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Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs[☆]

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ABSTRACT

Flexible electricity systems allow a higher penetration of variable renewable energy, and flexibility can be achieved through pumped hydropower storage (PHS). This assessment of European PHS potential focuses on linking two existing reservoirs to form a PHS system, the reservoirs must have adequate difference in elevation (head) and be close enough so that they can be reasonably linked. The results show that the theoretical potential energy storage is significant as it reaches 54 TWh when a maximum distance of 20 km between the existing reservoirs is considered. When constraints are applied, e.g. discounting populated areas, protected natural areas or transport infrastructure, the so-called maximum realisable potential is halved to 29 TWh. Comparing with the existing PHS storage capacity reported for 14 countries suggests that the theoretical potential is 3.5 times the existing capacity, whereas the realisable potential is still twice the existing capacity.

1. Introduction

The contribution of renewable energies to the world's total energy demand has increased particularly during the last two decades, and they will continue gaining market share. Because the natural resources that fuel those renewables (e.g. insolation, wind or precipitation) follow their own pattern of availability, the renewable energy production from them may not be forced to follow energy demand. Therefore, a mismatch occurs between generation (in particular of electricity) from renewables and consumer demand.

The electricity systems offer several alternatives to solve this mismatch, some of which were originally developed as a response to the fluctuations in demand and to protect against the loss of large generation power plant. These alternatives are: interconnections between electricity systems; energy storage; smart networks; and demand-side response (DSR) [1]. Utility-level energy storage for electricity systems is limited to pumped hydropower storage (PHS) – although the storage effect of reservoir-based conventional hydropower schemes is also considered energy storage depending on the authors. Compressed air energy storage (CAES) is still a technology under development whereas batteries and other technologies offer smaller capacities.

The European energy and climate policies have as one of their targets 20% of final energy from renewable origin by 2020 [2]. This target entails an even higher penetration of renewable energy in the electricity mix, possibly between 35 and 40%, and a high component of this will be non-dispatchable[1] renewables such as wind and solar. Moreover, the EU's 2050 decarbonisation objectives, with a target of 80–95% reduction in greenhouse gas emissions [3], will require a significantly higher share of renewables in the electricity mix.

In its 2012 Communication *Renewable Energy: a major player in the European energy market* [4], the European Commission points out the need for storage facilities to contribute to the flexibility encouraged in the electricity market. As part of its review of that Communication, the (Energy) Council of the European Union required that consideration is given "*on ways and means to strengthen the potential for development of RES (*renewable energy sources) in an integrated, secure and cost-efficient and effective way, in relation to grid infrastructure (e.g. addressing loop flows), ***storage***, *back-up capacity and better operational solutions*" [5].

☆ The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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[1] Dispatchable generation refers to sources of electricity that can be dispatched at the request of power grid operators; that is, generating plants that can be turned on or off, or can adjust their power output on demand.

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0960-1481/

Table 1
Electricity generated in 2011 from some renewable energies in the EU. Source: Eurostat table nrg_105a [7].

Electricity	Hydropower without PHS	Wind	Solar	PHS production	PHS demand	Total gross production	Final consumption
TOTAL (TWh)	335	179	46	29	38	3280	2768
Percentage of gross production	10.2	5.5	1.4	0.9	1.15	100	84

Different studies suggest that energy demand in Europe could double by 2025 and still increase afterwards, and a storage capacity of 40 TWh will be necessary by 2040 for periods from days to weeks, and sometimes months in the EU [6].

A gross total of 567 TWh of electricity was generated from non-biomass RES in the EU during 2011. Of this, hydropower excluding PHS contributed with 335 TWh from 104 GW of installed capacity [7].

Table 1 shows EU electricity production and consumption data. Total gross production reaches around 3280 TWh, non-PHS hydropower contributes 10% of the total annual consumption, and a further 1% is contributed by PHS plants from water previously pumped.

Conventional hydropower is one of the means of using stored energy. When not based on an existing lake, a hydropower system is built by creating a reservoir generally by closing a valley with a dam and allowing the corresponding river to fill up the reservoir, then generating renewable energy by releasing the water through a turbine. The unwanted effects of this approach include river disruption and other environmental issues, e.g. when the river natural distribution and timing of stream flow is altered, affecting riparian areas, altering the geomorphological process and thus dramatically disturbing the aquatic biodiversity by preventing free migration of many aquatic species including fish. Another undesirable effect is, in some cases, forced relocation of people or important landscape changes caused by filling up the entire valley with water [8,28]. Finally, conventional reservoir hydropower is not capable of storing excess electricity when it occurs in the system, e.g. when wind electricity is abundant and demand is low.

Table 2
Brief description of the different PHS topologies from the point of view of assessing PHS potential. Source: SETIS expert workshop on the assessment of the potential of pumped hydropower storage [9].

Topology	Description
T1	Linking two existing reservoirs with one or several penstock(s), and adding a powerhouse to transform them to a PHS scheme
T2	Transformation of one existing lake or reservoir to PHS by detecting a suitable site for a second reservoir. The second reservoir could be on a flat or non-sloping area, by digging or building shallow dams, on a depression or in a valley[a]
T3	A greenfield PHS based on a suitable topographical context: either valleys which can be closed with a dam, depressions, hill tops which could be slashed, etc. This topology is broader i.e. neither based on existing lakes or reservoirs nor assuming a flat area for building the second reservoir
T4	Sea-based PHS: a greenfield PHS that uses the sea as the lower reservoir and a new nearby reservoir, or the sea as upper basin and a cavern as lower reservoir[b]
T5	Multi-reservoir systems including both PHS and conventional hydropower
T6	The lower reservoir is basically a large river providing sufficient inflow into the PHS system. An example is the Jochenstein-Riedl PHS where the Danube acts as lower reservoir[c]
T7	Use of an abandoned mine pit as the basis for the PHS. The methodology to be used would be similar to the topology 2 one. An example is the old coal mine of As Pontes, in Spain[d]

[a] In this study we do not consider valleys due to the environmental issues.
[b] For an example of the former see the Okinawa Yanbaru PHS at http://en.wikipedia.org/wiki/Okinawa_Yanbaru_Seawater_Pumped_Storage_Power_Station. For the details of the latter option see http://www.psh-offshore.com/en/concept/?
[c] See the web of Verbund where a clear scheme shows this topology: http://www.verbund.com/pp/en/pumped-storage-power-plant/riedl.
[d] For more information see http://www.lagodeaspontes.com/.

An alternative or complement to conventional hydropower is PHS, which is the most established technology for utility-scale electricity storage. By pumping water to the upper reservoir PHS schemes allow the storage of surplus electricity in the form of the potential energy of water; by releasing it through a turbine they allow the transformation back to electricity. This has traditionally been used to support the integration of electricity from non-flexible power plant (such as nuclear and base load coal plant), and is lately being used to help integrating variable renewable energies.

When analysing the potential for new PHS several topologies are possible – as shown in Table 2.

Even when there are no official figures for ***storage capacity*** in PHS in Europe or the EU, there are figures for PHS electricity ***installed*** generation ***capacity***: around 42.6 GW in the EU [7]. In terms of electricity generation and consumption, in total in Europe, Platts [10] gives the figures of 40 TWh generated per year consuming 54 TWh in pumping, these from 232 operational PHS plants. The corresponding Eurostat figures for the EU in 2011 are 29 TWh of electricity generated from 38 TWh used for pumping.

The objective of this work is to assess the potential for energy storage in pumped hydropower schemes in Europe based in two existing reservoirs (T1 in Table 2 above). For this, the methodology defined by a team of the Joint Research Centre (JRC) and University College Cork (UCC) staff [11,12] was applied, after it was validated in a workshop of international experts [9].

The chosen approach of assessing the potential only under topology 1 introduces some limitations, the most important of which is that the results only reflect a part of the European PHS potential, and possibly a small part of the total. Despite these limitations, this approach was chosen because of its expected much lower environmental impact than, for example, creating a new reservoir.

Through this innovative study, the purpose to assess a PHS potential in Europe has been reached for the first time, and this was made possible by developing and applying a GIS-based software model.

The next section includes a basic description of the methodology applied and a more thorough indication of the limitations encountered, and how these were addressed. Section 3 presents the results for the EU and other European countries, as well as Turkey.[2] Section 4 concludes and provides with some recommendations for further work in the area.

2. Application of the methodology and issues

2.1. Methodology definition

The methodology is based on a geographical information system (GIS) model fed with a digital elevation model (DEM) – which is a topographical description- and with data of existing reservoirs including the geographical coordinates of the centre of the dam and

[2] Although the majority of the Turkish territory is not in Europe, and the majority of the Turkish PHS potential is not in the European continent, to the effects of this assessment the Turkish potential has been considering European because of the status of Turkey as candidate country for accession to the European Union.

Table 3
Constraints or assumptions, and values applied.

Description (assumptions)	Value
Maximum distance between two existing reservoirs	1, 2, 3, 5, 10 & 20 km
Minimum head	150 m
Assumed minimum new reservoir capacity	100 000 m^3
Minimum distance to inhabited sites	500 m
Minimum distance to existing transportation infrastructure	200 m
Minimum distance to UNESCO site	500 m
Maximum distance to electricity transmission network	20 km
Minimum distance to a Natura 2000 conservation area	Should not be within

their water storage capacity. Other data was fed at later stages including transport and grid infrastructure and land use including inhabited areas and nature-and culture-protected areas. Assumptions were built into the search criteria, e.g. minimum distance to inhabited areas, as described in Table 3 below and in more detail by Lacal-Arántegui et al. [12].

The model was run to identify and assess the potential new storage under different scenarios which are basically varying distances between the two reservoirs, i.e. from 1 to 20 km. The resulting bottom-up energy storage potential of the prospective PHS schemes was added to provide a country potential for each topology [11,12].

The practical application of the methodology encountered several problems. To start with, the digital elevation model (DEM) used by the GIS application is not available for latitudes above 60°. Importing country borders left some gaps that had to be fixed. Also, no single source could offer complete reservoir data; those from different sources were at times patchy, and it was necessary to carefully assess all datasets before choosing the most appropriate. Land use data derive from CORINE Land Cover (CLC) 2006 [12], and these data are not available for all European countries. Georeferenced cultural heritage data downloaded from UNESCO allocate a single coordinate to multi-site centres with the consequent lack of accuracy. Finally, because the study was performed at country level possible transboundary sites were not captured (see Section 2.3 for more details of the latter).

There are different potentials depending on the depth of the analysis and the constraints, or filters, included in each analysis. Fig. 1 shows the methodology flowchart including all the stages at which a measure of potential could in principle be obtained: theoretical, human-use, environmental, realisable (or grid-connected), and economic potential. The two energy storage potentials obtained in this modelling exercise are the theoretical and realisable ones.

Theoretical potential: is the result of feeding the GIS software model with topographical information, the database of reservoirs with a minimum capacity of 100 000 m^3 of water or which have hydroelectricity production rated 1 MW or more,[3] and scenarios for the parameters head and maximum distance between reservoirs. Six scenarios were evaluated and the corresponding energy storage potentials were estimated.

Realisable potential: is the result of applying to the theoretical potential a series of social, infrastructure and environmental constraints. These constraints resulted in the removal of the related sites, roads, etc. from the topography available for the model, plus the removal of a terrain buffer set around them and the subsequent gaps were excluded from the search. Also within this potential a maximum distance to the nearest electricity grid was set up. Table 3 shows the lists of constraints applied.

[3] As explained in Section 2.2, the second group was not considered during the execution of this analysis.

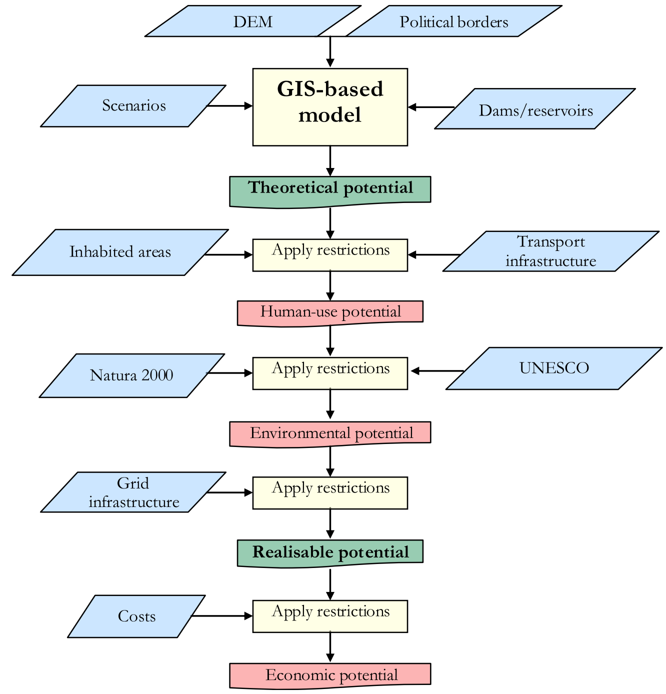

Fig. 1. Methodological flowchart with the inclusion of intermediate potentials.

For an explanation of the detailed implications of the parameters above, see the previous research work in Lacal-Arántegui et al. [12,9].

It would be possible to calculate other potentials, but the current search process does not present intermediary results. For example, it would make sense to calculate a figure for “human-use” potential, the result of applying to the theoretical potential constraints on inhabited areas and on transport infrastructure; or an environmental potential which removes Natura 2000 and other nature-protection areas, and UNESCO World Heritage sites from the available land for research. Finally, based on the realisable potential, the cost of building the PHS, e.g. cost of penstock, of the grid connection, etc., could be taken into account (but are currently not) so that the model would provide an economic potential.

Following the recommendations of the *SETIS Expert workshop on the assessment of the potential of pumped hydropower storage* [9], the values of the constraints were modified to reduce the minimum separation distance to inhabited, nature-protected and UNESCO sites and to infrastructure (see Table 3). Also following these recommendations, from the original methodology [12] the analysis for a maximum distance of 4 km between reservoirs was dropped, and further analyses were carried out for 10 km and for 20 km.

2.2. Data and software limitations

With the purpose of extracting the information needed for a country-based assessment, political borders were downloaded from the DIVA-GIS website [13], where country-level, free spatial data are provided. This is considered to be a reliable, accurate and ready-to-use source [12].

The countries for which PHS potential was analysed comprise most of the European countries as follows (ISO code between brackets):

- EU Member States Austria (AT), France (FR), Germany (DE), Cyprus (CY), Sweden (SE), Czech Republic (CZ), Spain (ES),

Fig. 2. Existing PHS system La Muela (Valencia, Spain)and prospective site calculated by JRC GIS-model.

Belgium (BE), Ireland (IE), Romania (RO), Poland (PL), Bulgaria (BG), Hungary (HU), Italy (IT), Portugal (PT), Greece (GR), Slovakia (SK), Slovenia (SI), Finland (FI), United Kingdom (UK);
- non-EU countries including Croatia (HR), Norway (NO), Turkey (TR), FYROM (MK), Switzerland (CH), Montenegro (ME), Iceland (IS), Serbia (RS), Albania (AL), Kosovo[4] (XK), and Bosnia and Herzegovina (BA).

Several European countries have not been analysed because of different reasons. In some cases no reservoir data were available e.g. Estonia, Latvia, Lithuania, Luxemburg, Liechtenstein and Malta; or by physical limitations in some cases, as it occurs with very flat countries, e.g. the Netherlands and Denmark.

The data needed on existing reservoirs include the reservoir name and geographical location, its water storage capacity and whether it has hydropower exploitation, in which case the generation capacity is also needed. From each one of the existing reservoirs the GIS model searches for potential new PHS referred to a single point of the nearby reservoirs, and with existing reservoirs sized from several thousand square metres to several square kilometres, it was necessary to choose the "single point" between, e.g. the centre of the reservoir or the centre of the dam. The latter was chosen as geographical location primarily because databases generally provide dam locations, and because it tends to be the point where the reservoir is deeper and the hydropower water intakes are installed.

However, this is not always the case. Fig. 2 shows the PHS La Muela, where the water intakes are placed at a distance of less than one kilometre whereas following the procedure above, the model takes the distance between dams, 3.2 km. As a consequence, the potential identified is included under the 5-km scenario and not under the 1-km scenario.

The option of using lakes was discarded because of the difficulty to obtain data such as the centre of lake geographical coordinates and because lakes generally involve less human disruption to the

[4] Kosovo does not have official ISO code.

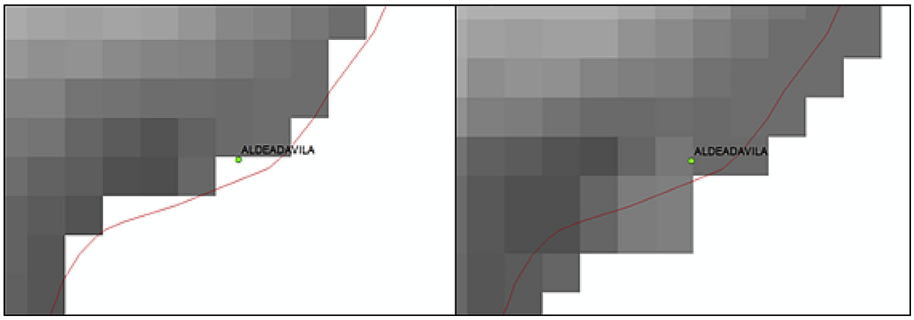

Fig. 3. The left figure shows a case of "no data", affecting the Aldeadavila dam in Portugal, as result of the extraction of elevation; the right figure shows the expansion of DEM beyond the borders avoiding "no data" output when extracting elevation data.

river ecosystem than reservoirs.[5] The re-inclusion of the reservoirs which were discarded because of their small size (<100 000 m^3) but which have hydropower generation was not carried out because of incomplete generation data.

Reservoir data were provided by the European Environmental Agency (EEA) from its ECRINS (European Catchments and RIvers Network System) database [14]. This is a database of watersheds, rivers, lakes, monitoring stations, dams, etc., of which only dam and reservoir data were used. ECRINS originated from the JRC CCM 2.1 (Catchment Characterisation and Modelling) [15] and was then refined, corrected and completed with data from other sources: see the Annex to reference [9] for a more detailed explanation of ECRINS and CCM.

Some of the gaps still in the ECRINS database were filled through a direct collaboration with EEA by using the European Environment Information and Observation Network (EIONET) DAM POSitioning (DAMPOS) web tool [16].

When a reservoir has more than one dam, ECRINS only allocated reservoir capacity to the main dam. In these cases, the GIS model disregarded secondary dams as the basis for searching for potential new sites. This methodological decision can be controversial: in large reservoirs, e.g. more than 7 km long, secondary dams can be as suitable as the main dam as the basis for searching a potential site for a second reservoir, and other points can be as well. This decision introduces a conservative bias in that it reduces the number of potential sites.

Man-made ponds are included in ECRINS but they were judged not appropriate as the basis for a potential new PHS scheme. Most are expected to be smaller than 100 000 m^3 in capacity. However, because of the workload involved in their individual identification, they were not discarded. Only the smallest among them were automatically discarded at the first stage of the process, when all small reservoirs are discarded by the search process.

ECRINS is not a complete database, currently some countries such as Lithuania are missing, and some others are not complete. The most outstanding case is probably Norway: according to the Norwegian Directorate for Water and Energy (NVE), Norway has 905 existing reservoirs, 886 of them with a reservoir volume of >100 000 m^3 [17], which have to be compared with the 129 ECRINS reservoirs available for this study.

The elevation information of the dams was extracted using the digital elevation model from Shuttle Radar Topography Mission (SRTM) data. The main reasons for using SRTM include its ease of use, a 90-m resolution, coverage of the whole of Europe up to 60°N, easy access by download in 5° by 5° blocks, broad acceptance in the scientific community and among the industry. The scope of this study permits the consideration of 90-metres resolution as a good balance between accuracy and computation speed.

A problem was presented when extracting from DEM the elevation of dams near country borders because gaps were created between the raster layer and the vector layer (border), giving as a result a "no data" area. The solution applied was to extract the DEM dots beyond the country borders to eliminate the gaps, Fig. 3 illustrates this case. A tool in ArcGIS was created to automate the process.

During the search of a suitable DEM for the Nordic countries ASTER GDEM[6] 30-metre resolution DEM was assessed. However, this option was discarded due to the high computing time needed due to the higher resolution, and also because it occasionally contains large data gaps. The DEM finally used for these countries was the 250-metre resolution GMTED2010[7] which provides coverage up to 84° N. However, such resolution does not allow the same accuracy of analysis in Nordic countries as for the rest of Europe.

Data for inhabited sites, rivers and lakes derive from the remotely-sensed project CORINE Land Cover (CLC) refined version 2 from the year 2006 (with the exception of Greece for which only the 2000 CLC is available), in 100 m resolution. Three of the CLC categories make up the GIS layer of inhabited areas: continuous urban fabric, discontinuous urban fabric and industrial/commercial units. Rivers and lakes were extracted from the corresponding classes in CLC but only with the objective of representing the river network in graphic final outputs.

Main roads and railroads make up the transport network layer, obtained from free GIS data sources, DIVA-GIS in this case.

The environmental constraint layer is based on Natura 2000 data from the EEA database. It is comprised of Special Areas of Conservation (SAC) and Special Protection Areas (SPAs). It was assumed that all the key conservation areas, e.g. all national parks as named by the authorities of each country studied, are included there but this point was not verified.

The absence of Natura 2000 areas in Turkey was partly covered with the inclusion Turkey's 13 Ramsar areas, available from the Ramsar Sites Information Service (RSIS) web site.[8]

Cultural protection sites were also taken into consideration and are part, with Natura 2000, of the named "Environmental

[5] The difference considered here is that "lakes" existed before any human intervention, whereas "reservoirs" where created thanks to humans building a dam and thus disrupting the natural river flow.

[6] http://asterweb.jpl.nasa.gov/gdem.asp.

[7] The description of this DEM can be found at http://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf.

[8] http://www.ramsar.wetlands.org.

potential".[9] The United Nations Educational, Scientific and Cultural Organization (UNESCO) was considered the best source of information and the official list was downloaded from UNESCO World Heritage Centre website.[10] This list includes the corresponding geographical coordinates for each Human Heritage site.

However, multi-location World Heritage sites such as a set of caves are defined by a single point, with the consequent risk, for this project, that not all of these sites are taken into account. The impact of this limitation was evaluated and the final decision was to accept the official list because for the purpose of this assessment this is accurate enough. If necessary for a more detailed study, coordinates for multi-location cases could be added in the future.

Electricity grid infrastructure is the last constraint implemented in the GIS model and the results obtained after applying it are considered the "realisable potential", the final output presented by the model.

The information, sourced from Platts [18], permits the model to calculate the distance between the PHS scheme proposed and the nearest grid transmission infrastructure. Details on whether the grid can accommodate the additional PHS capacity are not considered by the search process.

2.3. Other limitations of the GIS model

The model builds a circle around each existing reservoir which is half the size of the maximum distance, i.e. a 10-km radius for the 20-km scenario. When two such circles have some overlapping surface, whichever its extent, the search process records a "hit" and the two reservoirs are considered the basis of a potential PHS (theoretical potential): the connection between them is less than the 20 km of the example.

When the environmental restrictions are applied, sometimes a Natura 2000 area touches the intersection between both circles, and the search process then removes the pair of reservoirs as a potential PHS. However, this might not necessarily be a sensible removal: the connection needed between two existing reservoirs is merely the space of the penstock, and this can be underground thus having no impact on the protected area. Still, this characteristic of the model was maintained.

In the 20-km (and perhaps the 10-km) scenario it could happen that the connection between the two reservoirs stretch over deep valleys, fjords or large natural lakes, which in some cases would render the construction of the penstock(s) unpractical. The likelihood of this case was not explored.

The inflow and outflow rates of other reservoir users, e.g. drinking water or irrigation, or existing power plants were not included into the capacity calculations.

Because the assessment was made at country level, when an existing reservoir is close to the border the model did not search for potential sites beyond the border. To alleviate this problem a different unit could have been used, whether this is the river basin district (as defined in the EU Water Framework Directive[11]), or the mountain range, i.e. treating the Pyrenees as one single system. However, the problem would still exist although slightly changed, borders would be replaced by river basin or mountain range limits. The only solution for this problem is to treat the whole continent as a single unit in ArcGIS, but one drawback is that we could not dispose of enough computing power.

2.4. Solutions applied

Since the methodology was created [12] several changes have been adopted following the recommendations of the experts workshop [9]. Some of the original assumptions were maintained, namely a 150-metre minimum head, the minimum distance to inhabited sites (500 m) and to existing transport infrastructure (200 m), and the condition that prospective sites should not be within a Natura 2000 area, whereas others were fine-tuned. Table 4 shows the most significant changes applied.

One of the most significant changes was to reduce minimum capacity of the reservoirs used for the assessment from 1 000 000 m^3 to 100 000 m^3. However, this change has to be made with care: if the reservoir is being used for other purposes, e.g. drinking water or irrigation, a maximum drawdown could be imposed.

The maximum distance to the electricity grid was also reduced from 50 km to 20 km in order to minimise costs and the possible environmental and public objections for building the necessary new transmission lines.

The ArcGIS model can customise these assumptions freely.

Even when Natura 2000 areas do not exclude human (e.g. commercial) activities, the methodological decision was to exclude these areas from the assessment of PHS potential. This conservative assumption could be changed for example when analysing specific countries. Similarly, some of the best potential PHS sites that only slightly touch a Natura 2000 area were eliminated, although its creation would therefore not impede the conservation objective of the area.

At least in Germany, the use of dams for drinking water supply would not be allowed for an additional purpose such as pumped hydropower energy storage [19]; those reservoirs were not excluded from this assessment.

2.5. Validation and comparison with existing PHS capacity

The JRC (and previously the UCC team that supported the development of the GIS model) at several stages validated the model against reality. This subsection shows to which extent the JRC-calculated storage capacity matches data from other sources.

The results obtained after the search process reflect the maximum potential capacity which can be stored in the upper reservoir of the potential PHS system. By assumption, the energy storage capacity in the model is limited by the water storage capacity of the upper reservoir, which was assumed to always have less or equal capacity than the lower reservoir. The reasoning behind was that it is the lower of the existing reservoirs that is more likely to lie in a river and thus it has a contributing flow and more flexibility for releasing or accumulating water.

However, this assumption does not necessarily hold in all cases and thus Eurelectric [20] in its assessment of existing capacity sets

Table 4
Changes made to the assumptions in the initial methodology definition.

Description	Original T1	Current T1
Maximum distance between two reservoirs	1, 2, 3, 4, 5-km	1, 2, 3, 5, 10, 20-km
Assumed minimum reservoir capacity	1 000 000 m^3	100 000 m^3
Minimum distance to UNESCO site	5 km	500 m
Maximum distance to electricity transmission network	50 km	20 km

[9] Environmental potential is not an output in this study but it could eventually be obtained by modifying the model.

[10] http://whc.unesco.org/en/list.

[11] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.

either the lower or the upper reservoir as limiting factor. In effect, some PHS facilities exist where the lower reservoir has smaller water capacity than the upper reservoir; in these cases the energy storage capacity is limited by the water capacity of the lower reservoir, not the upper one. An example is Bleiloch PHS in Germany.

We explored how the energy storage calculated by the model compares to data from external sources. Table 5 contains a selection of individual PHS facilities for which reliable data could be obtained, along with JRC data.

In this table, electrical generation capacity (MW) and energy storage capacity (MWh) data were obtained from external sources, whereas the capacity of the upper reservoir of each PHS system, energy storage capacity (JRC) and storage hours were calculated by the GIS model or from its sources. Head was mostly from an external source but when absent it was calculated by the GIS model from DEM data. Specifically, the column "Storage from source" shows the storage capacity quoted by the external source of data, whereas column "Storage from JRC" shows the capacity calculated by the GIS model based on the capacity of the upper reservoir (ECRINS data) and the head.

It can be seen in the table that energy storage capacity data differ very little between the two sources, the most outstanding cases are Revin and Hohenwarte I PHS with a 20% difference, which could be due to the 80% PHS round-trip efficiency built into the JRC calculation.

Fig. 4 plots the results from external sources of data and calculated figures. The strength of the relationship between external sources and data from the GIS model turns out to be highly consistent: the Pearson correlation coefficient between the two data sources is 0.998.

Note that the storage capacity quoted does not take any account of any additional natural flow from rivers.

The relationship between the energy storage capacity of a PHS and its installed electrical capacity was explored as well by using the data in Table 5. When the two largest PHS are removed from the dataset, the relationship of installed electrical capacity to energy storage capacity, as shown in Fig. 5, gives a high correlation (Pearson coefficient 0.91). When both large PHS are taken into account the correlation is much lower (Pearson coefficient 0.55). This suggests that for small to medium storage capacity, up to 10 GWh, a consistent relationship could exist between both parameters but that this relationship does not stand for larger PHS systems.

One can choose to use large reservoirs and storage volumes and install low capacity, which will lead to slow changes in water levels (resulting in some types of environmental impact) in the lower and upper reservoirs. On the other hand, one can use relatively small reservoirs like most existing EU PHS have, and relatively large installed capacity, which will have other kinds of environmental impacts. These two relatively different types of PHS would also give different services to the electricity market, i.e. short-term or long-term storage and balancing [17].

The potential may have captured some of the existing PHS in what could be overlaps with existing PHS or else extensions to them, this was not validated.

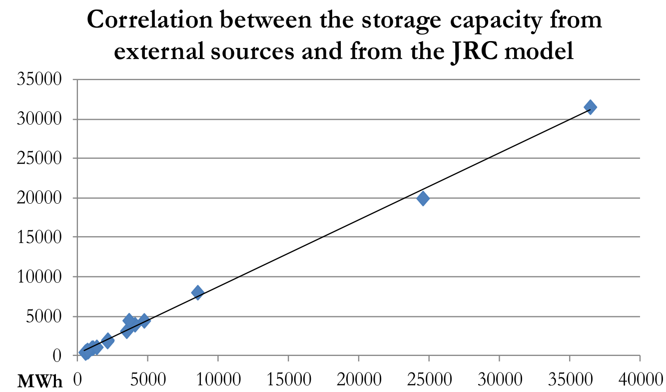

Fig. 4. Correlation on PHS storage capacity data from external sources and from the JRC model.

Table 5
Comparison between external and JRC storage data. Sources: (1) Wänn [21], (2) DENA [22], (3) Martínez Campillo [23], (4) Ursat et al. [24], (5) Sallaberger [25], (6) Hartmann et al., [26]. *DENA [22] does not contain head information, Hartmann et al. [26] does. **Storage hours calculated from storage capacity and installed electrical capacity. Note: JRC figures include the assumption of a PHS cycle round-trip efficiency of 80%.

Country	PHS name	Capacity upper reservoir m^3	Head*	Generation capacity (MW)	Storage from source (MWh)	Storage from JRC (MWh)	Storage hours**	Source
DE	Bleiloch	5 600 000	46	80	640	572	7	1, 2
DE	Erzhausen	1 618 000	287	220	1032	1030	5	6
DE	Geesthacht	3 600 000	80	120	600	640	5	2
DE	Glems	900 000	283	90	560	566	6	2, 6
DE	Goldisthal	12 000 000	302	1060	8480	8050	8	2
DE	Hohenwarte I	3 280 000	56	63	504	408	7	2
DE	Hohenwarte II	3 002 000	304	320	2087	2027	6	2
DE	Koepchenwerk	1 533 000	155	153	590	529	3	2, 6
DE	Langenprozelten	1 500 000	297	168	950	990	6	2, 6
DE	Makersbach	6 300 000	285	1050	4018	3989	4	2
DE	Niederwartha	1 981 000	143	120	591	629	5	2, 6
DE	Rönkhausen	1 000 000	265	140	690	590	4	6
DE	Säckingen	2 100 000	400	353	2064	1866	5	2
DE	Waldeck I	700 000	296	140	487	461	3	6
DE	Waldeck II	4 400 000	324	440	3428	3167	7	2
DE	Waldshut	1 350 000	160	176	476	480	3	6
DE	Wendefurth	1 970 000	126	80	523	551	7	2
DE	Witznau	1 300 000	250	220	642	722	3	6
ES	Guillena	2 330 000	217	210	1300	1123	5	3
ES	La Muela II	20 000 000	450	628	24 500	19 993	32	3
FR	Montezic	33 600 000	423	910	36 400	31 573	35	4
FR	Revin	8 700 000	233	720	3600	4503	6	4
LU	Vianden M11	7 200 000	280	1100	4675	4478	4	5

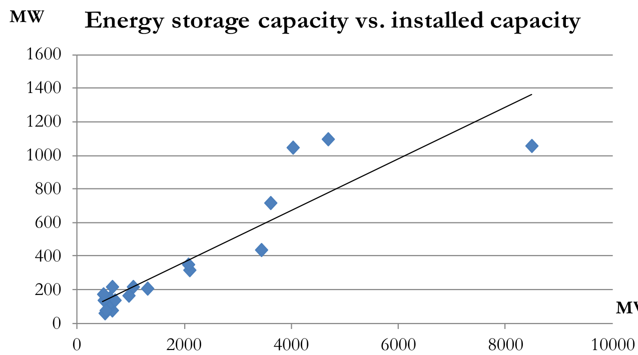

Fig. 5. Comparison of energy storage capacity data from the external sources with installed electrical capacity for PHS with less than 10 GWh storage capacity.

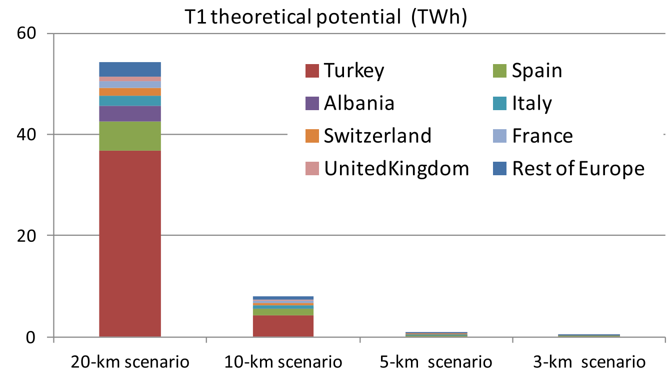

Fig. 6. Calculated theoretical PHS potential for different maximum distances between existing reservoirs.

3. Results: the European PHS potential

3.1. Potential under topology 1

The overall European theoretical potential with a maximum distance of 20 km between the two reservoirs is 54.3 TWh. This figure is reduced to a realisable potential of 28.7 TWh when the constraints described in previous sections are taken into account. The results obtained for this topology are presented in the graphics and tables below, differentiated by scenarios.

Table 6 shows the theoretical potential for new energy storage capacity. The table also illustrates the extent to which the potential depends on the maximum distance assumed between the two reservoirs that make up a PHS facility. As it can be expected, both the number of sites and the overall potential increase as the distance increases towards the limit set up for this study, 20 km.

The variations in the potential energy storage capacity are consistent with the increases seen on the total amount of sites in the different scenarios. Potential energy storage increases from almost zero in the 1-km scenario, explained by the difficulty to find two existing reservoirs so close to each other, to 0.83 TWh for the 5-km scenario and reaches more than 50 TWh in the 20-km scenario.

Overall, the results show that there is a considerable potential capacity for storing energy by connecting two existing reservoirs in large distances. The 54 TWh of theoretical potential will be reduced by the application of environmental and other restrictions, but there is still a significant potential when compared with the existing capacity reported by Eurelectric [20] of 2.5 TWh in 16 European countries.

Fig. 6 shows that Turkey has the most potential in the 20-km scenario, followed by Spain, Albania, Italy, Switzerland, France and the UK. However, for scenarios with lower distances the ranking changes significantly: Albania drops off the top-7 list for the 10-km scenario and Turkey for the 5-km scenario, where Spain leads followed by Italy in a similar ranking as for the 3-km scenario. Austria maintains a relatively significant potential to the 5-km scenario but this is diminished significantly for the 3-km scenario. Table 7 shows the results for these four more significant scenarios and the ten countries with the largest potentials. The 2- and 1-km scenarios show notably lower, in fact insignificant, theoretical potential: only 0.104 TWh between the two of them.

Table 6
Number of potential sites found and stored energy associated.

Theoretical potential						
Scenario	20 km	10 km	5 km	3 km	2 km	1 km
No. of sites	8268	1779	387	141	52	5
Potential energy storage (TWh)	54.31	8.00	0.83	0.31	0.10	0.004

Table 7
Top-ten countries by theoretical potential at 20 km and the situation at lower distances.

Scenario/country potential	20 km (TWh)	10 km (GWh)	5 km (GWh)	3 km (GWh)
Turkey	36.79	4319	36	24
Spain	5.79	1182	292	132
Albania	3.15	47	11	0
Italy	1.87	661	218	85
Switzerland	1.66	431	42	31
France	1.18	409	54	20
United Kingdom	0.99	199	23	4
Norway	0.99	332	33	5
Portugal	0.54	118	7	0
Austria	0.44	199	105	6

Table 7 shows as well that whereas for distances between dams of up to 5 km it is in EU Member States (Spain, Italy, France) and Switzerland that most of the potential exists, for longer distances countries outside the EU (Turkey, Albania) is where the largest theoretical potential exists. This change of trend is the clearest between 5 and 10 km: whereas at 5 km 85% of the potential is in the EU and only 15% in the rest of the countries under study, at 10 km 54% of the potential (4.32 TWh) is in candidate countries[12] and 36% in the EU (2.87 TWh).

At 20 km the potential in candidate countries reaches 37 TWh (overwhelmingly in Turkey), well above the potential in the EU with less than 25% (11.4 TWh).

Fig. 7 shows the country potential within a maximum of 20 km between existing reservoirs. At a first sight the most surprising item is the relatively low potential of Norway, the country which possesses by far the highest hydropower installed capacity in Europe, 30 GW. There are two main causes for this: a gap in the reservoir data available (see Section 2.2), and the large distance between reservoirs in that country.

It is perhaps surprising the relatively high potential in the UK, a country with significantly lower mountain areas than, for example, the Alps. Yet, the UK 20-km theoretical potential is similar to France's, of the same order of magnitude as Italy and Switzerland, and significantly higher than Austria, Slovenia or Germany.

[12] The description of the countries can be found at http://europa.eu/about-eu/countries/index_en.htm.

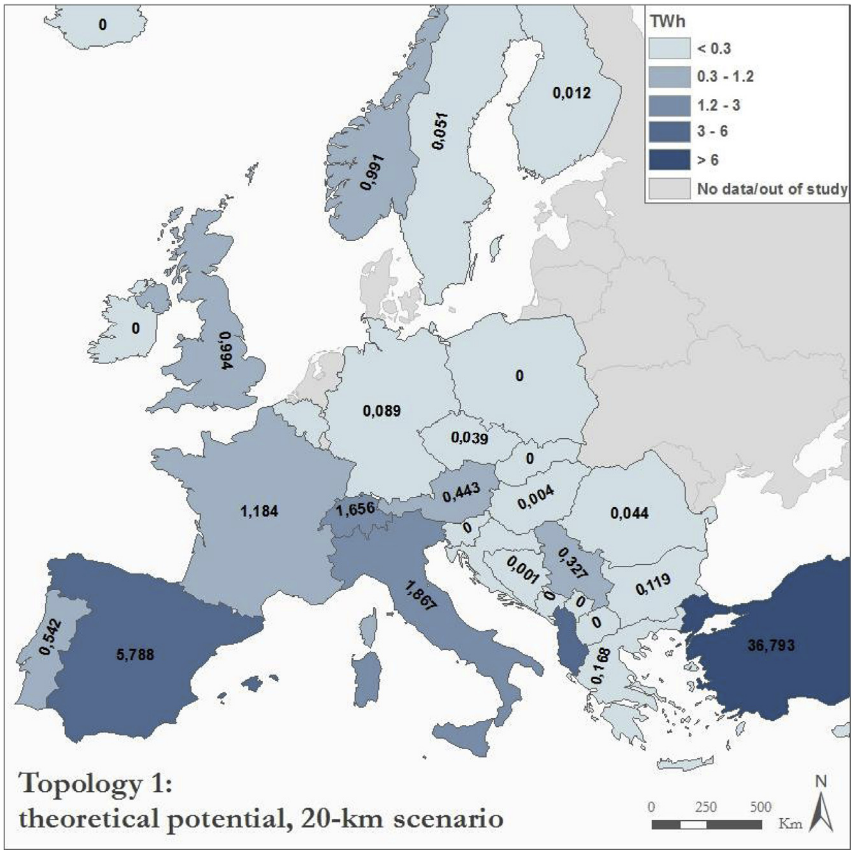

Fig. 7. Theoretical potential per country.

The number of theoretical potential sites decrease when the constraints are applied, eventually resulting in a realisable potential of 28.63 TWh of storage capacity.

Table 8 shows the potential sites which fulfil the restrictions proposed in the methodology for PHS assessment. The number of schemes where existing reservoirs could be connected to form new PHS decreased noticeably in all scenarios: from 8268 to around 3200 sites in the 20-km scenario, from 1779 to 538 in the 5-km one, and from 387 to 99, from 141 to 32, from 52 to 8 and from 5 to 1 sites in the 5-km, 3-km, 2-km and 1-km scenarios respectively.

Linked with the strong reduction in the number of prospective sites are the very low capacities found in scenarios 1- to 10-km. For example, the maximum potential reached in the 5-km scenario is 0.20 TWh, 0.63 TWh less than its theoretical potential. The relative reduction reaches its maximum at the 10-km scenario, where only 16% of the theoretical potential, i.e. 1.32 TWh passes the restrictions. The largest scenario show a significant reductions in absolute terms as it loses more than 25 TWh, although not so much in relative terms with 52% of theoretical passing the filters. Overall, the realisable potential is still significant at a 20-km distance.

Fig. 8 shows the total PHS realisable potential for the countries with the largest potential: Turkey, Albania, Spain, Switzerland, Norway, Italy and France. The figure does not show the results for scenarios 1- and 2-km as they have very small potential — as small potential exist for the 3- and 5-km scenarios. In total, these four scenarios make up only 0.303 TWh. The figure shows how the already small theoretical potential has shrank further because of the constraints applied.

Table 9 shows that almost negligible quantities of potential energy storage exist for Turkey and Albania below 20 km, and that the reductions from theoretical to realisable results are not linear. Turkey's 10-km realisable potential is less than 1% of the theoretical potential, whereas at 20-km it is 53% of its theoretical one. Excluding Turkey, the realisable potential of the other top-ten

Table 8
Number of potential sites found and stored energy associated.

Realisable potential						
Scenario	20 km	10 km	5 km	3 km	2 km	1 km
No. of sites	3229	538	99	32	8	1
Potential energy storage (TWh)	28.63	1.32	0.20	0.07	0.03	0.003

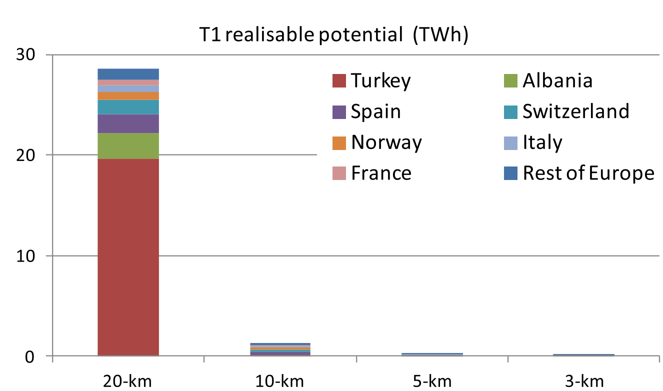

Fig. 8. Calculated realisable PHS potential for 10 and 20-km maximum distances between reservoirs.

Table 9
Realisable potential of the top-ten countries for four scenarios.

Scenario/country potential	20 km (TWh)	10 km (GWh)	5 km (GWh)	3 km (GWh)
Turkey	19.63	13	4	0
Albania	2.58	37	8	0
Spain	1.89	362	93	23
Switzerland	1.44	256	28	23
Norway	0.75	212	17	5
Italy	0.67	99	35	6
France	0.51	93	5	4
United Kingdom	0.50	106	4	0
Austria	0.28	102	4	3
Serbia	0.28	0	0	0

Table 10
Summary of potentials under the different scenarios.

	Potential storage (TWh) per scenario					
Potential	20 km	10 km	5 km	3 km	2 km	1 km
Theoretical	54.31	8.00	0.83	0.31	0.10	0.004
Realisable	28.63	1.32	0.20	0.07	0.03	0.003

countries is 53% of the theoretical at 20 km, 35% at 10 km, and 25% at 5 and 3 km.

A comparison with the theoretical potential for the 20-km scenario shows that the application of constraints eliminated the potential in Belgium, Greece, Hungary, Sweden and Romania, and greatly reduced it in Portugal, Germany, the Czech Republic, and Bulgaria. Other Member States kept at least 30% of their potential (Cyprus, France, Italy, Spain and the UK), whereas Austria and Finland kept 64% and 100% of their potential respectively, see Fig. 9. Outside the EU, most countries with significant theoretical potential (Norway, Switzerland, Albania and Turkey) kept a good part of it throughout the filtering process.

As it is the case for the theoretical potential, Spain, France, Italy and the United Kingdom provide the highest contributors to the total realisable potential in the EU, and Switzerland, Albania and specially Turkey, which has the higher potential, are the best contributors outside the EU. This is shown in Table 11 in Section 3.4. It has to be noted the issue of the lack of full reservoir data from Norway, see Section 2.2.

3.2. How these potentials compare to existing storage capacity

Possibly the most interesting question from a policy-making point of view is how this potential compares with the existing capacity.

There are no official figures reported to Eurostat for the existing pumped storage capacity in Europe, nor in the EU, but some figures have been compiled for a sample of countries [20]. A comparison for some of those (Spain, France, the UK, Austria, Switzerland, Greece, Bulgaria, Germany, Portugal, the Czech Republic, Poland, Belgium, Slovakia and Ireland) suggests that the theoretical potential is 3.5 times the existing capacity whereas the realisable potential is some twice as much the existing capacity.

In addition to those countries, the existing capacity of energy storage in PHS plant was reported for Norway by Harby [17], although using a different methodology. Pumping can be designed in different ways, and in Norway pumping is not used on a daily or weekly cycle but for seasonal pumping between very large

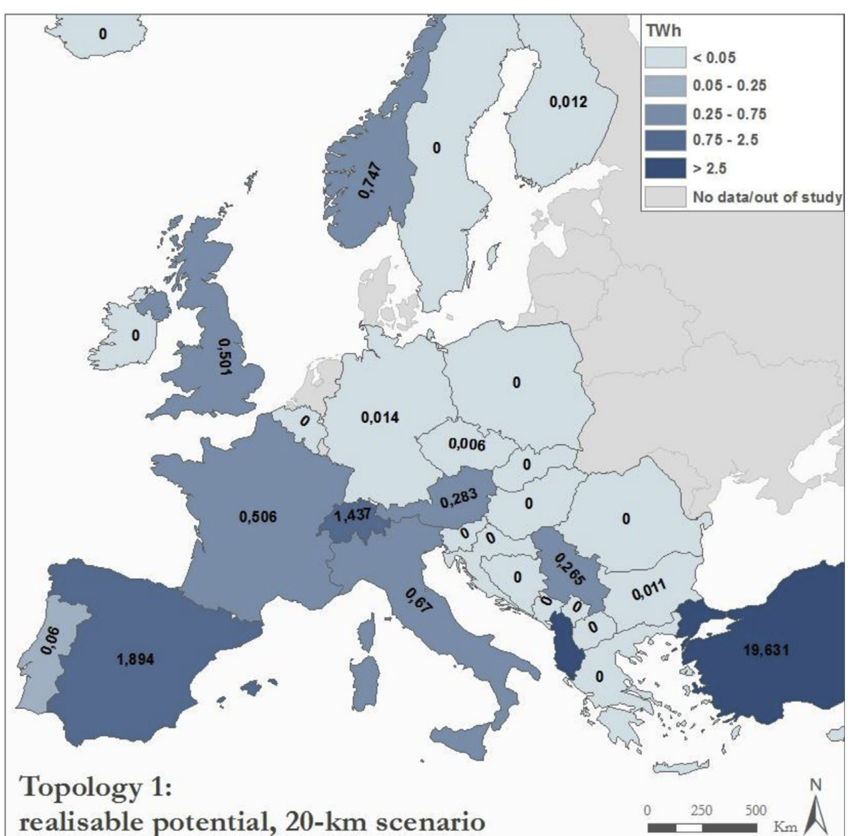

Fig. 9. Maximum realisable potential under topology 1 per country.

Table 11
Potential PHS energy storage capacity per country in GWh.

GWh	Theoretical potential						Realisable potential					
Country	20 km	10 km	5 km	3 km	2 km	1 km	20 km	10 km	5 km	3 km	2 km	1 km
AT	443	199	105	5.8	2.3	0	283	102	3.8	3.5	0	0
BE	12	5	5	5	2.5	0	0	0	0	0	0	0
BG	119	8.3	0	0	0	0	11	0	0	0	0	0
CY	31	8.2	0.1	0	0	0	9.1	0	0	0	0	0
CZ	39	12	5.3	4	3.8	0.2	6.4	2.5	0	0.4	0	0
FI	12	0	0	0	0	0	12	0	0	0	0	0
FR	1184	409	54	20	5.7	0	506	93	5.1	3.9	0	0
DE	89	19	0	0	0	0	14	4.8	0	0	0	0
GR	168	28	0	0	0	0	0	0	0	0	0	0
HU	3.5	0.5	0.2	0	0	0	0	0	0	0	0	0
IE	0	0	0	0	0	0	0	0	0	0	0	0
IT	1867	661	218	85	11	3	670	99	35	5.5	4.6	3
PL	0	0	0	0	0	0	0	0	0	0	0	0
PT	542	118	6.7	0	0	0	60	29	0	0	0	0
RO	44	3.2	0	0	0	0	0	0	0	0	0	0
SK	0	0	0	0	0	0	0	0	0	0	0	0
SI	0	0	0	0	0	0	0	0	0	0	0	0
ES	5788	1182	292	132	34	0	1894	362	93	23	12	0
SE	51	22	0	0	0	0	0.3	0	0	0	0	0
UK	994	199	23	3.6	1.8	0	501	106	4.3	0.4	0	0
EU	**11 387**	**2874**	**709**	**255**	**61**	**4**	**3967**	**798**	**141**	**36**	**16**	**3**
HR	2.5	0	0	0	0	0	0	0	0	0	0	0
EU + AC	**11 390**	**2874**	**709**	**255**	**61**	**4**	**3967**	**798**	**141**	**36**	**16**	**3**
NO	991	332	33	5.2	0	0	747	212	17	5.2	0	0
CH	1656	431	42	31	18	0	1437	256	28	23	10	0
EU + AC + FTA	**14 037**	**3637**	**784**	**291**	**79**	**4**	**6151**	**1266**	**186**	**65**	**27**	**3**
AL	3152	47	11	0	0	0	2580	37	8	0	0	0
BA	0.8	0	0	0	0	0	0	0	0	0	0	0
KV	0	0	0	0	0	0	0	0	0	0	0	0
EU + AC + FTA + PC	**17 189**	**3684**	**795**	**291**	**79**	**4**	**8731**	**1303**	**194**	**65**	**27**	**3**
IS	0	0	0	0	0	0	0	0	0	0	0	0
ME	0	0	0	0	0	0	0	0	0	0	0	0
MK	0	0	0	0	0	0	0	0	0	0	0	0
RS	327	1.3	0	0	0	0	265	0	0	0	0	0
TR	36 793	4319	36	24	24	0	19 631	13	4	0	0	0
EU + AC + FTA + PC + CC	**54 309**	**8004**	**831**	**315**	**103**	**4**	**28 627**	**1316**	**198**	**65**	**27**	**3**

reservoirs. Therefore the existing energy storage capacity in PHS plant in Norway, reported at 11 TWh, is not fully relevant for the assessment presented in this document. Moreover, in that country the pumping/generation capability is currently limited by the electricity capacity of the pumps and turbines installed and not by the reservoir size, since the reservoirs are very large and also connected to other conventional hydropower generators. As an example, a pumped-hydro station can pump water into lake Blåsjø ("Blue lake"), which has a reservoir capacity of 7000 GWh, and is used for storing water for several large hydro stations [17]. Of the countries reported by Eurelectric, Poland, Belgium, Luxemburg, Slovakia and Ireland have either minimum existing capacity or minimum potential. Fig. 10 compares, for the other countries in Eurelectric's report and Norway meaningful, to compare the existing capacity with the T1 potentials. However, this comparison has to be taken as illustrative only because the methodology for obtaining the existing capacity by Eurelectric [20] differs from the JRC GIS model's calculation of potential.

Considering only the sum of existing plus realisable potential, most of the potential is in five countries: Norway, Spain, Switzerland, France and the UK. These are followed by Sweden (no reported existing capacity), Austria, and Portugal.

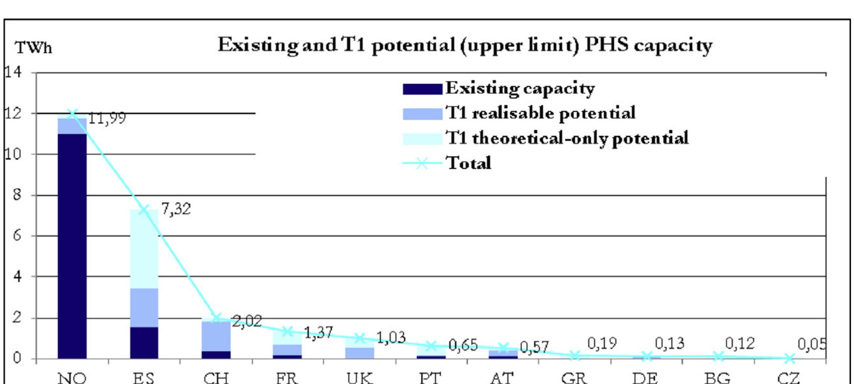

Fig. 10. Existing capacity (when available from Eurelectric [20]), T1 realisable and theoretical-only potential for selected EU and EFTA countries.

3.3. Summary of potentials

Table 10 allows a quick overview of potentials by showing both theoretical and realisable potentials under the six scenarios.

3.4. Results per country

The global figures for the EU do not convey the huge differences between countries. Table 11 shows a comprehensive list for the two potentials defined, theoretical and realisable.[13]

4. Conclusions and recommendations

4.1. Conclusions

This assessment, for the first time in scientific/technical literature, estimates the potential for pumped *storage capacity* in Europe under the assumptions of linking two existing reservoirs to form a new PHS system. This work does not attempt to assess the related potential *electricity installed capacity*, and in this respect it only makes a suggestion on a procedure to match both parameters.

The European theoretical potential is 54 TWh (11.4 TWh in the EU) when a maximum distance of 20 km between reservoirs is considered. This potential is drastically reduced for lower distances: 0.83 TWh for 5 km, of which 0.71 in the EU, and 4 GWh for 1 km, mostly in Italy. When restrictions on the use of land are applied the theoretical potential is reduced to a realisable potential of 29 TWh in Europe of which 4 TWh in the EU.

This study has taken due considerations of environmental as well as energy issues. This was one of the reasons why topology 1 was analysed: by using existing reservoirs there is no need to close a valley with a dam and thus cause a possible significant disruption to the ecology of the river.

In the choice between theoretical and realisable potentials, it was considered more realistic to take the theoretical potential as best representative. This is because the environmental impact of building a new penstock and powerhouse (the latter is nowadays built underground) can be very small. In addition, the "realisable potential" is based on a set of assumptions about what is somehow politically possible and what is not. The assumptions that building new reservoirs is not possible may for instance not always be the case. Adding new tunnels buried in protected areas may also be generally possible.

Overall it is believed that the order of magnitude of these potentials is correct for Europe as a whole and the EU in particular. Still, this does not preclude that the findings can be fine-tuned and the correction of data gaps in Norwegian reservoirs is an outstanding case. In another example, some discrepancies were detected in the reservoir data from ECRINS when compared with other sources. Similarly, the representation in the model of an existing reservoir as a point instead of as an area reduces the zone explored for connecting with a second existing reservoir.

This work and its related GIS model could prove useful to the agencies in charge of planning future electricity system development, to authorities in charge of spatial planning and to developers of hydropower schemes.

[13] Note the case of the Czech Republic as an example of the functioning of the model. Here, the analysis at 3 km shows a small potential which is non existing at 5 km, and the most likely cause is that the extension of the radius of search made the two former "hits" to touch upon a nature reserve area, and thus they are dropped.

4.2. Suggestions for future model development

As a result of the experience gained during this work, and fed with the opinion of external and internal reviewers, the following items are suggested for future improvements:

- To improve the database of reservoirs and to take into account a typology of lakes. One option could be to improve ECRINS, e.g. by adding Norwegian reservoirs, and then use its new dataset. Some validation is also possible through an updated GRanD database.
- To include existing reservoirs smaller than 100 000 m^3 which have hydropower exploitation above 1 MW.
- To extend to the lower reservoir the current assumption that the size of the upper reservoir is what limits the potential energy storage in a new prospective PHS.
- To include the inflow and outflow rates of other reservoir users or existing power plants to deduce them from the existing reservoir capacity so as to assign existing reservoirs a maximum water volume available for calculating the energy storage capacity of a prospective PHS.
- To include maximum and minimum water levels and water level change speeds and to use them to calculate the maximum installed power capacity at each prospective PHS.
- To compile DEM and reservoir data of areas across country borders and to define the cross-boundary potential.
- To carry out the assessment of other topologies.

In addition to the environmental protection constraints already taken into account, the maximum water level change rate in reservoirs is regarded as important criterion for environmental impact of PHS in some countries, due to its effect on erosion processes and habitat (e.g. fish stranding) [29]. An environmental filter could be added to reflect this criterion.

An environmental aspect that has an economic impact is the geology of the area having a potential for construction of the underground penstock. The difference in cost of constructing tunnels in granite or schist is considerable and in the Mediterranean basin earthquake risks can add up to additional construction constraints and therefore additional costs. Fortunately the available digital data describing these aspects on the subcontinent is considerably and can be taken into account in order to estimate with more precision the future cost of PHS investments.

This issue, costs, could be more developed. For example, it is claimed that for Norway the challenges are not the lack of storage volume but the total costs and the business model for developing pumped storage hydro, and in particular for increasing turbine capacity. In addition to the costs of building new reservoirs other aspects such as penstock sizing, could be incorporated to the GIS model or modelled after its output.

If electricity grid data on the capacity available at each substation can be sourced, the model could be improved to take this capacity into account, although one barrier is that those data might not be public.

It was suggested as well that analyses that would further enrich knowledge include country potential storage versus (a) population density; (b) country surface; (c) solar and wind resources (d) projections of electricity consumption and RES generation by, e.g., 2030. The country potentials could also be compared with country annual rainfall distribution. Furthermore, the main islands not connected to the continent could be analysed separately.

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The European maps in this paper were generated using border data from Natural Earth [27].

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Abbreviations and acronyms

Throughout this paper 2-letter country codes are used as for the International Organisation for Standardization: http://www.iso.org/iso/country_names_and_code_elements. Other abbreviations and acronyms are:

CAES: compressed air energy storage
CC: candidate countries to the European Union
CCM: catchment characterisation and modelling
CLC: CORINE land cover
CORINE: coordination of information on the environment
DAMPOS: DAM POSitioning – Eionet
DECC: Department of Energy & Climate Change, United Kingdom
DEM: digital elevation model
DSR: demand side response
ECRINS: European Catchments and RIvers Network System
EEA: European Environment Agency
EFTA: European Free Trade Association
EIONET: European Environment Information and Observation Network
ESRI: Environmental Systems Research Institute
EU: European Union
GIS: geographic information system
GRanD: Global Reservoir and Dam
JRC: Joint Research Centre, a directorate general of the European Commission
GW: Gigawatt (=1 000 000 000 W)
GWh: gigawatt hour
MS: member state
MW: megawatt
NASA: United States National Aeronautics and Space Administration
NVE: Norwegian Directorate for Water and Energy
PHS: pumped hydropower storage
RE: renewable energy
RES: renewable energy sources
RSIS: Ramsar Sites Information Service: http://www.ramsar.wetlands.org
SAC: special areas of conservation
SPA: special protection areas
SRTM: Shuttle Radar Topography Mission
TWh: terawatts hour
UCC: University College Cork, in Ireland
UNESCO: United Nations Educational, Scientific and Cultural Organization