{rt} = \eta_d \cdot \eta_c$. E.g. NaS BESS are often found in multiples of $P_d = P_c =$ 1 MW modules with $\Delta t_d =$ 6 h, therefore $E_{stor} =$ 6 MWh.

2.3. CAES

During charging a volume of air is compressed; during discharging the air is expanded and the work is converted to electricity. In conventional (diabatic) CAES, combustion of natural gas adds thermal energy E_{d+} during the generation–expansion phase to compensate for thermal losses E_{c-} which occurred during accumulation. E.g. the specifications of the CAES plant Huntorf in Germany [28] are $P_c =$ 60 MW, $P_d =$ 321 MW, $\Delta t_c \approx$ 12 h, $\Delta t_d \approx$ 2 h and $\eta_{rt} = 42\%$. Therefore $E_{stor} \approx$ 0.30 GWh and $E_{c-}/\eta_c \approx$ 0.42 GWh is lost. During the expansion phase, $\eta_d \cdot E_{d+} \approx$ 0.342 GWh of work is added by combustion of natural gas. In adiabatic CAES technology the heat generated during the compression phase is stored to improve the roundtrip efficiency ($E_{d+} \approx E_{c-} \approx 0$).

2.4. PHS

PHS plants are found with a variety of topologies [26]. Distinctions can be made depending on the nature of the reservoir (existing, modified and existing as well as artificial and natural) and on the natural in and out flows. Pure PHS plants do not have significant natural inflows, but mixed plants do. Plants may have multiple pump and turbine sets, consisting of separate pumps and turbines or reversible pump-turbine units. With a hydraulic bypass, pump and turbine modes may occur at the same instant, to improve control capabilities.

Charging occurs during pumping and discharging during operation in turbine mode. Storage capacity is estimated for a full cycle at rated power, assuming that the natural flow of water ($E_{d+} \approx E_{c-} \approx 0$) is negligible during charging and discharging. In reality the electricity storage capacity is dependent on the levels of evaporation and in and out flow. During a cycle (at least one of the reservoirs going from minimum to maximum or maximum to minimum water content), an amount of electric energy E_c is consumed during pumping for an amount of time Δt_c, moving a volume V, after which an amount of energy E_d is generated during turbine mode taking an amount of time Δt_d to move the same volume again. An amount of potential energy ΔE_{pot} (J) is needed to change the elevation of a body of water in the gravitational field:

$$\Delta E_{pot}(V, \Delta h) = \rho \cdot g \cdot V \cdot \Delta h \tag{9}$$

with ρ being the water density (± 1000 kg/m^3), V the water volume moved (m^3), g the gravity of earth (± 9.81 N/kg), and Δh the change in elevation (head) (m).

The upper and lower reservoirs may have different water volumes V_{upper}^{nom} and V_{lower}^{nom}. Furthermore, the usable capacity V_{upper}^{usable} and V_{lower}^{usable} of a reservoir is lower than the nominal reservoir capacity. Losses are incurred in the transformer, the motor, the pump, the water channel, the turbine and the generator.

The aim is to collect energy and power ratings, but often only a partial set of parameters is available. Then, any of following approximations are made:

$$\eta_{rt} = 75\%, \tag{10}$$

$$\eta_c = \eta_d = \sqrt{\eta_{rt}}, \tag{11}$$

$$V^{usable} = V^{nom}, \tag{12}$$

$$V^{usable} = \min(V_{upper}^{usable}, V_{lower}^{usable}), \tag{13}$$

$$E_d^{nom} = \Delta E_{pot}(V^{usable}, \Delta h) \cdot \eta_d, \tag{14}$$

$$E_c^{nom} = \Delta E_{pot}(V^{usable}, \Delta h)/\eta_c, \tag{15}$$

$$P_c^{nom} = P_d^{nom}. \tag{16}$$

Either the lower or the upper reservoir may limit the energy storage capabilities (13). Rivers, either as lower or as upper reservoir, are assumed to have an infinite volume:

$$V_{river}^{usable} = \infty. \tag{17}$$

In the absence of complete specifications, at least both reservoir volumes and the head are required to estimate energy storage capacity. The full-cycle equivalent annual number of storage cycles is determined based on the annual PHS generated $P^{\mathrm{PHS}}_{\mathrm{d,av}}$ (GWh/a) and consumed energy $P^{\mathrm{PHS}}_{\mathrm{c,av}}$ (GWh/a):

$$n_{\mathrm{c}} = \min(P^{\mathrm{PHS}}_{\mathrm{d,av}}/E_{\mathrm{stor}}, P^{\mathrm{PHS}}_{\mathrm{c,av}} \cdot \eta_{\mathrm{rt}}/E_{\mathrm{stor}}). \tag{18}$$

The minimum operator avoids taking net generation effects of mixed PHS into account. In the context of PHS plants in this paper, (T) refers to turbine mode and (P) refers to pump mode.

In a real PHS plant, during a full cycle, the time spent consuming and the time spent generating may differ substantially. E.g., the website for the Vianden pure PHS plant (LU) provides a high level of detail of the plant's former ($<$ 2014) characteristics, including $P_{\mathrm{c}} = 850$ MW, $P_{\mathrm{d}} = 1096$ MW, $E_{\mathrm{c}} = 6240$ MWh, $E_{\mathrm{d}} = 4630$ MWh [29] and it generated $P^{\mathrm{PHS}}_{\mathrm{d,av}} = 1061$ GWh/a and consumed $P^{\mathrm{PHS}}_{\mathrm{c,av}} = 1515$ GWh/a in 2012 [11]. By (1)–(8) and (18), $\eta_{\mathrm{rt}} = 74.2\%$, $\Delta t_{\mathrm{c}} = 7.3$ h and $\Delta t_{\mathrm{d}} = 4.2$ h, $\Delta t_{\mathrm{cycle}} = 11.5$ h, $n_{\mathrm{c}} = 229/\mathrm{a}$ and $u = 2635$ h/a $= 30.0\%$. More information on the Vianden PHS will be given in the Luxembourg-specific discussion in Section 3.2.12.

3. Storage Data: EU-28 + NO + CH

3.1. Countries currently without significant grid storage

Within the EU-28, the following eight countries currently do not have significant PHS capacities [11]: Cyprus (CY), Denmark (DK), Estonia (EE), Finland (FI), Hungary (HU), Latvia (LV), Malta (MT), and The Netherlands (NL).

Countries with low PHS potential often consider non-conventional PHS technology. For example underground reservoirs in Denmark [30], underground PHS with seawater in Estonia [31] and offshore seawater PHS plant off the coast of Belgium employing an artificially created head [32].

Some projects are planned for the near future (Table 1). In Estonia, the 500 MW seawater PHS project named Muuga is considered [31]. This would be the second seawater PHS in the world [31], following the Okinawa Yanbaru 31.4 MW (T) 31.8 MW (P) PHS with an upper reservoir at 150 m elevation close to the coast (1999) [35]. Conversely to the Okinawa Yanbaru plant, the Muuga project will use a lower second reservoir. The aim is to develop an underground reservoir in a granite rock formation at a depth of 500 m [31]. Next to the previous two seawater PHS plants, a 480 MW seawater PHS is also planned for Glinsk, Ireland and another 300 MW seawater plant for Hawaii [36]. In Hungary, a 420 MW conventional PHS project is discussed [33]. In Cyprus, a PHS feasibility study was conducted [37], proposing three candidate locations: Kourris (130 MW), Kannaviou (200 MW) and Arminou (200 MW) all rated at $\Delta t_{\mathrm{d}} = 8$ h.

3.2. Countries with significant grid storage

3.2.1. Austria (AT)

Austrian PHS plant data is given in Table 2. A roundtrip efficiency of 75% is assumed in the calculation of the storage capacity of all the plants. For illustration, the energy available in turbine mode with a full upper reservoir E_{d} is shown next to the energy storage capacity E_{stor}. In pure PHS plants, $E_{\mathrm{d}} = E_{\mathrm{stor}}$ but in mixed PHS E_{d} is often much larger than E_{stor}. The Limberg I+II PHS has been operational since 2011 and has an upper reservoir of $85 \cdot 10^6$ m^3, a lower reservoir of $81 \cdot 10^6$ m^3 and a head of 380 m [40]. The energy storage capacity is shown between brackets to indicate that this value is not counted towards the national value. This amounts to an estimated storage capacity of 72.82 GWh. Limberg I and Limberg II as well as Rodundwerk I and II share the same upper and lower reservoir. Roßhag and Häusling share the same lower reservoir. At the Malta plant, the Galgenbichl and Gößkar reservoirs are connected via a tunnel, forming a double reservoir. The lower reservoir of Naßfeld uses caverns in the mountain side. The Kops II plant uses hydraulic bypass technology, and can operate in pump and turbine modes at the same time with the aim of obtaining variable net pumping. Kraftwerksgruppe Fragant includes a number of classic hydro power plants as well as the Feldsee and the Innterfragant PHS plants. In the same sense, Roßhag and Häusling PHS plants belong to Kraftwerksgruppe Zemm-Ziller. Finally, Kops II, Lünersee, Rifa and Rodund I+II are part of an interconnected hydro complex. This makes it difficult to define a storage capacity for the whole system.

11 storage projects under construction or planned for the near future were found with a combined power of 3632 MW. The Tauernmoos 130 MW PHS [45] is under construction. This plant will provide power for both 50 Hz and 16.7 Hz (train). Kaunertal is a 400 MW PHS project in the Ötztaler Alps [7]. Limberg III adds two variable-speed Francis pump-turbines with asynchronous motor-generators (total 480 MW) to the current PHS plant [7]. Other PHS projects [40,17,9,46] are listed in Table 1.

3.2.2. Belgium (BE)

The three PHS plants in Belgium add up to 1301 MW in turbine mode and 1196 MW in pump mode with a storage capacity of 5.71 GWh (Table 3). The Coo-Trois-Ponts plant has a single lower reservoir ($8.54 \cdot 10^6$ m^3) but two separate upper reservoirs ($4 \cdot 10^6$ m^3 and $4.54 \cdot 10^6$ m^3) which are not hydraulically coupled [47]. Therefore, this plant is counted as two separate systems. It is characterized by a roundtrip efficiency of 75%, while the Plate-Taille PHS plant has a roundtrip efficiency of 70%.

In addition, there are plans to expand the Coo PHS system with a third upper reservoir and deepened lower reservoir, i.e., the Coo III PHS project [47], and to build an offshore PHS plant off the Belgian coast [32], i.e., the ‘iLand’ project.

3.2.3. Bulgaria (BG)

Data of the three Bulgarian PHS plants is given in Table 4. Chaira and Belmeken share the same upper reservoir, Belmeken, and both are limited by their separate, smaller lower reservoirs. The current Chaira lower reservoir nominal volume is $5.6 \cdot 10^6$ m^3 [7]. The extension of the lower reservoir requires the construction of a second dam, Yadenitsa, and a tunnel to connect to the current lower reservoir. This extension by $9 \cdot 10^6$ m^3 is one of the projects labeled as project of common interest [7]. With the expansion of the Chaira lower reservoir, it will be able to operate for 24 h in turbine mode [49]. Currently, Chaira has a Δt_{d} of 8.5 h [49], which is used to estimate E_{stor}. The combined rating of the PHS plants in Bulgaria is 1399 MW in turbine mode, 930 MW in pump mode, and 11.13 GWh.

3.2.4. Croatia (HR)

Croatian PHS plant data is given in Table 5. The total Croatian capacity is 246.05 MW in pump mode and 281.4 MW in turbine mode. The source quotes an energy storage density of 1.25 kWh/m^3 [52] at Velebit. Given the capacity of the smaller reservoir, energy storage is estimated at 2.34 GWh for this PHS. Since the other two PHS plants are relatively small compared to the Velebit PHS, it is assumed that 2.34 GWh is an accurate estimation of the Croatian storage capacity.

3.2.5. Czech Republic (CZ)

Data of the three Czech PHS plants is summarized in Table 6. The PHS plants have a combined power of 1145 MW in pumping mode and 1119 MW in turbine mode. Data from the owner's website [54] was further completed through personal communication with Mr. Matin Schreier of the CEZ group. The combined storage capacity is 5.72 GWh.

3.2.6. France (FR)

French PHS plant data is given in Table 7. The total French PHS power is considered 5512 MW in turbine mode and 4316.92 MW in pump mode. Total energy storage capacity is estimated at 83.37 GWh. The La Rance tidal power plant also uses reversible pump-turbines, but is not counted as a PHS plant in this work. The Lac Noir PHS is currently offline and is being upgraded to 55 MW [58]. The Le Cheylas PHS plant is being upgraded with variable speed pump-turbines [60], and the Revin PHS plant will be refurbished [61]. The Le Pouget complex has a generation capacity of 440 MW, but has limited pumping capabilities as only one of the power sets is reversible (41.5 MW turbine, 32.92 MW pump). In addition, EDF operates a 1 MW NaS battery system in La Reunion (a French overseas department). As part of the Nice Grid project [62], a total of 2.7 MWh of Li-ion BESS will be installed at different locations and different scales, including a 1.1 MW 0.5 MWh system at a substation.

3.2.7. Germany (DE)

Data of the 34 German PHS plants are given in Table 8. Reference [69] provides an overview of PHS energy storage capacity by market player. A multitude of references considers the country total energy storage capacity at 40 GWh [65,69–72]. The Goldisthal PHS uses 4 reversible Francis pump-turbines [63]. Two units are synchronous, the other two are asynchronous. The synchronous ones achieve 265 MW of power in both pump and turbine modes. Asynchronous sets can vary pumping power from 190 MW to 290 MW [63,73]. In turbine mode the synchronous units produce from 100 MW to 265 MW, the asynchronous can regulate their output from 40 MW to 265 MW [73]. The Happurg PHS is not functioning, because of reservoir leakage issues [20]. The pumps of the Wisenta PHS plant (3.76 MW) have been stopped since 1992 [63] but it remains operational as a hydroelectric power plant.

Riedl is a project of common interest PHS on the border with Austria, with a planned power rating of 300 MW and a 350 m head [7]. Other future storage projects [40,68,74,75] are listed in Table 1.

A single CAES has been operating in Germany since 1978, originally rated at 290 MW. In 2006 it was upgraded to 321 MW [28] (Table 24). ADELE is a demonstration project for adiabatic CAES. The project started in 2010 and planned to demonstrate a 90 MW 360 MWh in 2013, but this has been postponed until 2016 [76]. Battery energy storage has been used in Germany. From 1987 to 1993 a 17 MW 14 MWh Pb-acid battery storage was operated in west Berlin by utility BEWAG [77,78]. Furthermore, two 1.2 MWh Pb-acid BESS were operated, one in Bocholt and one in Herne [78]. Finally, two NaS battery systems are operating: a 0.8 MW unit with Enercon and a 1 MW unit with Younicos in Berlin [79]; at the latter site in combination with a 0.2 MW Li-ion BESS. Younicos and Wemag AG are building a 5 MW Li-ion BESS for primary reserves [80]. A 2 MW P2G unit started operation in Falkenhagen [81] (Table 24). Other P2G projects in Germany are discussed in [76].

3.2.8. Greece (GR)

Parameters of the two Greek PHS plants are given in Table 9. According to [41], the Sfikia dam has a height of 81 m and the Thisavros dam has a height of 172 m. The head was estimated from m^3/kWh figures in [82].

The planned Amfilochia 576 MW PHS is a project of common interest [7]. It will use two upper reservoirs, being Agios Georgios and Pyrgos, and for the lower reservoir the artificial reservoir of Kastraki will be used.

3.2.9. Ireland (IE)

Turlough Hill, also known as Tomaneena, is the only operational PHS in Ireland, and is owned by ESB. This PHS plant's data is given in Table 10. New PHS projects are considered, e.g. the Knocknagreenan 70 MW and Kippagh Lough 70 MW PHS plants.

The Glinsk project is a project of common interest [7] that considers a seawater PHS of 1200 MW [84].

3.2.10. Italy (IT)

Parameters of 25 Italian PHS plants are given in Table 11 and add up to a combined power rating of 7833.3 MW in turbine mode and 7640.15 MW in pump mode. The Chiotas and the Rovina PHS share the same lower reservoir and are part of the Entracque complex.

Campolattaro is a new 572 MW (T) 630 MW (P) PHS project [88]. The energy capacity is estimated at about 8.26 GWh, given the $7 \cdot 10^6\ m^3$ volume of the limiting reservoir and the 500 m head. Storage is considered crucial for the transmission system in southern Italy, where the installation of a total of 250 MW of battery storage is considered [7]. The first phase includes the installation of a 35 MW NaS battery [34]. Enel Distribuzione is equipping a substation with a 1 MW 2 MWh Li-ion BESS from Saft [89]. Moreover, ABB will build a 2 MW 0.5 h Li-ion BESS for Enel [90]. As part of the INGRID project a 1.2 MW water electrolysis unit with 39 MWh of storage capacity will be demonstrated in Puglia. FIAMM will provide 4 NaNiCl BESS with a combined 4.15 MWh for Terna in Sardinia [91]. An overview of storage projects is given in Table 1.

3.2.11. Lithuania (LT)

Lithuanian PHS plant data is given in Table 12. Currently, the total capacity in Lithuania is that of the Kruonis PHS with 900 MW available in turbine mode and 880 MW in pumping mode. Kruonis is able to generate 900 MW for about 12 h, resulting in an estimated storage capacity of 10.8 GWh. The expansion with a fifth pump-turbine set with variable speed technology, increasing the plant's pump power rating by 220 MW and the turbine power rating by 225 MW [7], was planned [93] but is postponed indefinitely.

3.2.12. Luxembourg (LU)

Luxembourg has a single PHS plant with a power rating of 1296 MW in turbine mode and 1050 MW in pump mode (Table 13) and 4.92 GWh storage capacity. Recently, a single 200 MW reversible pump-turbine has been added, and both the lower and upper reservoir volumes were increased [94].

3.2.13. Poland (PL)

Polish PHS plant data is given in Table 14. The Zarnowiec PHS was recently upgraded to 167 MW from the former 157 MW, but the more detailed data from [95] is used in the table. Development of the new Mloty 750 MW (T) 804 MW (P) PHS project is considered to stabilize the power system in the Lower Silesian Region in Poland, close to border with Germany and the Czech Republic [7].

3.2.14. Portugal (PT)

Data of the seven Portuguese PHS plants is given in Table 15. Energy storage values are obtained from [98]. Alqueva I and II use the same reservoirs.

PHS is considered crucial to facilitate the ambitious renewable energy targets (100% RES electricity supply) for Portugal [101]. The Alto Tamega complex is a project which comprises four dams, namely Daivoes, Gouaves, Padroselos and Alto Tamega, with a total power in turbine mode of 1200 MW and 900 MW in pump mode [9]. At the Graciosa island in the Azores, Younicos is building a 2.5 MW BESS together with local utility EDA [80]. The projects are listed in Table 1. A combined power rating for these projects is 4432.5–4612.5 MW.

3.2.15. Romania (RO)

There are five PHS plants in Romania. All these plants belong to the lower Olt cascade, and the pump-turbines have recently been

Table 2
Pumped hydro storage capacities in Austria.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{usable}		V_{lower}^{usable}		E_{stor} (GWh)	E_d(GWh)	
			name	(10^6 m^3)	name	(10^6 m^3)			
Feldsee	137.78 (T) 128 (P)	524	Feldsee	1.65	Wurten	2.58	2.04	2.04	[20]
Gosau	4.8 (T) 5.9 (P)	152	Vorderer Gosausee	24.7	Gosauschmied	–	–	8.86	[38]
Häusling	360 (T) 366 (P)	696	Zillergründl	86.7	Stillup	6.8	11.17	142.4	[20,39]
Hintermuhr	104 (T) 68 (P)	601	Rotgüldensee	15.6	Ölschützen	0.304	0.43	22.13	
Innerfragant	108 (T) 100 (P)	1185	Oschenik	30	Ausgleichbecken	0.175	0.49	83.90	
Kopswerk II	525 (T) 450 (P)	780	Kopssee	42	Rifa	1.27	2.34	77.31	[40,20]
Koralpe	50 (T) 35 (P)	735	Soboth	16.2	Drau (river)	∞	28.10	28.10	[41,42]
Kühtai	289 (T) 250 (P)	380	Finstertal	60	Längental	3	2.69	53.81	
Limberg I	112 (T) 124 (P)	380	Moserboden	85.4	Wasserfallboden	81.2	72.82	76.58	[17]
Limberg II	480 (T) 480 (P)	380	Moserboden	85.4	Wasserfallboden	81.2	(72.82)	(76.58)	[40,20]
Lünersee	232 (T) 224 (P)	974	Lünersee	78.3	Latschau	2.24	5.15	179.98	[13]
Malta Main	730 (T) 290 (P)	1102	Galgenbichl, Gößkar	6.2	Rottau	0.5	1.30	16.12	[17]
Malta Upper	120 (T) 116 (P)	198	Kölnbrein	200	Galgenbichl, Gößkar	6.2	2.90	93.45	[17]
Naßfeld	31.5	317	Bockhartsee	18.5	Naßfeld	0.23	0.17	13.84	[43]
Ranna	19 (T) 13.05 (P)	212	Rannastausee	2.35	Donau (river)	∞	1.06	1.06	[44]
Rifa	7 (T) 8 (P)		Partenen	0.13	Rifa	1.27	–	–	[13]
Rodundwerk I	198 (T) 41 (P)	353	Latschau	2.24	Rodund	2.1	1.75	1.87	[13]
Rodundwerk II	295 (T) 276 (P)	353	Latschau	2.24	Rodund	2.1	(1.75)	(1.87)	[41,20]
Roßhag	248 (T) 240 (P)	634	Schlegeis	127.7	Stillup	2.58	(3.86)	191.06	[17,39]
Total	4051.08 (T) 3246.45 (P)						132.41	992.51	

Table 3
Pumped hydro storage capacities in Belgium.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{nom} (10^6 m^3)	E_{stor} (GWh)	
Coo-Trois-Ponts I	474 (T) 435 (P)	245	4.0	2.34	[47]
Coo-Trois-Ponts II	690 (T) 600 (P)	245	4.54	2.66	[47]
Plate-Taille	137 (T) 161 (P)	245	6.90	0.71	[48]
Total	1301 (T) 1196 (P)			5.71	

Table 4
Pumped hydro storage capacities in Bulgaria.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{usable} (10^6 m^3)	V_{lower}^{usable} (10^6 m^3)	E_{stor} (GWh)	
Chaira	864 (T) 788 (P)	690–701	140	4.2	27.34	[49,50]
Belmeken	375 (T) 104 (P)	690	140	0.375	0.64	[49,50]
Orpheus	160 (T) 38 (P)	65.8	226.12	20.26	13.15	[49,50]
Total	1399 (T) 930 (P)				11.13	

Table 5
Pumped hydro storage capacities in Croatia.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{usable} (10^6 m^3)	V_{lower}^{usable} (10^6 m^3)	E_{stor} (GWh)	
Fuzine	4 (T) 4.8 (P)				–	[51]
Lepenica	1.4 (T) 1.25 (P)				–	[51]
Velebit	276 (T) 240 (P)	517–559	13.65	1.84	2.34	[51–53]
Total	281.4 (T) 246.05 (P)				2.34	

Table 6
Pumped hydro storage capacities in Czech Republic.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{usable} (10^6 m^3)	V_{lower}^{usable} (10^6 m^3)	E_{stor} (GWh)	
Dalesice	450	80	127	17.1	2.30	[54]
Dlouhe Strane	624 (T) 650 (P)	530	2.72	3.4	3.20	[54]
Stechovice II	45	220	0.50	11.2	0.22	[54]
Total	1119 (T) 1145 (P)				5.72	

refurbished [102]. The head and the flow rates are matched between all PHS plants in the cascade [103]. The combined power rating is 285 MW in turbine mode and 200 MW in pump mode [102]. The lower reservoir of the final PHS plant on the cascade, Izbiceni, has not yet been constructed. Therefore, its storage capacity is not counted. Because of the matched flow rates, the total energy storage capacity of the complex is higher than the sum of the individual installations.

In addition, the Tarnita – Lapustesti 1000 MW PHS plant is under construction [105]. Furthermore, in the upper Barzava region there are plans for the new Gozna-Semenic PHS of 200–500 MW [106].

3.2.16. Slovak republic (SK)

Parameters of the four identified Slovak PHS plants are given in Table 17. The combined PHS power rating in the Slovak republic is identified as 1016.4 MW in turbine mode and 790 MW in pump mode. Ref. [107] also mentions Dolny Jelenec 0.91 MW (T) 0.92 MW (P) and Miksova II 2.38 MW (T) 3.13 MW (P). As it could not be determined that these plants are still operational, they are not counted in the overview. Only for Cierny Vah the energy capacity could be determined, based on reservoir capacity data. It has by far the highest power rating and the highest head of all the plants. Therefore, the authors have chosen to use the Cierny Vah storage capacity as the national value.

3.2.17. Slovenia (SI)

Slovenian PHS plant data is given in Table 18. The Slovenian PHS power rating is 185 MW in turbine mode and 180 MW in pump mode. There is some interest in a 400 MW PHS, Kozjak, on the Drava river.

3.2.18. Spain (ES)

Parameters of the 26 Spanish PHS plants are stated in Table 19. Duration values Δt_d of the pure PHS plants Sallente (2 h), Tajo De La Ecantada (3 h), Bolarque II (7 h) and Aguayo (11 h) are taken from [111]. The country's total energy capacity is estimated at 59.8 GWh. Furthermore, given the number of PHS without traceable storage capacity, the country-wide figure of 70 GWh cited in [113,111] seems reasonable, and is therefore used as the Spanish reference value.

In the Canary Islands, three storage systems were recently commissioned [114]: a 1 MW 3 MWh Li-ion BESS, a 0.5 MW 18 s flywheel and a 4 MW 20 supercapacitors system. Furthermore, a 1 MW 3 MWh Li-ion BESS is operated at the Carmona 400/220 kV substation as part of the Alamacena project [115]. Furthermore, a 1 MW 0.56 MWh Li-ion BESS is used at the 1.2 MW PV plant at Tudela in northern Spain as part of the ILIS project [116]. In addition, seven PHS projects with a total of 3474 MW are considered for the near future (Table 1).

3.2.19. Sweden (SE)

A Swedish PHS capacity of 91 MW is obtained (Table 20). The Letten plant uses a river as the lower reservoir. Given the sizable upper reservoir, a substantial energy storage capacity is obtained at 72.12 GWh. The Kymmen plant operates between lakes Kymmen and Rottnan. The reservoir volume of lake Rottnan could not be determined. Historically, there was another PHS plant, Juktan, rated at 26 MW, but it was only used as a conventional hydro station in recent years.

3.2.20. United Kingdom (GB)

Data of the four United Kingdom PHS plants is given in Table 21. The total UK PHS power rating is 2788 MW in turbine mode and 2650 MW in pump mode. The Cruachan PHS is able to store a total of 22 h of supply of water in the top reservoir, however it is required to keep 12 h of emergency supply available at all times for black start ancillary services [22].

Table 7
Pumped hydro storage capacities in France.

	P_d^{nom}, P_c^{nom} (MW)	E_{stor} (GWh)	
Alrance	11	–	[55,20,21]
Argentat	48	–	[20,21]
Grand Maison	1790 (T) 1160 (P)	34.80	[56,57]
Lac Noir	55	0.90	[58,20]
La Coche	330 (T) 310 (P)	0.93	[57]
Le Cheylas	460 (T) 480 (P)	2.88	[57]
Le Pouget	440 (T) 32.92 (P)	0.71	[55,21]
Montezic	910 (T) 870 (P)	36.40	[12,57]
Revin	720 (T) 720 (P)	3.60	[12,59,57]
Super-Bissorte	748 (T) 630 (P)	3.15	[57]
Total	5512 (T) 4316.92 (P)	83.37	

Table 8
Pumped hydro storage capacities in Germany.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	E_{stor} (GWh)	
Bleiloch	80 (T) 32 (P)	49.4	0.640	[13,63,64]
Einöden	200 (T) 200 (P)		1.600	[13]
Einsiedel	1.3 (T) 1.1 (P)	127.0	0.023	[13,64]
Erzhausen	220 (T) 230 (P)	293.0	0.940	[13,64]
Geesthacht	120 (T) 96 (P)	83.0	0.600	[12,13,63,64]
Glems	90 (T) 68 (T)	292.0	0.560	[12,13,64]
Goldisthal	1060 (T) 1110 (P)	302.0	8.480	[12,63–65]
Happurg	160 (T) 126 (P)	211.9	0.900	[13,66,64]
Häusern	144 (T) 104 (P)	200.0	0.527	[13,67,64]
Hohenwarte	63 (T) 36 (P)	56.5	0.504	[12,63,64]
Hohenwarte II	320 (T) 324 (P)	303.8	2.087	[12,63,64]
Höllbach III	1.5 (T) 0.8 (P)	89.0	–	[13,64]
Kirchentellinsfurt	1.3		–	[21]
Koepchenwerk	153 (T) 153.6 (P)	165.0	0.590	[12,64]
Langenprozelten	168 (T) 154 (P)	310.4	0.950	[12,20,66,64]
Leitzachwerk I	49 (T) 45.4 (P)	128.0	0.550	[13,20,64]
Leitzachwerk II	49.2 (T) 36.8 (P)	128	(0.550)	[13,20,64]
Markersbach	1050 (T) 1140 (P)	288.3	4.018	[12,63–65]
Maxhofen-Oberberg	10.4 (T) 10.8 (P)	220.0	0.122Sterner2010,	[13,64]
Niederwartha	120 (T) 120 (P)	142.5	0.591	[12,13,63,64]
Reisach Rabenleite	105 (T) 81 (P)	188	0.630	[13,64]
Rönkhausen	140 (T) 140 (P)	266	0.690	[12,64]
Ruselkraftwerke	3.5 (T) 2 (P)		-	[21]
Säckingen	353 (T) 301 (P)	413	2.064	[12,13,64]
Schwarzenbachwerk	45 (T) 43 (P)	368.0	–	[13,64]
Sorpetalsperre	9.9 (T) 7.3 (P)	56	–	[13,64]
Tanzmühle Rabenleite	35 (T) 24.5 (P)	122	0.404	[13,64]
Waldeck I	140 (T) 70 (P)	296.0	0.487	[12,66,64]
Waldeck II	440 (T) 476 (P)	329	3.428	[12,66,64]
Waldshut	176 (T) 80 (P)	160	0.476	[12,64]
Warmatsgrund	4.6 (T) 2.2 (P)		0.021	[68]
Wehr/Hornbergstufe	992 (T) 1000 (P)	626	6.073	[13,64,65]
Wendefurth	80 (T) 72 (P)	125	0.523	[12,63,64]
Witznau/Albbecken	220 (T) 128 (P)	250	0.642	[12,64]
Total	6804.7 (T) 6416.8 (P)		39.12	

Table 9
Pumped hydro storage capacities in Greece.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{Upper}^{nom} (10^6 m^3)	V_{lower}^{nom} (10^6 m^3)	E_{stor} (GWh)	
Sfikia	315	63	17.6	10	1.32	[16,41,82]
Thisavros	420	135	565	12	3.82	[16,41,82]
Total	735				4.97	

Table 10
Pumped hydro storage capacities in the Republic of Ireland.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	E_{stor} (GWh)	
Turlough Hill	292	549	1.80	[83]

The Glyn Rhonwy 99.9 MW 500 MWh PHS project in Wales uses a former quarry as a reservoir [123]. In Scotland, it is proposed to converse the Sloy conventional hydro power plant to a PHS plant and thereby adding 60 MW to the UK PHS capacity [124]. Furthermore, Coire Glas and Balmacaan PHS plants are proposed, both with ratings of 300–600 MW. The proposed energy storage capacities here are substantial, up to 30 GWh [124]. Furthermore, Larne CAES project considers storage in caverns created in bedded salt deposits [7]. When looking at battery storage, S&C electric, Samsung SDI and Younicos are deploying a fully automated 6 MW 10 MWh BESS at the Leighton Buzzard substation, north-east of London [80] (Table 1). Finally, a 2 MW Li-ion BESS is operating on the Orkney Islands [125] (Table 24).

3.2.21. Norway (NO)

In Norway there are 8 PHS plants with a combined rating of 1273 MW in turbine mode, 892 MW in pump mode and 399.39 GWh of energy storage capacity (Table 22). The estimated energy storage capacities are substantial because of the large (nominal) reservoir volumes.

A preliminary study [128] discusses a number of scenarios to increase the power output of hydroelectric power plants in southern Norway. Under the first scenario, 5 PHS plants are considered with a combined power rating of 4.9 GW. Project details are given in Table 1.

3.2.22. Switzerland (CH)

For Switzerland, a total of 20 PHS plants are obtained (Châtelard-Barberine 1+2 counted as a single plant as ratings could not be determined separately). The combined rating is 2291 MW in turbine mode, 1512 MW in pump mode, and 311.48 GWh storage capacity (Table 23). A 1 MW Li-ion BESS is operated since 2012 in the grid of the local utility EKZ in Zürich [133], including a peak shaving application (Table 24). Seven Swiss PHS developments are given in Table 1 with a combined rating of 5040 MW. The Nant De Drance PHS project, which will become operational early 2018, will be co-operated by the Swiss Federal Railway company (SBB), Alpiq, and energy suppliers IWB and FMV [134].

Table 11
Pumped hydro storage capacities in Italy.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	E_{stor} (GWh)	
Anapo	500 (T) 600 (P)	312	4.00	[85,86,14]
Campo Moro	36.5	138.6	–	[14]
Capriati	113 (T) 110.82 (P)	654.5	–	[14,86]
Casuzze	9	471.63	–	[14]
Chiotas	1184 (T) 1240 (P)	1048	17.04	[85,86]
Dietro La Torre	5 (T) 4.5 (P)	335	–	[14]
Edolo	977.55	1265.6	4.89	[85,86,14]
Fadalto	210	109	–	[14]
Gargnano	137.2	431	–	[14]
Guadalami	80	166	–	[86,14]
Pont Ventoux	150	502.92	0.54	[86,87]
Pracomune	42 (T) 35.6 (P)	377	–	[86,14]
Presenzano	1000 (T) 1028.93 (P)	495.5	7.00	[85,14]
Provvidenza	141	287.5	–	[86]
Roncovalgrande	1040	736.25	17.68	[85,86,14]
Riva del Garda I	115	583.3	–	[14]
Riva del Garda II	1	243.57	–	[14]
Rovina	133.7 (T) 125 (P)	598	2.00	[85,86]
San Fiorano	560 (T) 210 (P)	1424	–	[86,14]
San Giacomo	448	656.6	–	[86,14]
San Massenza I	350	580.9	–	[14]
San Massenza II	27.5	220.9	–	[14]
Sellero	2.85	16.27	–	[14]
Suviana (Bargi)	330	375.2	2.64	[85,86,14]
Taloro	240	290	12.48	[85]
Total	7833.3 (T) 7640.15 (P)		68.27	

Table 12
Pumped hydro storage capacities in Lithuania.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	η_{rt} (%)	E_{stor} (GWh)	
Kruonis	900 (T) 880 (P)	100	74	10.80	[92]

Table 13
Pumped hydro storage capacities in Luxembourg.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V (10^6 m^3)	E_{stor} (GWh)	
Vianden 2013	1096 (T) 850 (P)	266.5–291.3	6.84	4.63	[29]
Vianden now	1296 (T) 1050 (P)	266.5–291.3	7.34	4.92	[29,94]

4. Comparison

In total, 160 PHS plants are obtained within EU-28, and 188 in EU-28+NO+CH (Tables 2–23). The combined energy storage capacity within the EU-28, at 602 GWh is smaller than the combined energy storage capacity of Switzerland and Norway, at 711 GWh. Fig. 2 shows the combined discharge characteristic of the 188 PHS stations. For 7.543 GW, the energy storage capacity could not be determined (15% of the total), so there the discharge duration is unknown. The most common discharge durations are in the range of 3–24 h, with extremes of less than one hour to more than a month.

On the country level, different trends are noticed in the historical PHS generation data (GWh/a). It is noted that changes in the market and in PHS power availability cannot be distinguished based on this data. In Italy, Spain, Poland, Ireland and Greece generation volumes have decreased substantially in the last few years. Conversely, in Austria, Bulgaria, Czech Republic and Slovakia the use of PHS has grown substantially. Romania and Slovenia have only used PHS since a few years (Fig. 3).

Additional statistics are gathered to interpret the results. P_{av} is the total net consumption (2012) [135], P_{inst} is the net generation

Table 14
Pumped hydro storage capacities in Poland.

	P_d^{nom}, P_c^{nom} (MW)	$\Delta t_c, \Delta t_d$ (h)	E_{stor} (GWh)	
Dychow	91.5 (T) 20 (P)	4 (T) 16.5 (P)	0.25	[95]
Niedzica	92.8 (T) 89 (P)	154 (T) 8.9 (P)	0.60	[95,96]
Porabka-zar	500 (T) 540 (P)	4 (T) 5.5 (P)	2.00	[95,96]
Solina	200 (T) 62 (P)	192 (T) 18 (P)	0.84	[95,96]
Zarnowiec	716 (T) 800 (P)	5.5 (T) 6 (P)	3.60	[95–97]
Zydowo	157 (T) 136 (P)	4.3 (T) 6.6 (P)	0.67	[95,96]
Total	1757.3 (T) 1647 (P)		7.96	

Table 15
Pumped hydro storage capacities in Portugal.

	P_d^{nom}, P_c^{nom} (MW)	E_{stor} (GWh)	
Aguieira	336	2.352	[98]
Alqueva I	240	5.760	[98,99]
Alqueva II	220	(5.760)	[99,100]
Alto Rabagao	68	8.160	[98]
Frades I	196	23.520	[98]
Torrao	140	0.980	[98]
Vilarinho das Furnas	79	–	[100]
Total	1279	40.77	

Table 16
Pumped hydro storage capacities in Romania.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{nom} (10^6 m^3)	V_{lower}^{nom} (10^6 m^3)	E_{stor} (GWh)	
Ipotesti	57 (T) 40 (P)	13.5	99.34	82.75	(2.64)	[102–104]
Draganesti	57 (T) 40 (P)	13.5	82.75	91.75	(2.64)	[102–104]
Frunzarii	57 (T) 40 (P)	13.5	91.75	82.21	(2.62)	[102–104]
Rusanesti	57 (T) 40 (P)	13.5	82.21	62.8	(2.00)	[102–104]
Izbiceni	57 (T) 40 (P)	13.5	62.80	–	0	[102–104]
Total	285 (T) 200 (P)				10.2	[102]

Table 17
Pumped hydro storage capacities in the Slovak Republic.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V (10^6 m^3)	E_{stor} (GWh)	
Cierny Vah	734.4 (T) 600 (P)	397.55–434	3.7	3.63	[107,108]
Dobsina	24 (T) 18 (P)	285.5		–	[107,108]
Liptovska Mara	198 (T) 106 (P)	30–47.3		–	[107,108]
Ruzin	60 (T) 66 (P)	52.7		–	[107,108]
Total	1016.4 (T) 790 (P)			3.63	

Table 18
Pumped hydro storage capacity in Slovenia.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{usable} (10^6 m^3)	V_{lower}^{usable} (10^6 m^3)	E_{stor} (GWh)	
Avce	185 (T) 180 (P)	506	2.17	0.416	0.50	[109]

Table 19
Pumped hydro storage capacities in Spain.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	E_{stor} (GWh)	
Aguayo	339	328.5	3.7	[110]
Aldeadavila II	432 (T) 400 (P)		–	[110]
Bolarque II	208	224	1.4	[12]
Conso	298 (T) 228 (P)		–	[110]
Gabriel Y Galan	115 (T) 100 (P)		–	[110]
Gobantes	3		–	[110]
Guijo De Granadilla	53		–	[110]
Guillena	210	209	1.3	[12,110,111]
Ip	88 (T) 84 (P)		–	
La Muela I	628 (T) 555 (P)	450	24.5	[12,110,111]
La Muela II	852	450	(24.5)	[12,111]
Montamara	96 (T) 88 (P)		–	[110]
Moralets	204 (T) 228 (P)	753	27	[110,111]
Pintado	14		–	[110]
Puente Bibey	285 (T) 64 (P)		–	[110]
Sallente	446 (T) 468 (P)	372	0.9	[110]
Santiago Jares	51		–	[110]
Soutelo	206		–	[112]
Soutelo II	82 (T) 76 (P)		–	[110]
Tajo De la Encantada	380 (T) 360 (P)	341	1.0	[110]
Tanes	129 (T) 114.5 (P)		–	[110]
Torrejon	130		–	[110]
Urdiceto	7		–	[110]
Valparaiso	67		–	[110]
Valdecanas	225		–	[110]
Villarino	810 (T) 728 (P)		–	[9,110]
Total	6358 (T) 5858.5 (P)		59.8	

Table 20
Pumped hydro storage capacities in Sweden.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{nom} (10^6 m^3)	E_{stor} (GWh)	
Kymmen	55	85	97	–	[117]
Letten	36	191	160	72.12	[117]
Total	91			72.12	

capacity (December 2012) [135], and $P_{d,av}^{PHS}$ is the gross electricity generation and $P_{c,av}^{PHS}$ is the consumption (charge) of PHS (2012) [11].

Fig. 4 compares the PHS plants by country in the EU-28. With 34, Germany has the highest number of PHS plants (column 1). Italy has the highest combined power rating, at 7.833 GW (column 2). Norway and Switzerland have the highest storage capacity (> 300 GWh). Within the EU-28 Austria has the highest storage capacity at 132.41 GWh (column 3), of which 72.83 GWh is at the Limberg plant (Table 2). The ratio E_{stor}/P_d^{nom} reflects the number of hours of sustained

Table 21
Pumped hydro storage capacities in the United Kingdom.

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V (10^6 m^3)	E_{stor} (GWh)	
Cruachan	400	365–334	11.3	10	[118,119]
Dinorwig	1728 (T) 1650 (P)	542–494	6.7	9.1	[20,120,121]
Ffestiniog	360 (T) 300 (P)	320–295	1.7	1.3	[118,121]
Foyers	300	178–172	13.6	6.3	[118,122]
Total	2788 (T) 2650 (P)			26.7	

Table 22
Pumped hydro storage capacities in Norway.

	$P_\mathrm{d}^\mathrm{nom}, P_\mathrm{c}^\mathrm{nom}$ (MW)	Δh (m)	$V_\mathrm{upper}^\mathrm{nom}$		$V_\mathrm{lower}^\mathrm{nom}$		E_stor (GWh)	
			Name	(10^6 m^3)	Name	(10^6 m^3)		
Aurland III	270	400	Nyhellervatn	448	Vetlebotnvatn	10	9.44	[126]
Brattingfoss	11						–	
Duge	200	215	Svartevatn	1400	Gravatn	275	139.53	[126]
Jukla	40						–	
Nygard	56						–	
Saurdal	640 (T) 320 (P)	465	Blasjo	3105	Sansavatn	228	250.2	[126]
Stolsdal	17 (T) 6 (P)	95	Sandsavatn	228	Vasbottvatn	1	0.22	[127]
Tevla	50	165	Fjergen	166			–	[126]
Total	1273 (T) 892 (P)						399.39	

Table 23
Pumped hydro storage capacities in Switzerland.

	$P_\mathrm{d}^\mathrm{nom}, P_\mathrm{c}^\mathrm{nom}$ (MW)	Δh (m)	E_stor (GWh)	
Bortealp	2.35 (T) 2.62 (P)		–	[129]
Châtelard-Barberine 1+2	112 (T) 30 (P)	275	8.96	[129]
Engeweiher	5 (T) 5.3 (P)		–	[129]
Etzelwerk Altendorf	135 (T) 54 (P)	483.3	104.93	[129,130]
Ferrera 1	180 (T) 90 (P)	524	22.63	[129]
Grimsel 2	348 (T) 352 (P)	397	53.42	[129]
Handeck 3 (Isogyre)	55 (T) 47.8 (P)	108	0.51	[129]
Mapragg	279.9 (T) 159 (P)	483	3.08	[129]
Mottec	71 (T) 31.7 (P)	617	0.22	[129]
Oberems (Argessa)	8.2 (T) 5.67 (P)		–	[129]
Ova Spin	54 (T) 52 (P)	175	2.58	[129]
Palü	10.4 (T) 3 (P)		–	[129]
Peccia (Sambuco)	54 (T) 24 (P)	381	0.10	[129,131]
Rempen	66.24 (T) 16 (P)	252.5	0.14	[129]
Robiei	173 (T) 157 (P)	338	6.50	[129,131]
Tierfehd Limmern	261 (T) 34 (P)	559	0.15	[129]
Tierfehd Umwälzwerk	140 (T) 140 (P)	1045.5	0.52	[129,132]
Veytaux	240 (T) 256 (P)	878	107.74	[129]
Zermeiggern (Mattmark)	74 (T) 46 (P)	459	–	[129]
Zervreila	22 (T) 5.8 (P)		–	[129]
Total	2291.09 (T) 1511.89 (P)		311.48	

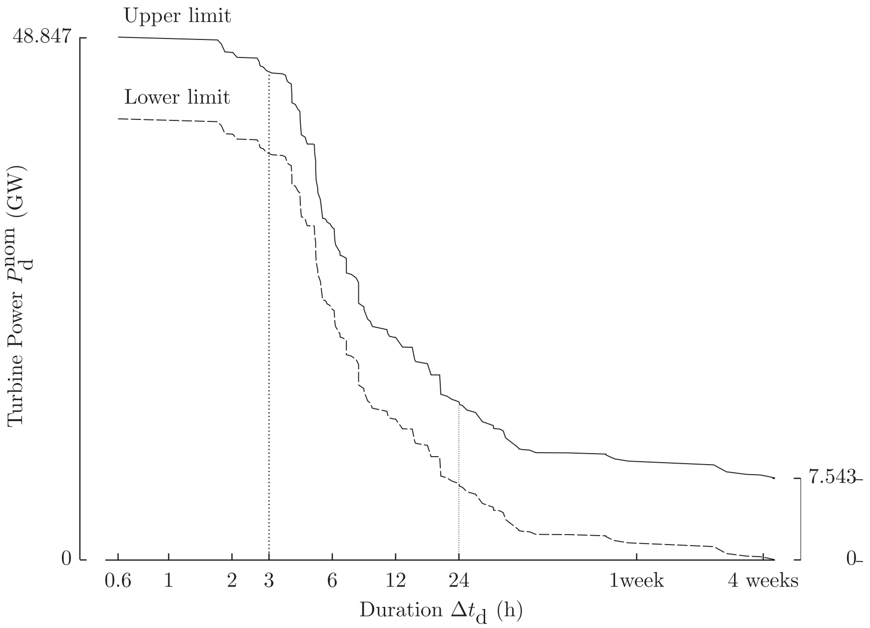

Fig. 2. Combined discharge characteristic of the 188 PHS. For 7.543 GW, the energy storage duration could not be obtained, therefore the actual discharge characteristic is somewhere between the indicated upper and lower limit. Logaritmic scale on horizontal axis.

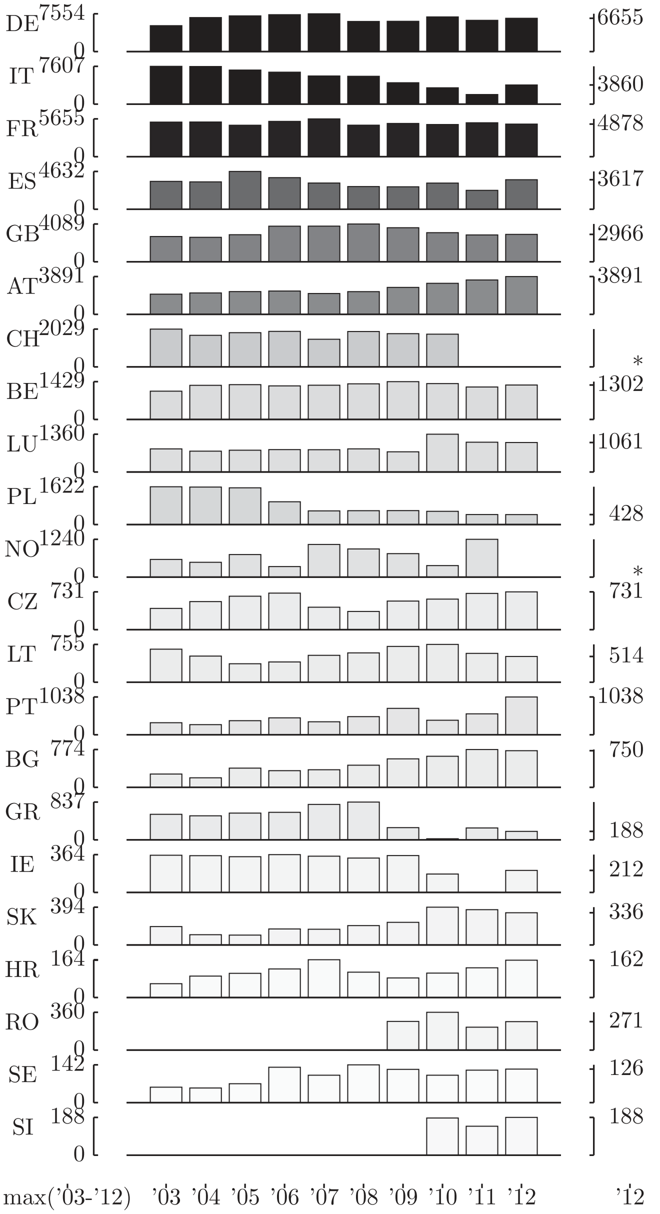

Fig. 3. Evolution of PHS generation since 2003 [11]. Maximum generation during the last ten years indicated on the left (GWh/a), 2012 value indicated on the right (GWh/a). Darker color indicates higher 10 year average. Missing data indicated ∗: '11-'12 for CH and '12 for NO.

operation at maximum power in turbine mode (column 4). Sweden can sustain such operation for over a month because of the Letten plant, however the power rating is low (Table 20). The ratio $E_{\text{stor}}/P_{\text{av}}$ (column 5) reflects how long the average electricity consumption can be covered with a single discharge cycle of PHS (while neglecting the power constraints of the plants). Only Switzerland (42.1 h) and Norway (27.0 h) have ratings of more than one day. Austria is third with 16.7 h. The ratio $P^{\text{PHS}}_{\text{d,av}}/P_{\text{av}}$ reflects the annual electricity generation by PHS divided by the total electricity consumption in the country (column 6). Here, Luxembourg is first, with 17% of the electric energy provided by PHS. It is noted that in reality this plant is often operated in a cross-border context. Finally, the ratio $P^{\text{nom}}_{\text{d}}/P_{\text{inst}}$ (column 7) shows the installed power of PHS in turbine mode as a share of the installed generation capacity. Again, Luxembourg is first with 72.8%.

Fig. 5 visualizes estimates of the utilization as storage of the national PHS plants in perspective of the available storage capacities. The utilization could not be determined at the plant level because $P^{\text{PHS}}_{\text{c,av}}$ and $P^{\text{PHS}}_{\text{d,av}}$ statistics are not available at that level of detail. In LU, GB, SE, AT, FR, SI, and BE, energy storage capacity varies substantially (0.5–132.4 GWh), nevertheless their utilization is similar and high, at 27.3–36.9%. In ES and IT, storage capacity is high but utilization is low. Italy is the only country with $P^{\text{PHS}}_{\text{c,av}} < P^{\text{PHS}}_{\text{d,av}}$ (2012), which suggests that PHS plants largely have been operated as hydro power plants.

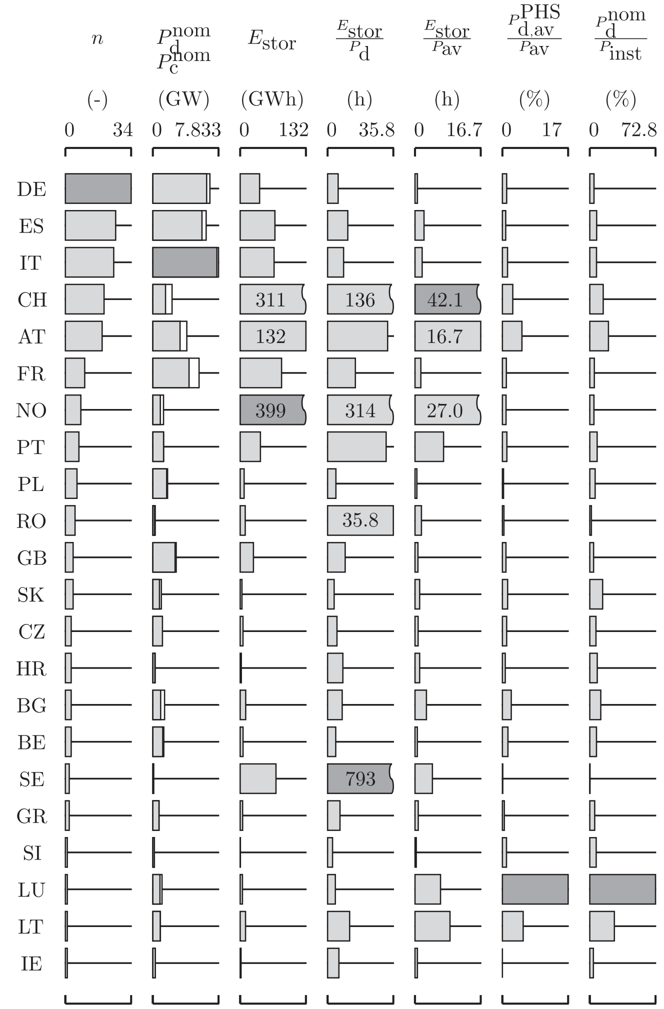

Fig. 4. Statistics by country (EU-28+NO+CH) of current PHS plants, sorted by number of plants per country: number of PHS plants (col. 1), charge (grey) and discharge (white) power (col. 2), storage capacity (col. 3), discharge duration (col. 4), hours of average consumption stored (col. 5), share of PHS in generation (col. 6) and share of PHS in installed generation capacity (col. 7). Countries without PHS plants not shown. Data, references and symbols in Table 25.

5. Conclusions

Within the EU-28, eight countries currently do not have substantial electric energy storage capabilities. Even though storage capacity is higher in Norway and Switzerland (711 GWh) than in the EU-28 (602 GWh), power ratings are relatively low. A total of 45.283 GW in turbine mode and 40.790 GW in pump mode is obtained for the EU-28 and adding Norway and Switzerland only increases this to a total of 48.847 GW in turbine mode and 43.194 GW in pump mode. This represents about 5% of current installed generation capacity. Whereas the collected power

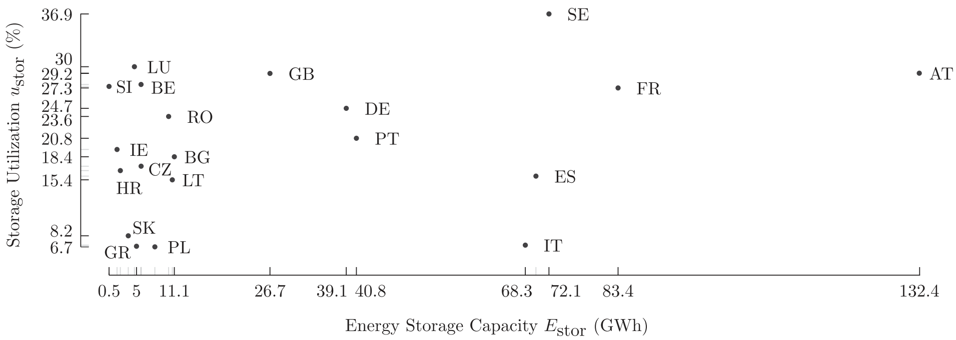

Fig. 5. Utilization of PHS as storage and the energy storage capacity at the national level in 2012. Assumes operation at rated power in pump and turbine modes. NO and CH, as well as countries without PHS, not shown. LU calculated for pre-2014 rating.

Table 24
Active non-PHS storage systems in Europe (> 1 MW/1 MWh).

	System	Technology	Specifications
DE	Huntorf	CAES	$P_{\text{d}}^{\text{nom}} =$ 321 MW, $P_{\text{c}}^{\text{nom}} =$ 60 MW, $\eta_{\text{rt}} = 42\%$
DE	Younicos	BESS	NaS 1 MW 6 h, Li-ion 0.2 MW
DE	Enercon	BESS	NaS 0.8 MW 6 h
DE	Falkenhagen	P2G	2.0 MW
FR	Reunion	BESS	NaS 1.1 MW 0.56 MWh
FR	Nice Grid	BESS	Li-ion 1.1 MW
ES	Almacena	BESS	Li-ion 1 MW
ES	Canary islands	–	BESS Li-ion 1 MW 3 MWh, flywheel 0.5 MW 18 supercapacitors 4 MW 20 s
ES	ILIS proj.	BESS	Li-ion 1 MW 0.56 MWh
UK	Orkney	BESS	Li-ion 2 MW 0.8 MWh
CH	Zürich	BESS	Li-ion 1 MW

Table 25
PHS plant data overview.

	n	$P_{\text{d}}^{\text{nom}}$ (GW)	$P_{\text{c}}^{\text{nom}}$ (GW)	E_{stor} (GWh)	P_{av} (TWh/a)	P_{inst} (GW)	$P_{\text{d,av}}^{\text{PHS}}$ (GWh/a)	$P_{\text{c,av}}^{\text{PHS}}$ (GWh/a)	n_{cycles} (1/a)
AT	19	4.051	3.246	132.41	79.258	23.164	3891	5558	29.39
BE	3	1.301	1.196	5.71	84.758	20.813	1302	1721	226.05
BG	3	1.399	0.930	11.13	33.465	13.581	750	1097	67.39
HR	3	0.281	0.246	2.34	17.278	4.010	162	231	69.23
CY	0	–	–	–	4.665	1.093	0	0	0
CZ	3	1.119	1.145	5.72	62.986	19.300	731	982	127.80
DK	0	–	–	–	34.241	14.028	0	0	0
EE	0	–	–	–	8.198	2.634	0	0	0
FI	0	–	–	–	85.248	17.680	0	0	0
FR	10	5.512	4.317	83.37	489.436	128.672	4878	6696	58.51
DE	34	6.805	6.417	39.12	559.264	171.649	6655	8121	155.69
GR	2	0.735		4.97	52.738	15.903	188	269	37.83
HU	0	–	–	–	39.905	9.140	0	0	0
IE	1	0.292		1.80	25.724	8.648	212	347	117.78
IT	25	7.833	7.640	68.27	328.220	124.233	3860	2689	29.54
LV	0	–	–	–	7.448	2.569	0	0	0
LT	1	0.900	0.880	10.80	10.607	3.905	514	698	47.59
LU	1	1.296	1.050	4.92	6.236	1.779	1061	1515	229.16*
MT	0	–	–	–	–	–	0	0	0
NL	0	–	–	–	115.784	27.477	0	0	0
PL	6	1.757	1.647	7.96	144.885	34.909	428	647	53.77
PT	7	1.279		40.77	49.063	18.536	1038	1331	24.48
RO	5	0.285	0.200	10.20	54.435	18.756	271	271	19.93
SK	4	1.016	0.790	3.63	26.837	8.431	336	357	73.76
SI	1	0.185	0.180	0.50	13.383	3.074	188	251	376.00
ES	26	6.358	5.859	70.00	266.850	98.719	3617	5023	51.67
SE	2	0.091		72.12	142.466	37.387	126	180	1.75
GB	4	2.788	2.650	26.70	312.740	77.854	2966	3978	111.09
$\sum$ 28	160	45.283	40.790	602.44	3046.118	907.944	33 174	41 962	
Mean	5.7	1.617	1.456	21.52	108.790	32.427	1185	1499	
NO	8	1.273	0.892	399.39	129.814	32.639			
CH	20	2.291	1.512	311.48	64.752	18.209			
$\sum$ 30	188	48.847	43.194	1313.31	3240.684	958.792			
Mean	6.3	1.628	1.439	43.78	108.023	31.960			
Data			2014	2012		2012	2012	2012	
Ref.			Tables 2–23	[135]		[135]	[11]	[11]	(18)

ratings are in line with the existing literature, the newly provided and methodically derived storage capacities present the largest contribution of this work. Previously only report [18] estimated the storage capacity at the European level, amounting to 2.5 TWh for 16 countries, all of which are included here. This information could not be reproduced and represents a major overestimation according to the authors.

Table 24 summarizes currently operational non-PHS stationary grid storage systems. Disregarding the 321 MW Huntorf CAES, the combined power is less than 20 MW, most of which BESS. This is dwarfed by BESS deployments elsewhere: e.g. the company AES developed and now operates a total of 115 MW in the US and another 64 MW in Chile [136]. Worldwide, the second most common grid storage technology is CAES (110 MW [137] + 321 MW [28]) and the third most common technology is NaS BESS with total $P_\mathrm{d}^\mathrm{nom} =$ 316 MW $E_\mathrm{stor} = 1.9$ GWh [5]. Even though Li-ion BESS have not had an equally large rollout, quite a few projects are found in Europe with this technology.

Mixed PHS stations operate both as a storage plant and as a conventional hydro plant. The utilization as storage plant is shown to vary substantially from country to country. New storage investments are made, including in countries with low utilization.

Table 1 provides an overview of new stationary storage developments of any technology. New storage projects may add 25.549–27.549 GW within the EU-28 (79 projects) or 35.489–37.489 GW within EU-28+NO+CH (91 projects). Others [2,26] expect an increase of 31.379 GW in the EU-28 by 2030. The PHS bulk energy storage potential in EU-28 remains substantial: 4 TWh[2] up to 33 TWh[3] [12]. Nevertheless, PHS remains geographically limited as it can only be located where the topography allows for it. Battery storage will not provide such bulk energy storage capabilities in the near term, with for example annual automotive Li-ion battery production capacity world-wide rated at about 23 GWh [138] (year end 2013). However, for such technology the location can be chosen to support power system services of higher value.

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Appendix A

A summary of the data used in this work is given in Table 25. Columns 1–4 contain the summary of the national data provided in Tables 2–23. Columns 5–8 indicate respectively the total net consumption 2012 [135], net generation capacity [135] and the gross electricity generation and consumption of PHS [11]. Data for Malta not included in [11]. The Luxembourg cycling data (marked *) is based on the former ratings of Vianden (4.63 GWh, 1096 MW (T) 850 MW (P)).

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[2] Scenario T1 realisable 20 km [12].

[3] Scenario T2 realisable 20 km [12].

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