European Commission

JRC SCIENTIFIC AND POLICY REPORTS

Assessment of the European potential for pumped hydropower energy storage

A GIS-based assessment of pumped hydropower storage potential

Marcos Gimeno-Gutiérrez
Roberto Lacal-Arántegui

2013

Joint Research Centre

Report EUR 25940 EN

European Commission
Joint Research Centre
Institute for Energy and Transport

Contact information
Roberto Lacal Arántegui
Address: Joint Research Centre, Institute for Energy and Transport. Westerduinweg 3, NL-1755 LE Petten, The Netherlands
E-mail: roberto.lacal-arantegui@ec.europa.eu
Tel.: +31 224 56 53 90
Fax: +31 224 56 56 16

http://iet.jrc.ec.europa.eu
http://www.jrc.ec.europa.eu

This publication is a Scientific and Policy Report by the Joint Research Centre of the European Commission.

JRC81226
EUR 25940 EN

ISBN 978-92-79-29511-9 (pdf)
ISBN 978-92-79-29512-6 (print)

ISSN 1831-9424 (online)
ISSN 1018-5593 (print)

doi:10.2790/86815

Luxembourg: Publications Office of the European Union, 2013

Printed in the Netherlands

Table of content

Acknowledgements

The authors would like to acknowledge the contribution of the 'Sherpas' of the European Strategic Energy Technology Plan (SET-Plan) Steering Group.

We would also like to express their high appreciation to the internal and external experts who reviewed the draft report and contributed with comments and ideas for the improvement of this report. They are: Mr Emmanuel Branche and Mr Gregory Fayet from Electricité de France; Mr Alejandro Perea Sánchez, Iberdrola Generación; Dr Atle Harby and Dr Peggy Zinke from SINTEF Energy Research; Mr Erland Eggen from the Research Council of Norway, Dr Paul Leahy from University College Cork, Dr Stefan P. Schmid from Hydroprojekt. Internal reviewers include the members of the Joint Research Centre Dr Alfred de Jager, Dr Efstathios Peteves, Dr Evangelos Tzimas, Dr Arnulf Jæguer-Waldau and Dr Katarin Bodis.

Last but not least we would like to acknowledge the help of the European Environmental Agency, represented in Mr Óscar Gómez Prieto and Dr Philippe Crouzet, which provided us with their database of dams and reservoirs, without which this work would not have been possible.

The European maps in this report were generated using border data from Natural Earth [Naturalearthdata, 2013]

ABSTRACT

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

Electricity systems need to be flexible in order to guarantee at every moment the equilibrium between generation and consumption. To achieve a high penetration of wind and solar energy, one way to introduce this flexibility is through pumped hydropower storage (PHS), currently representing almost 99 % of current worldwide electricity storage capacity. PHS behaves as load when pumping and as generation when it supplies electricity to the system, and can change between both in minutes. There exists no published scientific work, until now, has assessed what the potential for PHS could be in Europe.

This report presents the results of the assessment for PHS in Europe under certain topologies and scenarios. Earlier work by the JRC[2] defined the methodology used in this study which focuses on two topologies: (T1) when two reservoirs exist already with the adequate difference in elevation and which are close enough so that they can be linked by a new penstock and electrical equipment, and (T2) based on one existing reservoir, when there is a suitable site close enough as to build a second reservoir. The scenarios modelled consist of different maximum distances possible between the two reservoirs of a prospective PHS and, in one occasion, of a different minimum head for a similar maximum distance. The former are 1, 2, 3, 5, 10 and 20 km and the latter is 50 metres instead of the standard minimum of 150-metre head.

The results show that the theoretical potential in Europe is significant under both topologies, and that the potential of topology 2 is roughly double that of topology 1. Under T1 the theoretical potential energy stored reaches 54 TWh when a maximum of 20 km between existing reservoirs is considered; of this potential approximately 11 TWh correspond to the EU and 37 TWh to candidate countries, mostly Turkey. When a shorter maximum distance between existing reservoirs is considered, e.g. 5 km, the majority of the 0.83 TWh European theoretical potential is in the EU (85%).

Under T2 the European theoretical potential reaches 123 TWh when the distance between the existing reservoir and the prospective site is up to 20 km. Unlike topology 1, in topology 2 the majority of this potential (50%) lies within the EU. For a distance between reservoirs of 5 km a theoretical potential of 15 TWh -of which 7.4 TWh within the EU- was found.

The theoretical potential is reduced to a realisable potential through the application of constraints such as discounting potential sites close to a centre of population, protected natural areas or transport infrastructure. Under those conditions, the realisable potential for topology 1 and the 20 km distance is halved to 29 TWh, and for the 5 km scenario it is reduced to 0.2 TWh. Topology 2, by contrast, and probably owing to a larger amount of prospective sites available, is less affected by the application of constraints. Under the 20-km scenario the realisable potential in Europe reaches 80 TWh of which 33 TWh in the EU. Under the 5-km scenario those potentials reach 10 TWh for Europe of which 40% in the EU.

[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.

[2] *Pumped-hydro energy storage: potential for transformation from single dams* [JRC, 2011]

A comparison with the existing PHS reported in 14 countries suggests that the T1 theoretical potential is ***3.5 times the existing capacity*** whereas the T2 realisable potential is ***10 times as much the existing capacity***.

Further work should aim at facilitating the actual implementation of the potential by, for example, providing stakeholders with more accurate data on the potential sites identified, introducing the potential in grid-development computer models, adding economic parameters, and enabling policy-makers (in particular spatial planning authorities), project developers and engineering companies with the knowledge of the potential sites.

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 produced 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 that mismatch, which were originally developed as a response to the fluctuations in demand and to protect against the loss of generation power plant. These alternatives are: interconnections between electricity systems; energy storage; smart networks; and demand-side response (DSR) [DECC, 2012]. Utility-level energy storage for electricity systems include mostly the storage effect of reservoir-based conventional hydropower schemes, and pumped hydropower storage. 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 [EC, 2007]. 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 made of non-dispatchable renewables such as wind and solar. Moreover, the EU's 2050 decarbonisation objectives, with a target of 80 - 95 % reduction in greenhouse gas emissions [European Council, 2009], will require even higher share of renewables in the electricity mix.

In its recent Communication *Renewable Energy: a major player in the European energy market* [EC, 2012], 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 this 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[3] 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" [Council, 2012].

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 [Auer and Keil, 2012].

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 [Eurostat, 2013].

Table 1 shows EU electricity data. Total gross production reaches around 3 280 TWh, non-PHS hydropower contributes 10 % of the total annual consumption, and a further 1% is contributed by PHS plants from water previously pumped.

Electricity	Hydropower without PHS	Wind	Solar	PHS production	PHS demand	Total gross production	Final consumption
TOTAL (TWh)	335	179	46	29	38	3 280	2 768
% Energy produced over gross production	10.2	5.5	1.4	0.9	1.15	100	84

Table 1: electricity generated in 2011 from some renewable energies in the EU. Source: Eurostat table nrg_105a.

[3] RES - renewable energy sources

Conventional hydropower is one of the means of using stored energy. When not based on an existing lake, it is based on creating a reservoir 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 by-products 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 [Dameffects, 2013; WCD, 2000]. 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.

An alternative or complement to conventional hydropower is pumped hydropower storage (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 supports the integration of electricity from non-flexible power plant (such as nuclear and baseload coal plant), and, lately, of variable renewable energies.

When analysing the potential for new PHS, several topologies are possible.

Topology	Assessment based on:
1	Linking two existing reservoirs with one or several penstock(s), and adding a powerhouse to transform them to a PHS scheme
2	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[4]
3	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
4	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[5]
5	Multi-reservoir systems including both PHS and conventional hydropower
6	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[6]
7	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[7]

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 [JRC, 2012].

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 [Eurostat, 2013]. In terms of electricity generation and consumption, in total in Europe, Platts [2012] gives the figures of 40 TWh generated per year consuming 54 TWh in pumping, these from 232

[4] In this study we do not consider valleys due to the environmental issues.
[5] 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/?
[6] See the web of Verbund where a clear scheme shows this topology: http://www.verbund.com/pp/en/pumped-storage-power-plant/riedl
[7] For more information see http://www.lagodeaspontes.com/

operational PHS plants. The corresponding Eurostat figures for the EU in 2011 are 29 TWh generated from 38 TWh pumped.

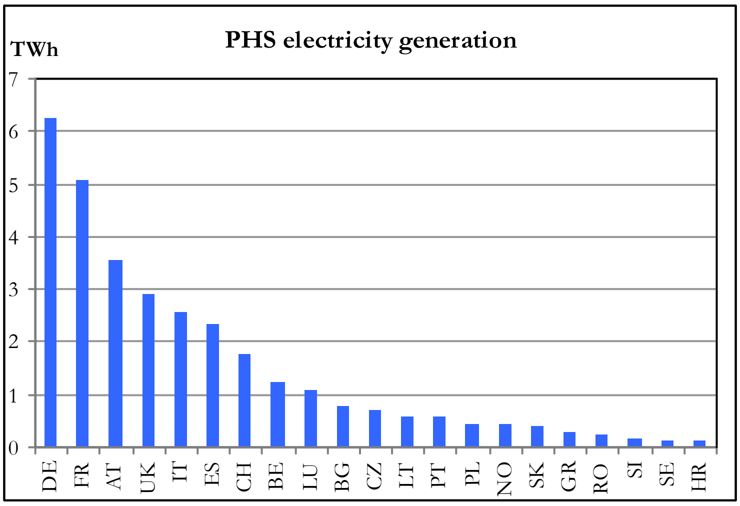


Figure 1: electricity generated in Europe from PHS during 2011. Croatia, Norway and Switzerland data from 2010. Source: Eurostat [2013].

The objective of this work is to assess the potential for energy storage in pumped hydropower schemes in Europe. For this, the methodology defined by a team of the Joint Research Centre (JRC) and University College Cork (UCC) staff [Fitzgerald et al., 2012; JRC, 2011] was applied, after its validation in a workshop of international experts [JRC, 2012].

The chosen approach of assessing the potential only under topologies 1 and 2 (see Table 2) introduces some limitations. For example, the geographic information system (GIS) model to assess the potential for topology 2 seeks (mostly) flat areas[8] to host the second reservoir, but the large majority of existing PHS schemes was not built by using a flat area but by closing a valley with a dam. Correspondingly, only some existing PHS schemes would be captured by this methodology, and this complicates the use of existing PHS schemes to validate the model. Another, more important, limitation is that by not considering closing a valley 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, closing a valley with a dam.

Through this innovative study, the purpose to assess the PHS potential in Europe has been reached for the first time, and this was made possible by developing and applying a GIS-based 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[9]. The final section 4 concludes and provides with some recommendations for further work in the area. The report also includes as annexes individual country files with the detailed results per country.

[8] It is possibly more correct to define it as "non-sloping" area The definition of such a flat area, how the energy storage is calculated and other methodological definitions are included in [JRC, 2011]

[9] 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.

2. METHODOLOGY APPLICATION

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 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 model, e.g. minimum distance to inhabited areas. Figure 2 shows the methodological flowchart.

For both T1 and T2 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 [Fitzgerald et al., 2012; JRC, 2012].

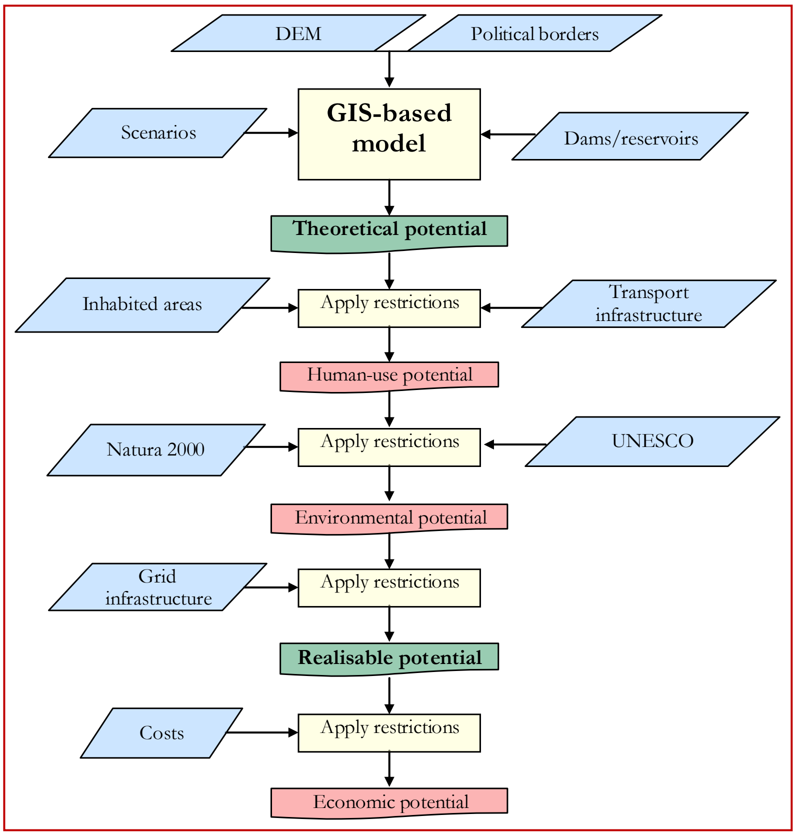


Figure 2: methodological flowchart with the inclusion of intermediate potentials

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 degrees. 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, 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. Figure 2 shows the methodology flowchart including all the stages at which a measure of potential could in theory be obtained: theoretical, human-use, environmental, realisable (or grid-connected), and economic potential. The two energy storage potentials described in this modelling exercise are the theoretical and realisable ones.

Theoretical potential: is the result of feeding the GIS model with topographical information, the database of reservoirs with a minimum capacity of 100 000 m³ of water or which have

hydroelectricity production rated 1 MW or more[10], and scenarios for the parameters head and maximum distance between reservoirs. Several scenarios were evaluated and the corresponding energy storage potentials were estimated for each topology, six for T1 and seven for T2.

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 model search. Also within this potential a maximum distance to the nearest electricity grid was set up. Table 3 shows the lists of proposed constraints applied.

Description	Topology 1	Topology 2
Maximum distance between two existing (T1) or existing and prospective (T2) reservoirs	1, 2, 3, 5, 10 & 20 km	1, 2, 3, 5, 10 & 20 km
Minimum head	150 m	50 m and 150 m
Assumed minimum new reservoir capacity	100 000 m^3	100 000 m^3
Minimum distance to inhabited sites	500 m	500 m
Minimum distance to existing transportation infrastructure	200 m	200 m
Minimum distance to UNESCO site	500 m	500 m
Maximum distance to electricity transmission network	20 km	20 km
Minimum distance to a Natura 2000 conservation area	should not be within	should not be within

Table 3: constraints and values applied in T1 and T2.

It would be possible to calculate other potentials, but the current model does not present intermediary results. For example, it would make sense to calculate a "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, of the second dam, etc., could be taken into account (but are currently not) so that the model would provide an economic potential.

Prospective second-reservoir sites under T2 are defined as flat or non-sloping areas (slope lower than 5%) in the vicinity (according to the maximum distance of each scenario) of an existing reservoir, that have a minimum surface of 7 000 m^2 where it is assumed that the new reservoir could reach 20 m deep and a part of the 7 000 m^2 will cover the rims and ancillary areas, leaving a minimum of 5 000 m^2 x 20 m (100 000 m^3) of useful storage. For T2 when more than one suitable site is found, the prospective site offering the largest energy storage potential is selected. The two main parameters considered for energy storage assessment are head and water storage capacity.

Following the recommendations of the Expert workshop on the assessment of the potential of pumped hydropower storage [JRC, 2012], 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, the original analysis [JRC, 2011] was dropped for a maximum distance of 4 km between reservoirs, and further analyses were introduced for a distance of 5 km with 50-m minimum head, for 10 km and for 20 km.

[10] As explained in section 2.2.2, the second group were not considered during the execution of this analysis.

2.2. Data and software limitations

2.2.1. Political borders

With the purpose of extracting the information needed for a country-based assessment, political borders were downloaded from the DIVA-GIS website, where country-level, free spatial data are provided. This is considered to be a reliable, accurate and ready-to-use source [JRC, 2011].

The list of countries for which PHS potential was analysed comprises most of the European countries as listed in Table 4.

Countries included in the analysis[2]						
EU Member States (EU)						
Austria (AT)	Belgium (BE)	Bulgaria (BG)	Cyprus (CY)	Sweden (SE)	Czech Republic (CZ)	Spain (ES)
France (FR)	Ireland (IE)	Romania (RO)	Poland (PL)	Germany (DE)	Hungary (HU)	Italy (IT)
Portugal (PT)	Greece (GR)	Slovakia (SK)	Slovenia (SI)	Finland (FI)	United Kingdom (UK)	
Acceding country (AC)						
Croatia (HR)						
EFTA Members						
Norway (NO)	Switzerland (CH)	(Iceland was included as part of the candidate countries group)				
Candidate countries (CC)						
Iceland (IS)	Serbia (RS)	Turkey (TR)	FYROM (MK)	Montenegro (ME)		
Potential candidates (PC)						
Albania (AL)	Bosnia and Herzegovina (BA)	Kosovo* (XK)				

Table 4: list of countries assessed for PHS potential. Source: http://europa.eu/about-eu/countries/index_en.htm
*(Kosovo does not have official ISO code).

Several EU Member States have not been analysed because of different reasons. In some cases no reservoir data were available e.g. Estonia, Latvia, Lithuania, Luxemburg and Malta; or by physical limitations in some cases, as it occurs with very flat countries, e.g. the Netherlands and Denmark. Candidate countries (CC), Iceland, Montenegro, Serbia, the Former Yugoslav Republic of Macedonia and Turkey were also analysed, along with the potential candidates (PC) Albania, Bosnia and Herzegovina and Kosovo. Three of countries in the European Free Trade Association (EFTA)[11], Norway, and Switzerland were analysed, Iceland was analysed and included in the CC country group and Liechtenstein was not analysed.

2.2.2. Dams and reservoirs data

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. The model searches for potential new sites referred to a single point, and with existing reservoirs sized from several thousand square meters 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 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. Figure 3 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 assumes 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.

[2] European Free Trade Association members can be found on: http://www.efta.int/

The option of using lakes was discarded because of the difficulty to obtain data (e.g. centre of lake geographical coordinates) and because lakes generally involve less human disruption to the river ecosystem than reservoirs[12]. The re-inclusion of the reservoirs which were discarded because of their small size (< 100 000 m^3) but 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 [EEA, 2012]. 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) [Vogt et al., 2007] and was then refined, corrected and completed with data from other sources: see the Annex to JRC [2012] for a more detailed explanation of ECRINS and CCM.

Figure 3: existing PHS system La Muela, and prospective site calculated by JRC GIS-model (Valencia, Spain).

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 [EIONET, 2012].

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 model.

ECRINS is not a complete database, 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 [Harby, 2013], which have to be compared with the 129 ECRINS reservoirs usable for this study.

[12] 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.

2.2.3. Digital elevation model (DEM)

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 60ºN, easy access by download in 5º by 5º blocks, broad acceptance in the scientific community and among the industry. The scope of this study permits the consideration of 90-meters 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, Figure 4 illustrates this case. A tool in ArcGIS was created to automate the process.

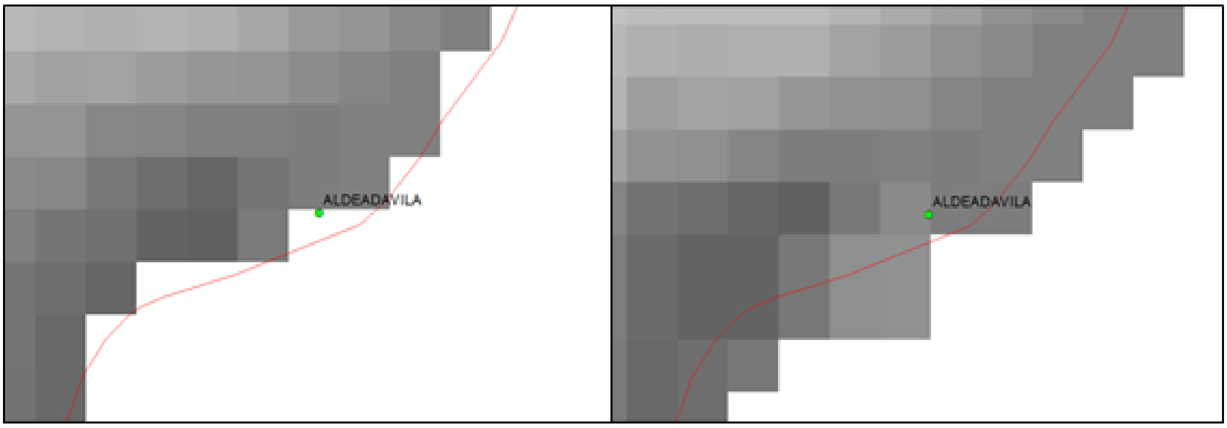


Figure 4: the left figure shows a case of "no data", affecting the Aldeadavila dam in Portugal, as result of the extraction of elevation; the right figure shows the expansion of DEM beyond the borders avoiding "no data" output when extracting elevation data.

During the search of a suitable DEM for the Nordic countries ASTER GDEM[13] 30-meter 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[14] which provides coverage up to 84º N. However, such resolution does not allow the same accuracy of analysis in Nordic countries as for the rest of Europe.

2.2.4. Inhabited sites, rivers, lakes and transport infrastructure.

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 meters 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.

[13] http://asterweb.jpl.nasa.gov/gdem.asp
[14] The description of this DEM can be found at http://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf

2.2.5. Environmental protection: Natura 2000

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[15].

2.2.6. UNESCO World Heritage sites

Cultural aspects were also taken into consideration and are part, with Natura 2000, of the named "Environmental potential" [16]. 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 [17]. 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.

2.2.7. Grid infrastructure

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 [2006], 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 model.

2.3. Other limitations of the model

In the search for topology 1 potential 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 model 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 model then eliminates the potential PHS. Although this should not be the case -the connection needed between two existing reservoirs under topology 1 is merely the space of the penstock, and this can be underground thus having no impact on the protected area- 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.

[15] http://www.ramsar.wetlands.org
[16] Environmental potential is not an output in this study but it could eventually be obtained by modifying the model
[17] http://whc.unesco.org/en/list

The inflow and outflow rates of other reservoir users, e.g. drinking water or irrigation, or existing power plants were not included into the model 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[18]), 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

2.4.1. Modified assumptions

Since the methodology was created [JRC, 2011] several changes have been adopted following the recommendations of the experts workshop [JRC, 2012]. Some of the original assumptions were maintained, namely the minimum distance to inhabited sites (500m) and to existing transport infrastructure (200m), and the condition that prospective sites should not be within a Natura 2000 area, whereas others were fine-tuned. Table 5 shows the most significant changes applied.

Description	Original T1	Current T1	Original T2	Current T2
Maximum distance between two existing or one existing and any prospective reservoirs	1, 2, 3, 4, 5-km	1, 2, 3, 5, 10, 20-km	1, 2, 3, 4, 5-km	1, 2, 3, 5, 10, 20-km
Minimum head	150 m	150 m	150 m	150m generally, 50m added at 5km
Assumed minimum new reservoir capacity	1 000 000 m^3	100 000 m^3	1 000 000 m^3	100 000 m^3
Minimum distance to UNESCO site	5 km	500 m	5 km	500 m
Maximum distance to electricity transmission network	50 km	20 km	50 km	20 km

Table 5: changes made to the assumptions in the initial methodology definition.

One of the most significant changes was to reduce minimum capacity of the existing reservoirs 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.

[18] 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

2.4.2. Other methodological remarks

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 for an additional purpose as pumped hydropower energy storage would not be allowed for [Schmid, 2013]; 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 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.

2.5.1. Maximum energy storage capacity

The results obtained after running the model reflect the maximum potential capacity which can be stored in the upper reservoir for both topologies 1 and 2. By assumption, the energy storage capacity in the model is limited by the water storage capacity of the upper reservoir proposed, which was assumed to always have less or equal capacity than the lower reservoir. The reasoning behind was that the existing reservoir is likely to lie in a river and thus it was contributing flow and more flexibility for releasing or accumulating water.

However, this assumption does not necessarily hold in all cases and thus Eurelectric [2011] in its assessment of existing capacity sets 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.

2.5.1. Calculated storage capacity versus existing PHS facilities

We explored how the energy storage calculated by the model compares to data from external sources. Table 6 contains a selection of individual PHS facilities for which reliable data could be obtained, along with JRC data. 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 from the JRC model or its sources. Head was mostly from an external source but when absent it was calculated by the JRC 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 JRC 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.

Figure 5 plots the results from external sources of data and calculated figures. The strength of the relationship between external sources and data from the JRC model turns out to be highly consistent: 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.

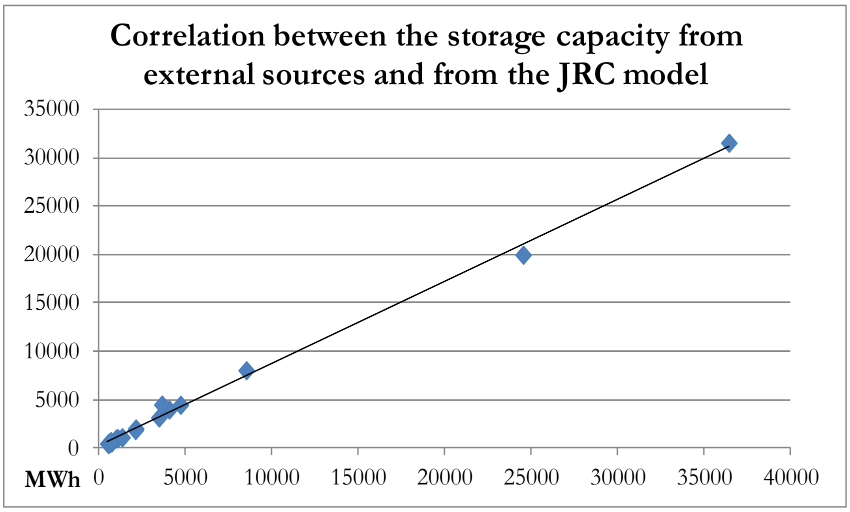


Figure 5: correlation on PHS storage capacity data from external sources and from the JRC model.

Country	PHS	Capacity upper reservoir m³	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	1 032	1 030	5	6
DE	Geesthacht	3 600 000	80	120	600	640	5	2
DE	Glems	900 000	283	90	560	566	6	2, 7
DE	Goldisthal	12 000 000	302	1 060	8 480	8 050	8	2
DE	Hohenwarte I	3 280 000	56	63	504	408	7	2
DE	Hohenwarte II	3 002 000	304	320	2 087	2 027	6	2
DE	Koepchenwerk	1 533 000	155	153	590	529	3	2, 7
DE	Langenprozelten	1 500 000	297	168	950	990	6	7, 2
DE	Makersbach	6 300 000	285	1 050	4 018	3 989	4	2
DE	Niederwartha	1 981 000	143	120	591	629	5	2, 7
DE	Rönkhausen	1 000 000	265	140	690	590	4	7
DE	Säckingen	2 100 000	400	353	2 064	1 866	5	2
DE	Waldeck I	700 000	296	140	487	461	3	7
DE	Waldeck II	4 400 000	324	440	3 428	3 167	7	2
DE	Waldshut	1 350 000	160	176	476	480	3	7
DE	Wendefurth	1 970 000	126	80	523	551	7	2
DE	Witznau	1 300 000	250	220	642	722	3	7
ES	Guillena	2 330 000	217	210	1 300	1 123	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	3 600	4 503	6	4
LU	Vianden M11	7 200 000	280	1 100	4 675	4 478	4	5

Table 6: comparison between external and JRC storage data. Sources: (1) Wänn [2012], (2) DENA [2008], (3) Martínez Campillo [2010], (4) EdF [2011], (5) Andritz Hydro [2010] (7) ZfES [2012]. *DENA [2008] does not contain head information, ZfES [2012] does. **Storage hours calculated from storage capacity and installed electrical capacity.

2.5.2. Energy storage capacity versus installed electrical capacity

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 6. When the two largest PHS are removed from the dataset, the relationship of installed electrical capacity to energy storage capacity, as shown in Figure 6, 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, there is a consistent relationship between both parameters but that this relationship does not stand for larger PHS systems.

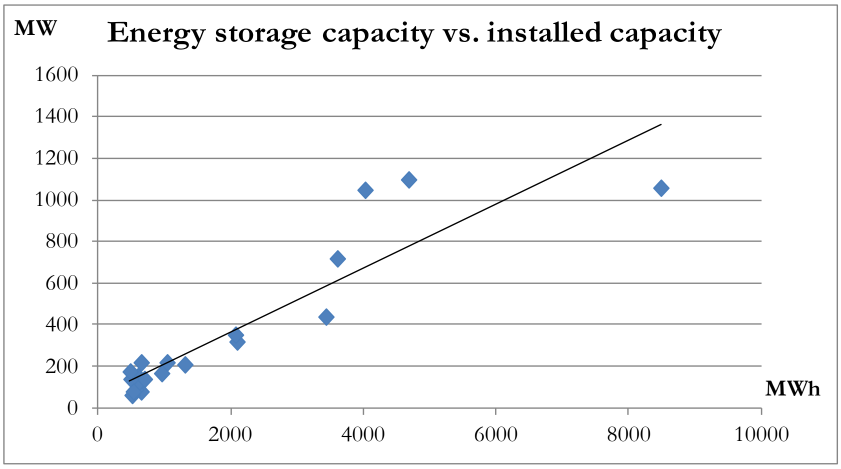


Figure 6: comparison of energy storage capacity from the external sources with installed electrical capacity for PHS with less than 10 GWh storage capacity.

One can choose to use large reservoirs and storage volumes and install low capacity, which will lead to slow changes in water levels (and a kind of environmental impact) in the lower and upper reservoirs. On the other hand, one can use relatively small reservoirs like most existing EU PHS 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 [Harby, 2013]

2.5.3. T2 results vs. T1 results and existing schemes.

T1 potential may have captured some of the existing PHS in what could be overlaps with existing capacity or else extensions to them, this was not validated. T2, by contrast, is likely to be mostly new capacity.

The merging of T1 and T2 results was not carried out. For existing reservoirs presenting results under both topologies, this could be done through subtracting the capacity needed for the T1 result from the reservoirs capacity usable for T2 assessment. The resulting T2 potential would be lower and, somehow, T1 potential would be a subset of T2.

3. RESULTS: THE EUROPEAN PHS POTENTIAL[19]

3.1. Potential under topology 1

The overall European theoretical potential under topology 1 and 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.

3.1.1. T1 theoretical potential

Table 7 shows the theoretical potential for new energy storage capacity under topology 1. 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 is 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.

T1 theoretical potential						
Scenario	**20 km**	**10 km**	**5 km**	**3 km**	**2 km**	**1 km**
No. of sites	8 268	1 779	387	141	52	5
Potential energy storage (TWh)	54.31	8.00	0.83	0.31	0.10	0.004

Table 7: number of potential sites found and stored energy associated.

Figure 7 shows large differences between scenarios, especially from 5 km upwards. For example, increasing the distance from 5 to 10 km results in an increase in the number of prospective sites from 387 to 1 779, and a further increase in distance to 20 km results in 8 268 potential sites.

The variations in the potential energy storage capacity are consistent with the increases seen on the total amount of sites in the different scenarios (Figure 7). 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.

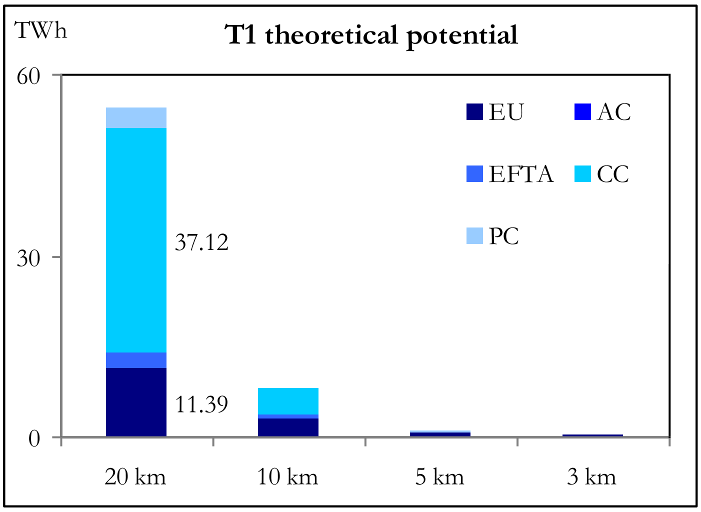


Figure 7: calculated theoretical PHS potential for different maximum distances between reservoirs for topology 1.

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 (see section 3.1.2) when compared with the existing capacity reported by Eurelectric [2011] of 2.5 TWh in 16 European countries (see section 3.2.3 for details).

[19] Except for EE, LV, LT, LU and MT. See section 2.2.1

Figure 7 shows the absolute contribution of the groups of countries analysed to the total potential. The figure does not show the results for the 1- and 2-km scenarios, which have very small potential: in total, these two scenarios make up only 0.104 TWh.

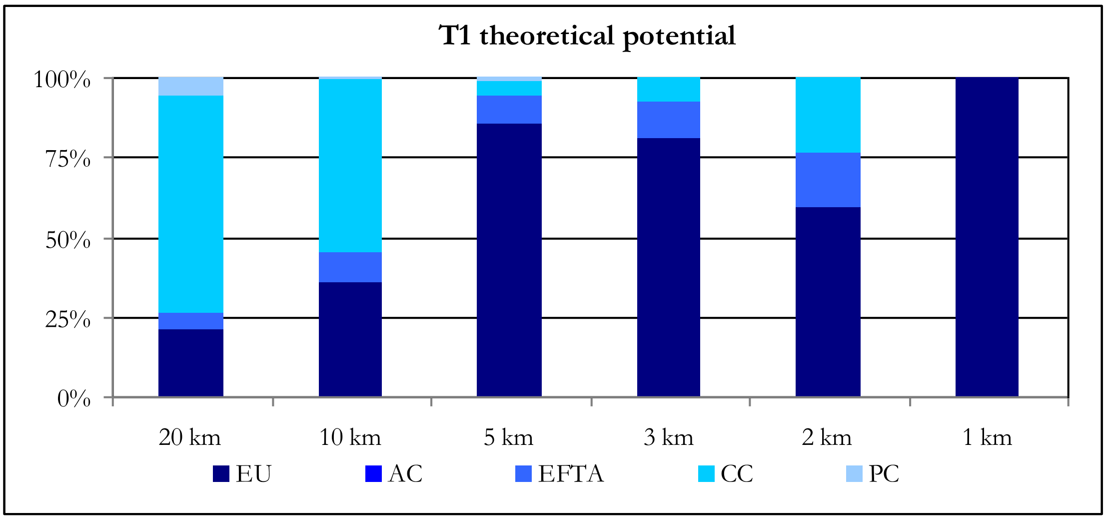


Figure 8: contribution to topology 1 theoretical potential energy per country group.

Countries analysed were grouped into EU Member States, members of the European Free Trade Association (EFTA) acceding candidates (AC), candidate countries (CC) and potential candidates (PC), Table 4 shows the exact grouping of countries.

As shown in Figure 8, whereas for short distances between dams it is in the EU Member States that most of the T1 potential exists, for longer distances it is in the candidate countries –and mostly Turkey- that offer the largest theoretical potential. This change of trend is the clearest

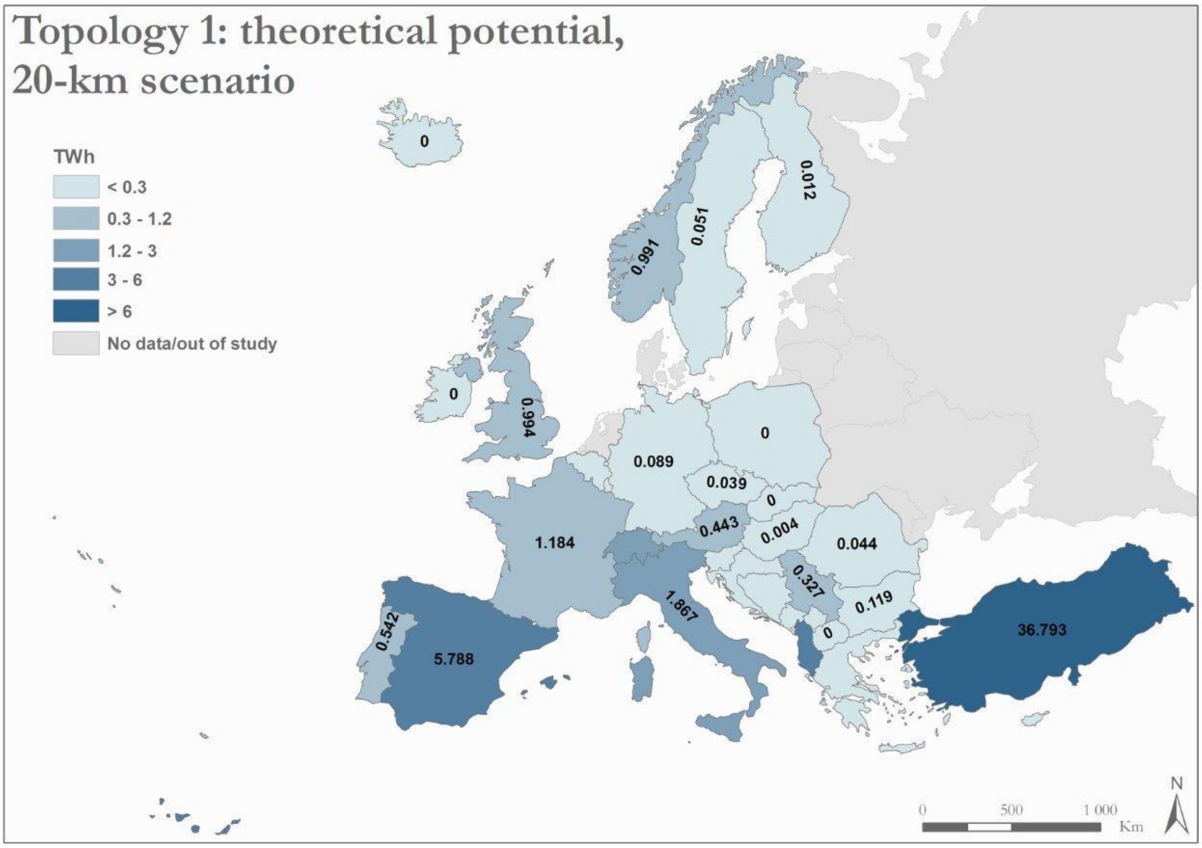


Figure 9: T1 theoretical potential per country

between 5 and 10 km: whereas at 5 km 85% of the potential is in the EU and only 4% in candidate countries, at 10 km 54% of the potential (4.32 TWh) is in candidate countries 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 in second position with less than 25% (11.4 TWh), then potential candidates, (3.1 TWh) and countries from EFTA (2.65 TWh).

Figure 9 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 2.2.2), and the large distance between reservoirs in that country. After Turkey, Spain, Italy, United Kingdom, France, Switzerland, and Albania are the next countries with high T1 theoretical potential, details are given in Table 13 in section 3.4 below.

As for the other scenarios, Figure 8 shows that in the 1-km scenario only the EU country group is contributing. The EU also contributes most to the 2-km scenario with more than 50%; candidate countries, having more than 25% of the total amount; and EFTA members follow.

3.1.2. T1 realisable potential

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: to around 3 200 sites in the 20-km scenario, 538 in the 5-km one, and 99, 32, 8 and 1 sites in the 5-km, 3-km, 2-km and 1-km scenarios respectively.

T1 realisable potential						
Scenario	**20 km**	**10 km**	**5 km**	**3 km**	**2 km**	**1 km**
No. of sites	3 229	538	99	32	8	1
Potential energy storage (TWh)	28.63	1.32	0.20	0.07	0.03	0.003

Table 8: number of potential sites found and stored energy associated.

Linked with the number of prospective sites are the very low capacities found in scenarios 1- to 5-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 two largest scenarios show significant reductions in the potential energy stored as well, with the 20-km scenario losing more than 25 TWh. On the other hand, the realisable potential is still significant at that large distance.

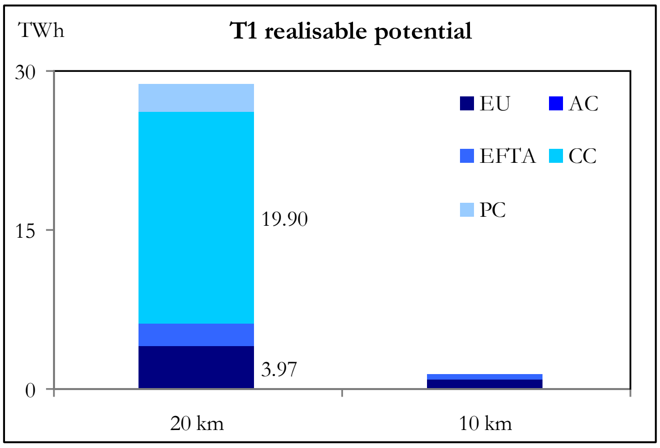


Figure 10: calculated realisable PHS potential for 10 and 20-km maximum distances between reservoirs for topology 1

Figure 10 shows the total PHS realisable potential per group of countries. The figure does not show the results for scenarios 1 to 5 km as they have very small potential. 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. Almost negligible quantities of potential energy storage exist below 10 km.

The reductions from theoretical to realisable results are not linear. Whereas in general the reduction is around 25-30 %,

the situation changes at larger distances, from 10 km and further. Only 17 % of the theoretical potential becomes realisable in the 10-km scenario, but this ratio rises to 53 % for the 20-km scenario. In the latter case the potential for candidate countries is the largest as a consequence of the pre-eminence of Turkish potential.

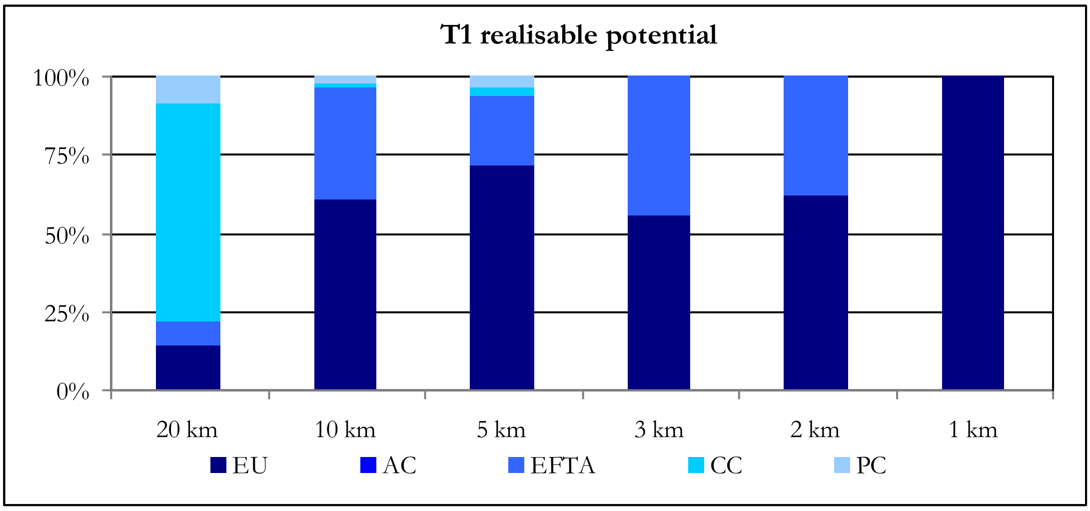


Figure 11: contribution to topology 1 total realisable potential energy per group of countries.

Figure 11 shows that the 1-km scenario only found a minimal potential in EU countries, whereas the 2- and 3-km scenarios show a similar share between EU and EFTA countries but no potential in candidate countries. The 5-km scenario, with 200 GWh of storage capacity (see Table 10), shows some potential in candidate and potential candidate countries but still the large majority of potential lays in the EU (around 70%) and EFTA members (23%). The 10- and 20-km scenarios show very different composition. In the first case, the EU has more than half the potential storage capacity and nearly all the rest is contributed by EFTA countries. The 20-km scenario, however, shows that candidate countries contribute the most to the potential storage capacity with almost 75 % of the total, and it is Turkey that provides most of that potential, see the detail in the Annexes. The EU, with a 15% of total, and EFTA countries make up the rest.

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. However, 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. Outside the EU, most

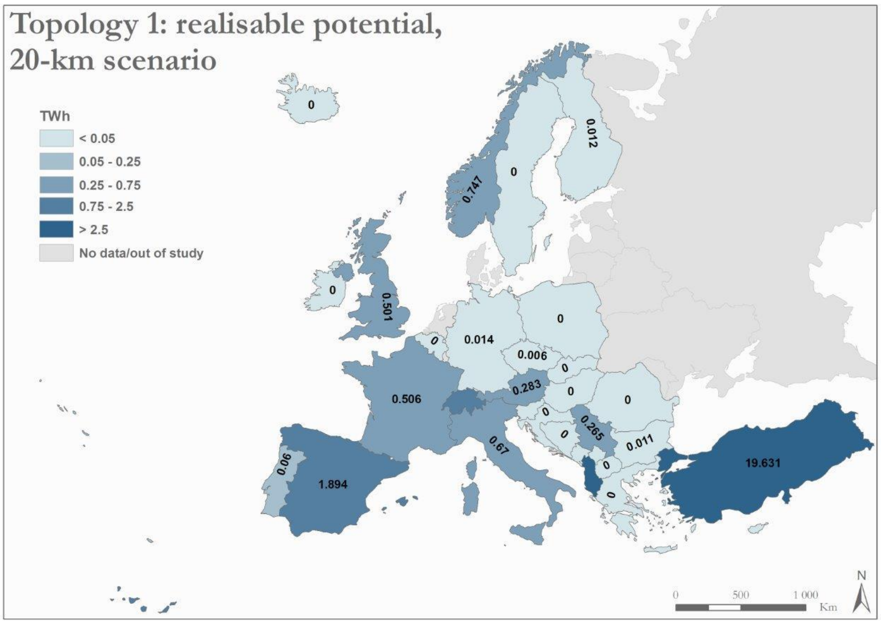


Figure 12: maximum realisable potential under topology 1 per country

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 13 in section 3.4 below. It has to be noted the issue of the lack of full reservoir data from Norway, see section 2.2.2.

3.2. Potential under topology 2

Topology 2 presents significantly higher potential than topology 1, both theoretical and realisable, and a more balanced spread among groups of countries and among scenarios. The overall European theoretical potential under topology 2 and a maximum of 20 km between the existing and the best site for a prospective reservoir is 123 TWh. This figure is reduced to realisable potential of 80 TWh when constraints are taken into account.

In general, increasing the distance of search (following the scenarios) for any given existing reservoir resulted in a "best site" with increasing potential and thus the best site found for one given scenario was superseded by that one found in the next scenario. Table 9 shows the potential "best site" found for the Chandreja reservoir in Spain at the different scenarios

Scenario	20 km	10 km	5 km	3 km	2 km	1 km
Head (m)	435	266	263	203	220	167
Surface available (m^2)	1 053 425	443 186	253 211	223 003	161 546	89 392
Potential energy storage (GWh)	22.90	5.89	3.33	2.26	1.78	0.75

Table 9: different "best sites" for a second reservoir and corresponding head and prospective energy storage for the Chandreja reservoir in Spain.

The table shows the key elements of the prospective PHS: the head regarding the prospective site for a second reservoir, the surface available for this second reservoir and the storage potential of the new PHS, which assumes a second-reservoir depth of 20 metres.

3.2.1. T2 theoretical potential

The theoretical potential energy storage under topology 2 is more than double the figures for topology 1: 123 TWh here versus 54 TWh in the latter case. Figure 13 shows that the growth of the potential with the distance between dams (in this case between the existing dam and the prospective site giving the best potential in each individual case), is smoother than for T1. For example,

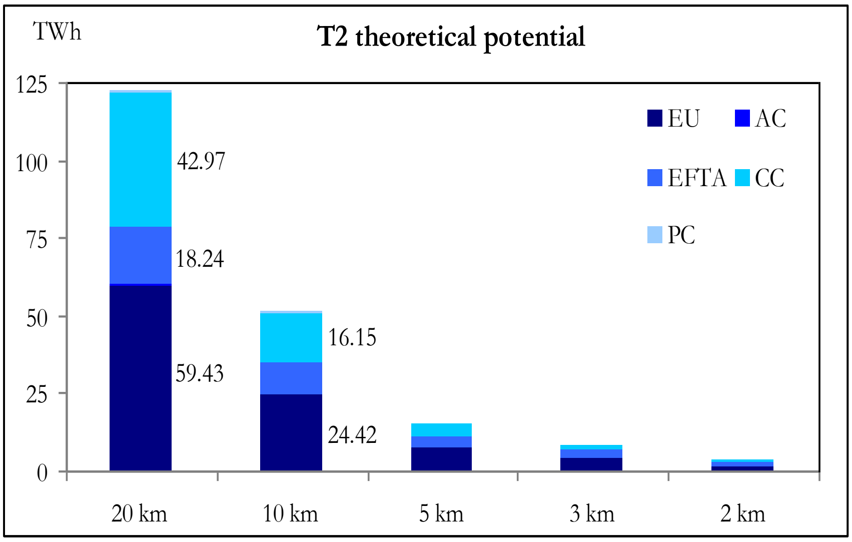


Figure 13: calculated theoretical PHS potential for different maximum distances between reservoirs for topology 2

the 20-km scenario under T1 offers nearly seven times the potential under the 10-km scenario there, whereas for T2 the 20-km scenario offers only 2.5 times the potential under the 10-km scenario. The same order the magnitude is found when comparing the 10-km and the 5-km scenarios in each case: nearly ten times for T1 versus only three times for T2.

Table 10 shows the results for topology 2 under the different scenarios.

T2 theoretical potential						
Scenario	**20 km**	**10 km**	**5 km**	**3 km**	**2 km**	**1 km**
No. of sites	4 883	4 067	2 737	1 595	776	82
Potential energy storage (TWh)	122.87	51.09	15.31	7.98	3.11	0.37

Table 10: number of potential sites found and stored energy associated.

Unlike the topology 1 assessment, topology 2 shows more balance between the theoretical potential in the EU and that one in the other four groups of countries. Figure 14 shows this as it shows that the potential in the EU is consistently around 50% of the total potential, with the exception of the 1-km scenario.

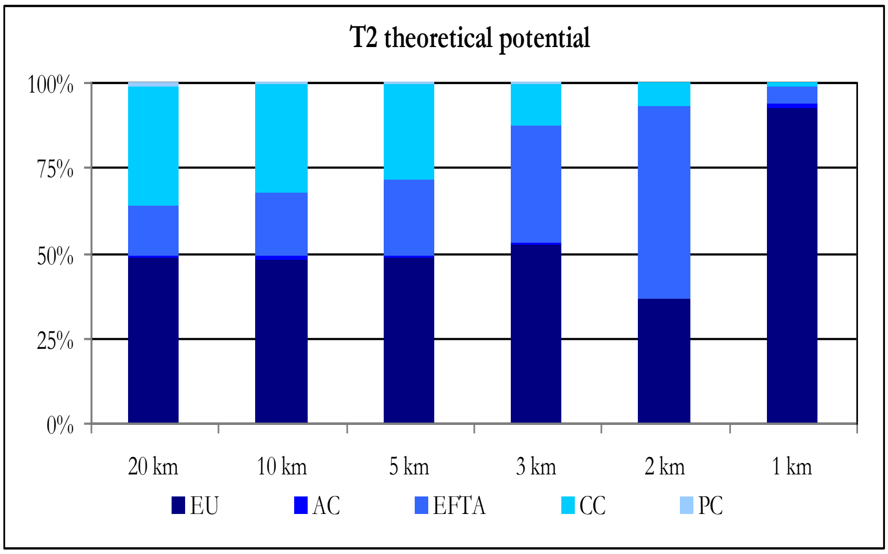


Figure 14: contribution to topology 2 total theoretical potential energy per country grouping

Figure 13 shows as well the absolute potential per group of countries, and how the EU has, in this case, a much higher theoretical potential under topology 2 than under topology 1: 59.4 TWh here vs. 11.4 TWh in the T1 case. Modelled EFTA countries Norway and Switzerland have a significant potential under T2, e.g. 18.2 TWh in scenario 20 km. To recall, EFTA members had very little theoretical potential under T1, e.g. 2.65 TWh in the 20-km scenario. Finally, unlike T1, under T2 there is some capacity in the 5-km scenario.

Also in percentage terms T2 presents a more balanced spread among group of countries than T1. Other than the more limited 1-km scenario, under all other scenarios the EU contributes around 50% to the total theoretical potential, and both EFTA and candidate countries contribute significant amounts of potential (see Figure 14). As in the case of T1, under T2 the EU is the only significant contributor to the small potential that exists under scenario 1 km: of the total 365 GWh the EU contributes 336 GWh.

At country scale in the EU it is Spain with 17.6 TWh that hast the largest potential, followed by Sweden (10 TWh), the UK, France and Italy (all around 6 TWh), see full data in Table 13 and the Annexes. In comparison with the T1 theoretical potential, in relative terms Sweden makes a quantum leap from 51 GWh, followed by Romania (1 430 GWh vs. 44 GWh), Bulgaria, Germany and Greece. Outside the EU Turkey with 41.4 TWh and Norway with 16.6 TWh are outstanding.

3.2.2. T2 realisable potential

The T2 realisable potential reaches 80 TWh in Europe on the 20-km scenario, from 4 600 available sites as shown in Table 11. The reduction in potential as a result of applying constraints is significantly lower under T2 than under T1. From the point of view of sites, under T2 the number of realisable potential sites is hardly reduced from its theoretical potential. For example, under the 20-km scenario the number of sites in the T1 realisable potential was 40% of the T1 theoretical potential (3 230 out of 8 270 sites), but the corresponding figure under T2 is 94% of sites.

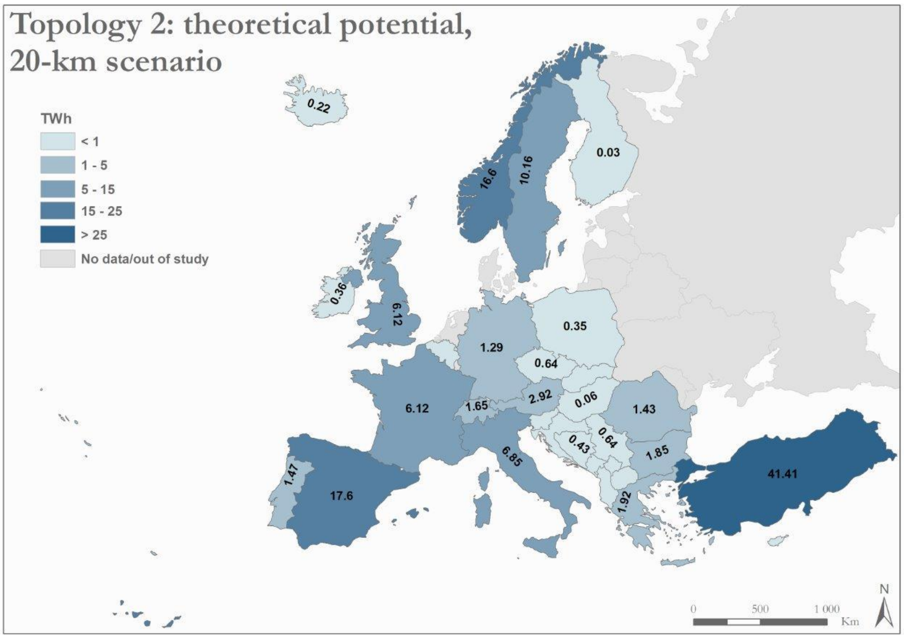


Figure 15: maximum theoretical potential per country under topology 2 (one existing reservoir)

T2 realisable potential						
Scenario	**20 km**	**10 km**	**5 km**	**3 km**	**2 km**	**1 km**
No. of sites	4,603	3,428	2,025	1,071	485	45
Potential energy storage (TWh)	79.76	33.32	10.21	4.72	1.89	0.18

Table 11: number of potential sites found and stored energy associated.

There is, however, a more significant reduction in energy storage terms as a result of applying constraints, e.g. to 80 TWh from 123 TWh in the 20-km scenario. The T1 realisable potential in this scenario was 53% of the theoretical potential (29 out of 54 TWh), and it is 65% under T2.

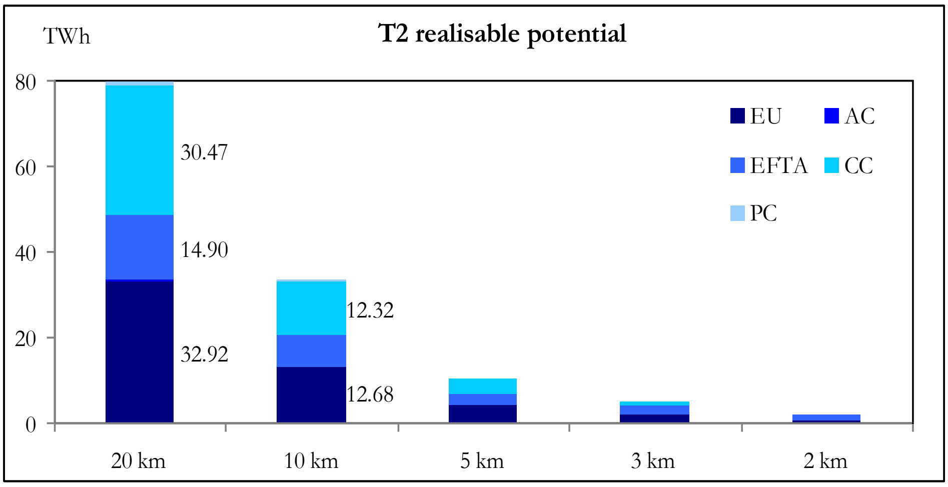


Figure 16: calculated realisable PHS potential for different maximum distances between reservoirs for topology 2

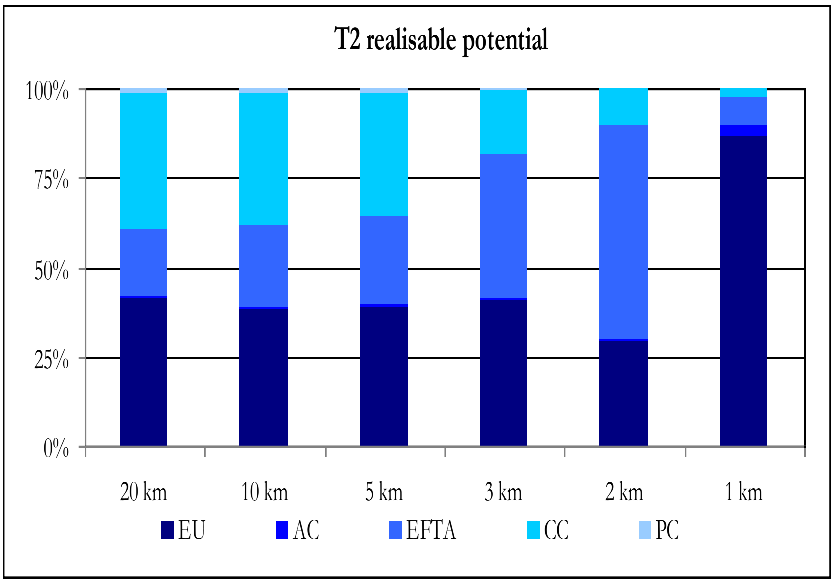


Figure 17: contribution to topology 2 total realisable potential energy per country grouping

Figure 16 shows how the T2 realisable potential varies per country grouping and scenario. Figure 17 shows these results in percentage terms, and that the breakdown is similar to the T2 theoretical potential one. The main (although subtle) difference is the reduction in the relative contribution of the EU across scenarios, from around 50% in the theoretical to around 40% in the realisable potential. The difference is now made roughly equally by the EFTA and candidate countries.

Figure 18 shows the T2 realisable potential per country for a maximum of 20 km between reservoirs. Turkey is again the country with the highest potential (29 TWh) whereas Norway follows with 13 TWh. In the EU, Spain suffered a 47% reduction from the theoretical potential and now leads with 9.4 TWh, followed by the UK (5.3 TWh and little reduction), Italy and France (4 TWh each) and Sweden (3 TWh).

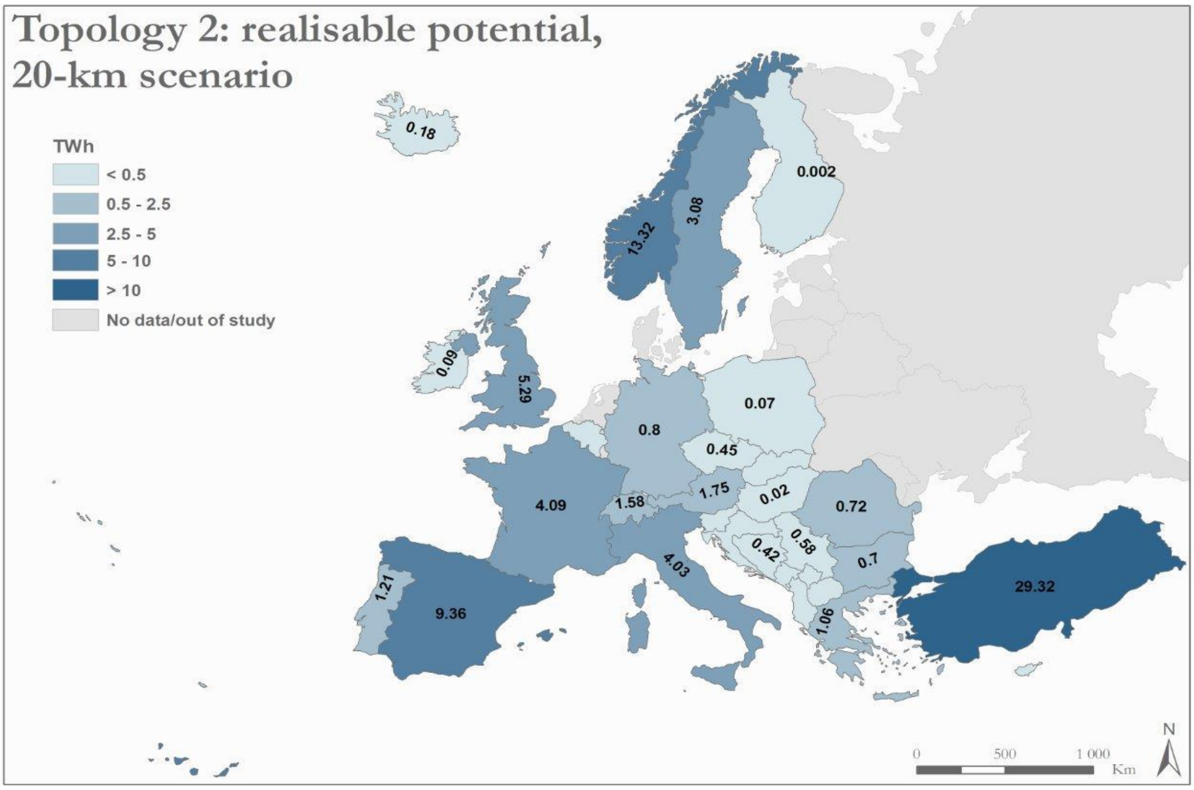


Figure 18: realisable potential per country under topology 2 and a maximum of 20 km between reservoirs

3.2.3. Comparison with the existing 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 [Eurelectric, 2011]. 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 T1 theoretical potential is 3.5 times the existing capacity whereas the T2 realisable potential is 10 times 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 [2013], 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 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, 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 that 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 [Harby, 2013].

Of the countries reported by Eurelectric, Poland, Belgium, Luxemburg, Slovakia and Ireland have either minimum existing capacity or minimum potential. For the other countries it was possible, and meaningful, to compare the existing capacity with the T2[20] potentials as shown in Figure 19.

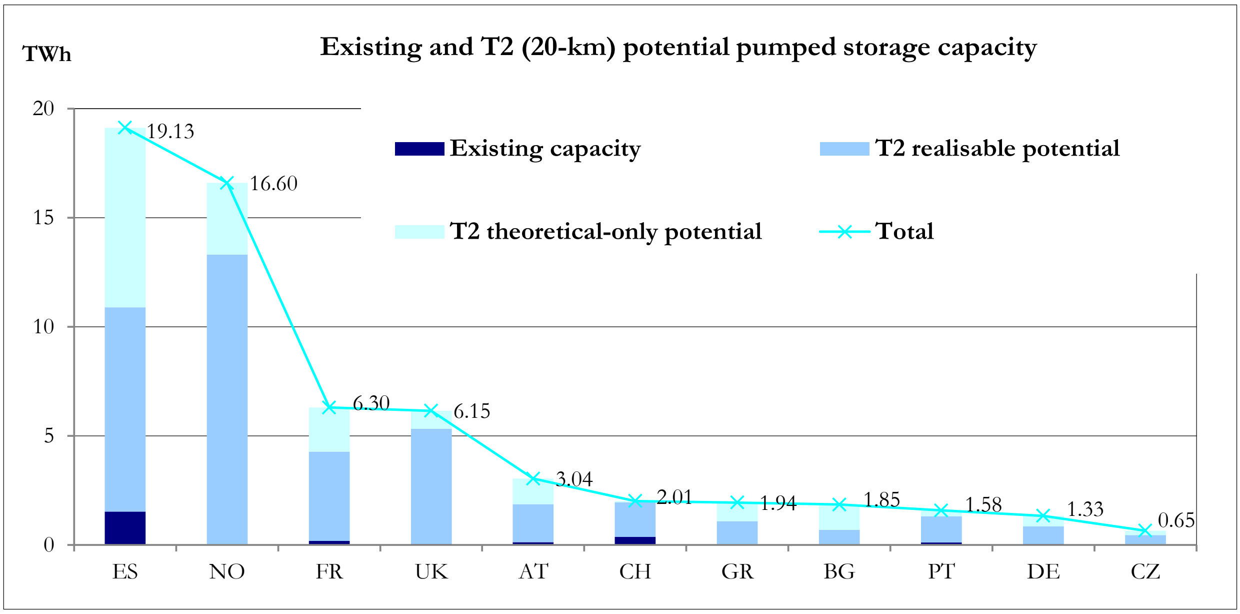


Figure 19: existing capacity (when available from Eurelectric [2011]), T2 realisable and theoretical-only potential for selected EU and EFTA countries

[20] A similar comparison using T1 is meaningless because the methodology for obtaining the existing capacity by Eurelectric [2011] differs from the JRC model's calculation of potential.

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

3.3. Summary of potentials

Table 12 allows a quick overview of potentials by showing both theoretical and realisable potentials under both topologies and the six scenarios[21].

	Potential storage (TWh) per scenario					
Topology	**20 km**	**10 km**	**5 km**	**3 km**	**2 km**	**1 km**
T1 theoretical	54.31	8.00	0.83	0.31	0.10	0.004
T1 realisable	28.63	1.32	0.20	0.07	0.03	0.003
T2 theoretical	122.87	51.09	15.31	7.98	3.11	0.37
T2 realisable	79.76	33.32	10.21	4.72	1.89	0.18

Table 12: summary of potentials under the different scenarios and topologies

[21] The seventh scenario, the 50-m head and 5-km distance between reservoirs, only applies to T2 and it is, anyway, aimed at sensitivity analysis and not a general scenario.

3.4. Results per country

The global figures for the EU do not convey the huge differences between countries. Table 13 shows a comprehensive list for the four potentials defined (T1 & T2, theoretical and realisable) under three scenarios.

Topology and scenario/country	T1 theoretical			T1 realisable			T2 theoretical			T2 Realisable		
	1 km	5 km	20 km	1 km	5 km	20 km	1 km	5 km	20 km	1 km	5 km	20 km
AT	0	105	443	0	4	283	1	335	2 915	1	120	1 747
BE	0	5	12	0	0	0	0	9	21	0	4	12
BG	0	0	119	0	0	11	0	215	1 849	0	76	696
CY	0	0	31	0	0	9	0	33	130	0	18	86
CZ	0	5	39	0	0	6	1	169	644	0	79	450
FI	0	0	12	0	0	12	0	0	33	0	0	2
FR	0	54	1 184	0	5	506	9	811	6 118	4	631	4 090
DE	0	0	89	0	0	14	2	232	1 291	1	139	804
GR	0	0	168	0	0	0	1	171	1 920	1	110	1 062
HU	0	0	4	0	0	0	0	9	59	0	3	23
IE	0	0	0	0	0	0	0	10	355	0	9	94
IT	3	218	1 867	3	35	670	9	1 183	6 846	6	633	4 034
PL	0	0	0	0	0	0	0	19	350	0	15	73
PT	0	7	542	0	0	60	0	151	1 472	0	99	1 209
RO	0	0	44	0	0	0	0	165	1 429	0	83	719
SK	0	0	0	0	0	0	0	6	46	0	3	39
SI	0	0	0	0	0	0	0	12	77	0	11	45
ES	0	292	5 788	0	93	1 894	28	2 096	17 596	10	915	9 363
SE	0	0	51	0	0	0	278	661	10 160	128	283	3 081
UK	0	23	994	0	4	501	7	1 144	6 120	3	750	5 292
EU	**4**	**709**	**11 387**	**3**	**141**	**3 967**	**336**	**7 430**	**59 431**	**155**	**3 982**	**32 922**
HR	0	0	2	0	0	0	6	64	719	6	47	408
EU+AC	**4**	**709**	**11 390**	**3**	**141**	**3 967**	**342**	**7 494**	**60 149**	**161**	**4 028**	**33 331**
NO	0	33	991	0	17	747	18	3 218	16 597	13	2 356	13 315
CH	0	42	1 656	0	28	1 437	0	226	1 645	0	197	1 583
EU+AC+EFTA	**4**	**784**	**14 037**	**3**	**186**	**6 151**	**360**	**10 938**	**78 391**	**174**	**6 582**	**48 228**
AL	0	11	3 152	0	8	2 580	0	72	651	0	71	481
BA	0	0	1	0	0	0	0	36	430	0	36	424
XK	0	0	0	0	0	0	0	6	159	0	5	158
EU+AC+EFTA+PC	**4**	**795**	**17 189**	**3**	**194**	**8 731**	**360**	**11 052**	**79 630**	**174**	**6 694**	**49 291**
IS	0	0	0	0	0	0	2	4	218	2	4	183
ME	0	0	0	0	0	0	0	190	966	0	69	377
MK	0	0	0	0	0	0	0	0	10	0	0	10
RS	0	0	327	0	0	265	1	131	638	1	109	577
TR	0	36	36 793	0	4	19 631	3	3 936	41 412	3	3 338	29 319
EU+AC+EFTA+PC+CC	**4**	**831**	**54 309**	**3**	**198**	**28 627**	**366**	**15 313**	**122 874**	**180**	**10 214**	**79 758**

Table 13: potential PHS energy storage capacity per country under the two topologies, in GWh.

3.5. Sensitivity analysis: the impact of head

In addition to comparing scenarios based on different distances, a sensitivity analysis was carried out based on head difference. For this, the scenario 5km/50m head was created and should be compared with the 5-km scenario which has a 150m minimum head condition. A by-product of this analysis is the question of how head and reservoir capacity compare to provide a given amount of storage potential.

Harby [2013] noted that there is an economic issue linked to the head/reservoir capacity. The bigger head, the less water is needed to produce the same amount of energy and, on the one hand, very low head PHS requires large pumps/turbines to move a lot of water. On the other hand, very high head PHS has some technical challenges and more research is needed for "ultra-high head PHS" above 800-1000m of head.

The 5-km scenario yielded results only for 5 Member States (MS) and 4 other countries under T1, and thus the sensitivity analysis would not be very meaningful under T1. Therefore, this analysis was carried out only under topology 2, where 19 out of 20 EU MS have shown results as well as 10 out of 11 other countries assessed for potential.

Table 14 includes the results of this sensitivity analysis for T2 theoretical potential for the EU MS and the EU total.

	T2 theoretical potential 5 km/50m scenario				T2 theoretical potential 5 km/150m scenario			
	No. of sites	Avg. head (m)	Avg. storage (GWh)	Total energy storage (GWh)	No. of sites	Avg. head (m)	Avg. storage (GWh)	Total energy storage (GWh)
AT	104	310	4	423	73	404	5	335
BE	8	137	2	18	3	220	3	9
BG	110	194	3	283	66	274	3	215
CY	24	159	2	42	14	210	2	33
CZ	88	197	2	217	57	255	3	169
FI	2	66	6	12	0	0	0	0
FR	358	268	3	967	245	353	3	811
DE	145	166	2	301	78	228	3	232
GR	44	238	6	277	31	311	6	171
HU	10	235	2	15	7	282	1	9
IE	11	189	1	12	8	222	1	10
IT	320	332	4	1 345	240	422	5	1 183
PL	20	166	2	47	12	238	2	19
PT	75	248	3	192	55	322	3	151
RO	74	170	3	226	41	255	4	165
SK	8	151	1	11	5	206	1	6
SI	4	332	3	13	3	421	4	12
ES	847	230	4	3 192	523	323	4	2 096
SE	86	175	15	1 319	54	237	12	661
UK	648	193	2	1 397	457	237	3	1 144
EU	**2 986**	**231**	**3.5**	**10 310**	**1 972**	**308**	**3.8**	**7 430**

Table 14: theoretical potential results for a 5-km scenario with two different heads, EU Member States.

More than 1 000 new potential sites are identified when the head is reduced to 50m, with a total increase in energy storage of nearly 3 TWh (39%). Spain presents the largest absolute increase from 2.1 to 3.2 TWh (+52%) whereas Sweden presents the largest relative increase (+100 % to 1.3 TWh) among the countries with more potential. Poland presented the largest relative increase (+147%) although with a low overall potential; Finland, which did not present any potential site in the 5-km scenario, presents now 2 sites with 12 GWh total capacity.

Consistently with the theoretical results obtained, the realisable potential was significantly increased. The number of new realisable potential sites increased by 937 and the total storage potential recorded was increased by 1 447 GWh, from 4 028 GWh to 5 475 GWh.

	T2 realisable potential 5 km/50m scenario				T2 realisable potential 5 km/150m scenario			
	No. of sites	Avg. head (m)	Avg. storage (GWh)	Total energy storage (GWh)	No. of sites	Avg. head (m)	Avg. storage (GWh)	Total energy storage (GWh)
AT	58	302	2	143	39	407	3	120
BE	6	135	1	7	2	242	2	4
BG	64	163	2	131	33	234	2	76
CY	21	158	1	27	12	214	2	18
CZ	66	165	2	131	35	226	2	79
FI	0	0	0	0	0	0	0	0
FR	306	251	3	778	198	341	3	631
DE	124	146	2	201	53	209	3	139
GR	32	211	6	182	20	287	6	110
HU	6	150	2	10	2	219	1	3
IE	10	184	1	11	7	220	1	9
IT	225	269	3	758	157	355	4	633
PL	16	183	1	20	9	252	2	15
PT	55	228	2	133	36	303	3	99
RO	55	154	2	124	25	245	3	83
SK	6	168	1	6	4	206	1	3
SI	2	512	5	11	2	512	5	11
ES	544	186	2	1 329	286	275	3	915
SE	67	164	7	440	38	221	7	283
UK	601	176	2	981	372	228	2	750
EU	**2 264**	**200**	**2.4**	**5 425**	**1 330**	**278**	**3.0**	**3 982**

Table 15: realisable potential results for 5-km scenario with two different heads, EU Member States.

Per countries again it is Spain that presents the most potential with 1 329 GWh in the 5km/50m scenario, 45% up from the 5-km scenario. Sweden, Greece, Bulgaria and the Czech Republic present increases above 55%.

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 and topologies considered. This work does not attempt to assess the related potential electricity installed capacity, it only makes a suggestion, in section 2.5.2, on a procedure to match both parameters.

In the cases where a PHS can be built based on linking two existing reservoirs (topology 1), 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.

When a PHS is built based on one existing reservoir and on a nearby, appropriately *non-sloping* site for a second existing reservoir, the theoretical potential at a maximum of 20 km reaches 123 TWh in Europe of which 60 TWh in the EU. The corresponding realisable potential is 80 TWh in Europe of which 33 TWh in the EU. For shorter distances between the existing dam and the best potential site the realisable potential is reduced to 10 TWh (5 km, Europe) of which 4 TWh in the EU, and 180 GWh (1 km, Europe), most of which in the EU (155 GWh).

This study has taken due considerations of environmental as well as energy issues. This was one of the reasons why only topologies 1 and 2 were analysed: in neither case there is a need, for example, 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 for topology 1 and the realisable potential for topology 2. This is because for topology 1 the environmental impact of building a new penstock and powerhouse (the latter is nowadays built underground) can be very small whereas for topology 2 a new dam has to be built and thus the impact of environmental restrictions can be considerable. 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 "under" protected areas may also not be possible in some cases or countries.

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 inclusion in T2 assessment of all the 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 a second reservoir site.

This work and its related 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.

4.2. Suggestions for future model development

As a result of the experience gained during this work, and of 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 the updated GRanD database.

- To include existing reservoirs smaller than 100 000 m^3 which have hydropower exploitation above 1 MW.
- To change the basis on which the model searches for a suitable site from the current "single point" to an area. This would require an update of the reservoir database from points to polygons.
- For T1, 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 T1.
- For each prospective site, to change the ranking of second-reservoir site options to facilitate fine-tuning. The existing ranking is currently automatic and based on energy storage potential, but there are suggestions that prospective second-reservoir sites with higher head and lower prospective storage potential can be preferred to others with slightly higher prospective storage potential.
- 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 model cross-boundary potential.
- To explore an alternative for the "flatness" criterion for second reservoir site identification. This could be based on some measure of concavity within the search buffer. This would also be a first step towards estimating costs associated with building the impoundment.
- To carry out the assessment of topology 6.

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) [Zinke, 2013]. 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 dam and reservoir construction, and for the underground penstock. The difference in cost of constructing dams in granite or schist is considerable and in the Mediterranean basin earthquake risks and flash flood occurrence 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 relate more to 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 model.

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 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.

REFERENCES:

Auer, J. and Keil, J. (2012), *"State of the art electricity storage systems. Indispensable elements of the energy revolution"*. Available at http://www.dbresearch.com/PROD/DBR_INTERNET_EN-PROD/PROD0000000000286166/State-of-the-%20art+electricity+storage+systems%3A+Indispensable+elements+of+the+energy+r%20evolution.pdf . Accessed 10/01/2013.

Andritz Hydro (2010): Recent Developments in Pump Turbines. Presentation at HydroVision 2010, accessed 18/03/2013, available at http://tm-info.no/getfile.php/tm-info.no/Presentasjoner/TM12052011/06_Ole%20Johnny%20Winther%20Andritz.pdf

Council (Council of the European Union), 2012: Council conclusions on Renewable Energy. 3204th TRANSPORT, TELECOMMUNICATIONS and ***ENERGY*** Council meeting. Brussels, 3 December 2012. Consulted on 18/03/13. Available at http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/trans/133950.pdf

Dameffects – http://www.dameffects.org Accessed 11.01.2013

DENA (2008): *Untersuchung der elektrizitätswirtschaftlichen und energiepolitischen Auswirkungen der Erhebung von Netznutzungsentgelten für den Speicherstrombezug von Pumpspeicherwerken*. Deutsche Energie-Agentur GMBH, Bereich Regenerative Energien, Berlin.

DECC (UK Department of Energy & Climate Change, 2012): *Electricity System: Assessment of Future Challenges – Summary*. London. Available at: http://www.decc.gov.uk/assets/decc/11/meeting-energy-demand/future-elec-network/6098-electricity-system-assessment-future-chall.pdf

DIVA-GIS: http://www.diva-gis.org/Data

ESRI (Environmental Systems Research Institute): www.esri.com

EdF (Electricité de France, 2011). *Experience of EDF in the field of pumped-storage power plants*. Presented at the conference Pumped storage Powerplants, Lyon, 23-24 November 2011.

Eurelectric (2011): *Hydro in Europe: Powering renewables. Full report.* http://www.eurelectric.org/media/26690/hydro_report_final-2011-160-0011-01-e.pdf

EC (European Commission, 2007): *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. An Energy policy for Europe* (COM/2007/1 final). Available at http://ec.europa.eu/energy/energy_policy/doc/01_energy_policy_for_europe_en.pdf

EC (European Commission, 2012): *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Renewable Energy: a major player in the European energy market* (COM/2012/0271 final). Available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52012DC0271:EN:NOT

EC (European Commission, 2013): Europe 2020 http://ec.europa.eu/europe2020/index_en.htm Accessed: 11.01.2013

EEA (European Environmental Agency, 2012) European Catchments and RIvers Network System (ECRINS) —. [online] Available at: http://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network [Accessed: 16 Apr 2013].

EIONET (2013) Dampos.eionet.europa.eu (2005) DAM Positioning - Eionet. [online] Available at: http://dampos.eionet.europa.eu [Accessed: 16 Apr 2013].

European Council (2009): Presidency conclusions to the European Council of 29/30 October 2009. Available at

http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/110889.pdf, accessed 25.03.2013

European Free Trade Association (EFTA): http://www.efta.int Accessed: 04.02.2013

Eurostat, European office of statistics: http://ec.europa.eu/eurostat. Accessed 20.02.2013

EU (European Union, 2013): *How the EU works. List of countries*. Available at http://europa.eu/about-eu/countries/index_en.htm. Accessed 04.02.2013

Fitzgerald, N., Lacal Arántegui, R., McKeogh, E., and Leahy, P., 2012: *A GIS-based model to calculate the potential for transforming conventional hydropower schemes and non-hydro reservoirs to pumped hydropower schemes*, Energy, Volume 41, Issue 1, May 2012, Pages 483-490. Available at http://www.sciencedirect.com/science/article/pii/S0360544212001399

GRanD (2011) Dams, v1.01: Global Reservoir and Dam (GRanD), v1 | SEDAC. [online] Available at: http://sedac.ciesin.columbia.edu/data/set/grand-v1-dams-rev01 [Accessed: 16 Apr 2013].

Harby, Atle (2013), Director, Centre for Environmental Design of Renewable Energy, SINTEF Energy Research, Norway. Personal communications.

IEA & IRENA, 2012: Energy supply technologies. Electricity Storage. Available at: http://www.iea-etsap.org/web/Supply.asp

JRC (Joint Research Centre) of the European Commission, 2011: *Pumped-hydro energy storage: Potential for transformation from single dams*. Lacal Arántegui, R., Fitzgerald, N., and Leahy, P. (2011). Joint Research Centre – Institute for Energy and Transport; Petten, The Netherlands. Available at http://setis.ec.europa.eu/setis-deliverables/studies-and-reports/report-pumped-hydro-energy-storage-potential-transformation

JRC (Joint Research Centre) of the European Commission, 2012: *SETIS Expert workshop on the assessment of the potential of pumped hydropower storage*. Lacal Arántegui, R., Tzimas, E., Bocin-Dumitriu, A., Zubyareva, A. (2012). Joint Research Centre – Institute for Energy and Transport; Petten, The Netherlands. Available at http://setis.ec.europa.eu/setis-deliverables/setis-workshops-hearings/setis-expert-workshop-assessment-of-potential-of-pumped

Martínez Campillo, R. (2010), Iberdrola Generación: *El almacenamiento de energía en sistemas eléctricos de potencia: centrales hidroeléctricas reversibles*. Presentation at the Universidad Pontificia de Comillas, 18/05/2010. Accessed 18/03/2013, available at http://www.upcomillas.es/catedras/crm/descargas/2009-2010/seminario%2018.05.2010.pdf

Naturalearthdata.com (2013) 1:50m Cultural Vectors | Natural Earth. [online] Available at: http://www.naturalearthdata.com/downloads/50m-cultural-vectors/ [Accessed: 16 Apr 2013].

PLATTS (2006): European Transmission Lines. Vector digital data. Boulder, CO. Platts. Online_Linkage: http://www.gisdata.platts.com/

PLATTS (2012): Platts Power Plant Database, retrieved September 2012.

Schmid, S. (2013). Hydroprojekt, Germany. Personal communication in the process of the review of this paper.

UNESCO World Heritage Centre: http://whc.unesco.org/en/list/

Vogt, J. V., Soille, P., de Jager, A., Rimavičiūtė, E., Mehl, W., Foisneau, S., Bódis, K., Dusart,J., Paracchini, M.L., Haastrup, P., Bamps, C. (2007): *A Pan-European River and Catchment Database*, European Commission, Directorate-General Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy, p. 119., JRC Reference Reports, EUR 22920 EN

Wänn, A (2012): database of European PHS plants used in the stoRE project, personal communication.

WCD (World Commission on Dams, 2000): *Dams and developments: A new framework for decision-making – The report of the World Commission on Dams*. Earthscan Publications. Available at: http://awsassets.panda.org/downloads/wcd_dams_final_report.pdf

ZfES Zentrum für Energieforschung Stuttgart(2012). *Stromspeicherpotenziale für Deutschland*. Hartmann, N., Eltrop, L., Bauer, N., Salzer, J., Schwarz, S., and Schmidt, M. Stuttgart, Germany, July 2012.

Zinke, P. (2013). SINTEF Energy Research, Trondheim, Norway. Personal communication in the process of the review of this paper.

ABBREVIATIONS AND ACRONYMS:

Throughout this report 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:

AC	Acceding countries to the European Union
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 Watts)
GWh	Gigawatt hour
METI	Ministry of Economy, Trade, and Industry of Japan
MS	Member State
MW	Megawatt
NASA	United States National Aeronautics and Space Administration
NVE	Norwegian Directorate for Water and Energy
PC	Potential candidate country/countries to the European Union
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	The United Nations Educational, Scientific and Cultural Organization

ANNEX I: CALCULATION OF ENERGY STORAGE FOR A PROSPECTIVE PHS SITE.

The present annex is an extract from [JRC, 2011] showing how the model calculates the energy storage capacity for the prospective PHS sites.

3.2.2 Energy storage potential

The equation to calculate the energy available in a body of water is defined as follows:

$$E = \rho \, g \, h \, V \, \mu$$

where:

E = energy available (Joules)

ρ = density (kg/m^3) (1019 kg/m^3 for water)

g = acceleration of gravity (9.81 m/s^2)

h = falling height, head (m)

V = volume (m^3)

μ= generation efficiency of (90%)

Example:

A reservoir has a capacity of 10 000 000 cubic metres with a 300-metre head.

E = (1 019 * 9.81 * 300 * 10 000 000 * 0.9) Joules

As 1 Wh = 3 600 Joules, the stored energy in reservoir = 7.5 GWh

ANNEX II: COUNTRY FILES

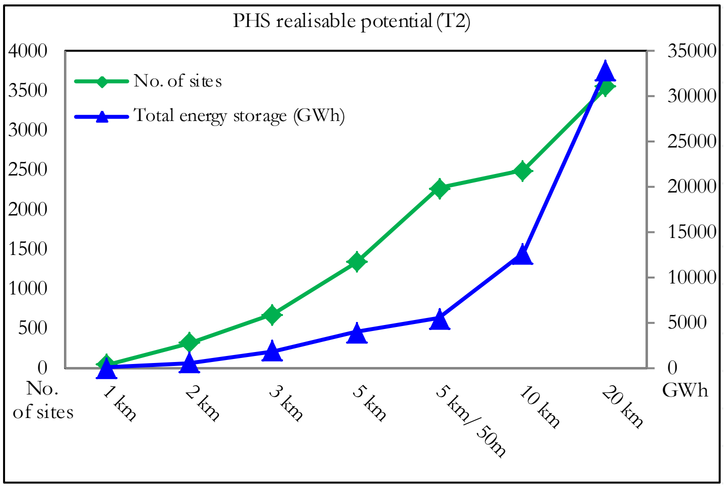
Eurostat data for 2011	GWh
Net electricity production	3 114 669
Net production natural hydro	330 389
Net production from PHS	28 803
Net production from wind	177 792
Net production from solar	46 012
Total variable RES electricity	223 804
PHS generation capacity (MW)	42 566
Conventional hydro generation capacity (MW)	146 537

Total PHS energy storage capacity	*No data*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	6 476
Of which capacity is inc.	5 778
Total capacity (Hm^3)	782 353
No. of reservoirs selected	5 225
Capacity of selected reservoirs (Hm^3)	782 350

EU-27



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	5	47	131	344		1 581	7 317
Average head (m)	201	281	301	307		319	363
Average energy storage (GWh)	1	1	2	2		2	2
Total energy storage (GWh)	4	61	255	709		2 874	11 387

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	6	25	77		421	2 553
Average head (m)	292	433	321	322		316	426
Average energy storage (GWh)	3	3	1	2		2	2
Total energy storage (GWh)	3	16	36	141		798	3 967

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	71	561	1 120	1 972	2 986	3 081	3 815
Average head (m)	222	230	259	308	231	411	555
Average energy storage (GWh)	5	2	4	4	3	8	16
Total energy storage (GWh)	336	1 118	4 179	7 430	10 310	24 416	59 431

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	36	315	670	1 330	2 264	2 499	3 551
Average head (m)	222	226	246	278	200	342	470
Average energy storage (GWh)	4	2	3	3	2	5	9
Total energy storage (GWh)	4	553	1 911	3 982	5 425	12 678	32 922

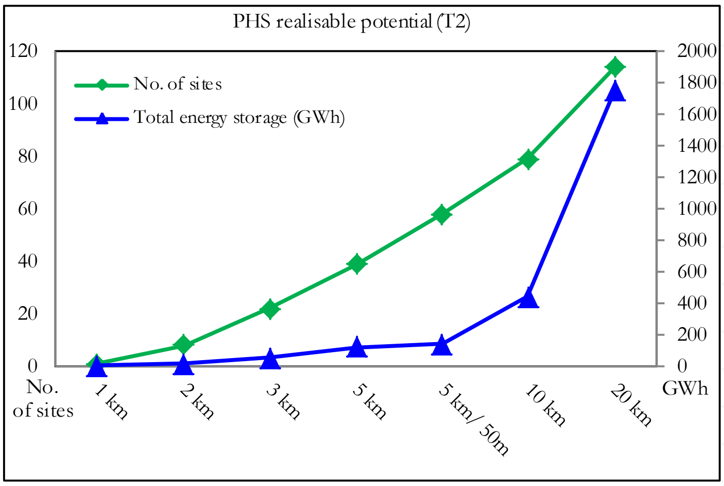
Eurostat data for 2011	GWh
Net electricity production	63 319
Net production natural hydro	36 399
Net production from PHS	3 504
Net production from wind	1 934
Net production from solar	174
Total variable RES electricity	2 108
PHS generation capacity (MW)	3 365
Conventional hydro generation capacity (MW)	12 980

Total PHS energy storage capacity	*125*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	167
Of which capacity is inc.	155
Total capacity (Hm^3)	7 766
No. of reservoirs selected	145
Capacity of selected reservoirs (Hm^3)	7 766

Austria



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	2	4	15		40	98
Average head (m)	0	498	477	460		557	607
Average energy storage (GWh)	0	1	1	7		5	5
Total energy storage (GWh)	0	2	6	105		199	443

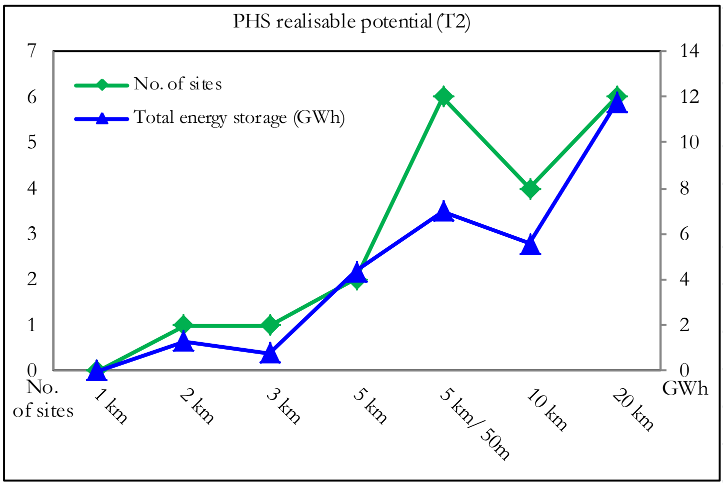
T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	2	3		13	45
Average head (m)	0	0	457	462		578	703
Average energy storage (GWh)	0	0	2	1		8	6
Total energy storage (GWh)	0	0	3	4		102	283

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	2	19	46	73	104	128	142
Average head (m)	202	315	305	404	310	638	869
Average energy storage (GWh)	0	2	3	5	4	9	21
Total energy storage (GWh)	1	44	147	335	423	1 143	2 915

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	8	22	39	58	79	114
Average head (m)	161	302	302	407	302	539	758
Average energy storage (GWh)	1	2	2	3	2	6	15
Total energy storage (GWh)	1	14	52	120	143	439	1 747

Eurostat data for 2011	GWh
Net electricity production	86 663
Net production natural hydro	1 410
Net production from PHS	1 217
Net production from wind	2 285
Net production from solar	1 169
Total variable RES electricity	3 454
PHS generation capacity (MW)	1 307
Conventional hydro generation capacity (MW)	1 426

Belgium



Total PHS energy storage capacity	*8*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	15
Of which capacity is inc.	12
Total capacity (Hm^3)	177
No. of reservoirs selected	12
Capacity of selected reservoirs (Hm^3)	177

JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	2	2		2	4
Average head (m)	0	252	252	252		252	247
Average energy storage (GWh)	0	3	3	3		3	3
Total energy storage (GWh)	0	3	5	5		5	12

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	3	3	8	5	8
Average head (m)	0	241	224	220	137	270	225
Average energy storage (GWh)	0	1	2	3	2	4	3
Total energy storage (GWh)	0	1	6	9	18	20	21

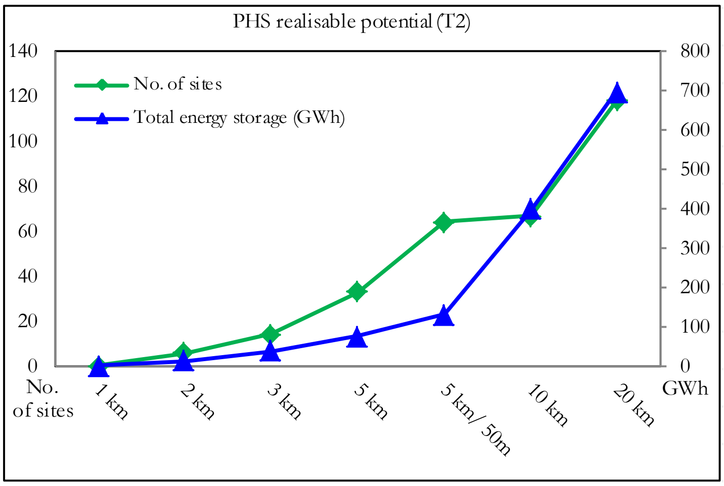
T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	1	2	6	4	6
Average head (m)	0	241	157	242	135	202	216
Average energy storage (GWh)	0	1	1	2	1	1	2
Total energy storage (GWh)	0	1	1	4	7	6	12

Bulgaria

Eurostat data for 2011	GWh
Net electricity production	45 844
Net production natural hydro	3 641
Net production from PHS	765
Net production from wind	861
Net production from solar	101
Total variable RES electricity	962
PHS generation capacity (MW)	864
Conventional hydro generation capacity (MW)	3 108

Total PHS energy storage capacity	*2*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)



Reservoir data (ECRINS)	
No. of reservoirs	163
Of which capacity is inc.	158
Total capacity (Hm^3)	7 524
No. of reservoirs selected	158
Capacity of selected reservoirs (Hm^3)	7 524

JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		2	27
Average head (m)	0	0	0	0		404	252
Average energy storage (GWh)	0	0	0	0		4	4
Total energy storage (GWh)	0	0	0	0		8	119

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	6
Average head (m)	0	0	0	0		0	206
Average energy storage (GWh)	0	0	0	0		0	2
Total energy storage (GWh)	0	0	0	0		0	11

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	13	33	66	110	110	146
Average head (m)	0	225	238	274	194	386	507
Average energy storage (GWh)	0	2	2	3	3	8	13
Total energy storage (GWh)	0	22	69	215	283	926	1 849

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	6	14	33	64	67	118
Average head (m)	0	232	216	234	163	332	386
Average energy storage (GWh)	0	2	3	2	2	6	6
Total energy storage (GWh)	0	14	38	76	131	398	696

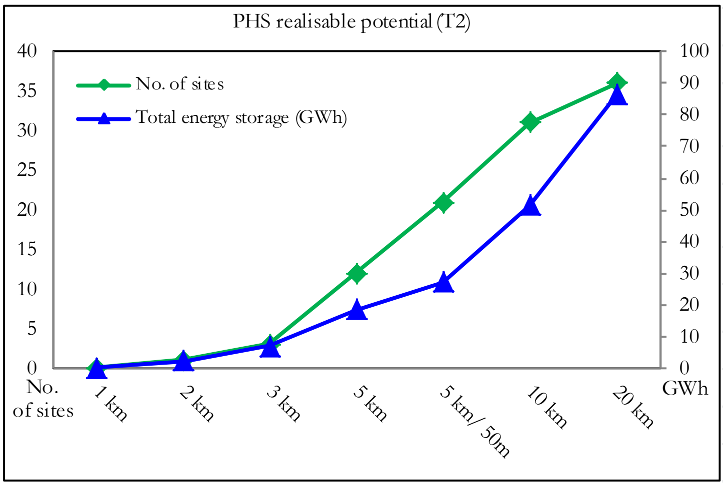
Eurostat data for 2011	GWh
Net electricity production	4 760
Net production natural hydro	0
Net production from PHS	0
Net production from wind	114
Net production from solar	12
Total variable RES electricity	126
PHS generation capacity (MW)	0
Conventional hydro generation capacity (MW)	0

Total PHS energy storage capacity	*0*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	52
Of which capacity is inc.	52
Total capacity (Hm^3)	286
No. of reservoirs selected	38
Capacity of selected reservoirs (Hm^3)	285

Cyprus



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	1		11	57
Average head (m)	0	0	0	252		314	370
Average energy storage (GWh)	0	0	0	0		1	1
Total energy storage (GWh)	0	0	0	0		8	31

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	16
Average head (m)	0	0	0	0		0	358
Average energy storage (GWh)	0	0	0	0		0	1
Total energy storage (GWh)	0	0	0	0		0	9

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	3	14	24	33	37
Average head (m)	0	188	229	210	159	406	667
Average energy storage (GWh)	0	2	2	2	2	2	4
Total energy storage (GWh)	0	2	7	33	42	74	130

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	3	12	21	31	36
Average head (m)	0	188	229	214	158	308	451
Average energy storage (GWh)	0	2	2	2	1	2	2
Total energy storage (GWh)	0	2	7	18	27	51	86

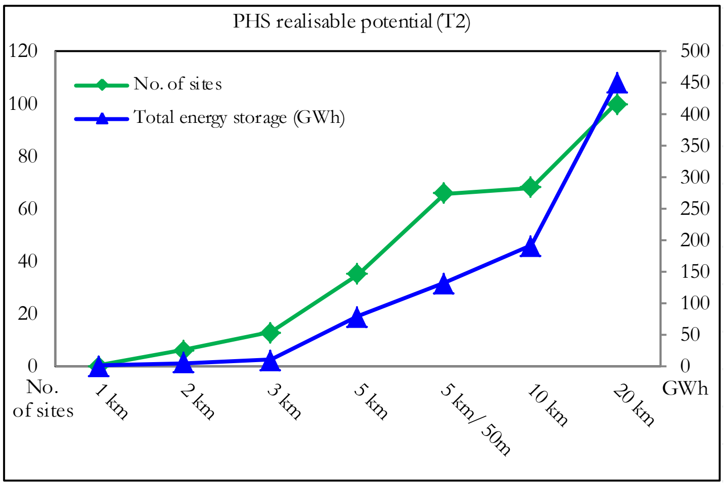
Czech Republic

Eurostat data for 2011	GWh
Net electricity production	80 921
Net production natural hydro	2 651
Net production from PHS	701
Net production from wind	395
Net production from solar	2 169
Total variable RES electricity	2 564
PHS generation capacity (MW)	1 147
Conventional hydro generation capacity (MW)	2 197

Total PHS energy storage capacity	*7*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	118
Of which capacity is inc.	117
Total capacity (Hm^3)	3 454
No. of reservoirs selected	116
Capacity of selected reservoirs (Hm^3)	3 454



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	2	3	5		12	39
Average head (m)	193	360	291	253		278	266
Average energy storage (GWh)	0	2	1	1		1	1
Total energy storage (GWh)	0	4	4	5		12	39

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	2	0		3	8
Average head (m)	0	0	174	0		339	306
Average energy storage (GWh)	0	0	0	0		1	1
Total energy storage (GWh)	0	0	0	0		3	6

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	13	26	57	88	85	112
Average head (m)	167	209	236	255	197	298	338
Average energy storage (GWh)	1	1	2	3	2	3	6
Total energy storage (GWh)	1	15	41	169	217	289	644

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	6	13	35	66	68	100
Average head (m)	0	189	221	226	165	266	302
Average energy storage (GWh)	0	1	1	2	2	3	5
Total energy storage (GWh)	0	5	10	79	131	191	450

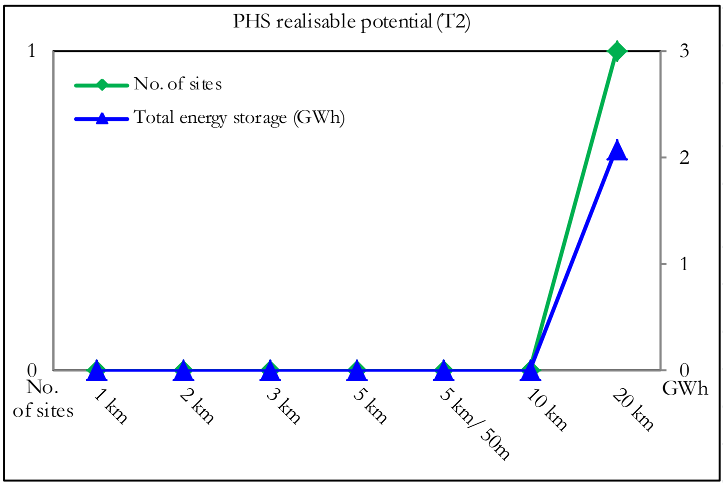
Eurostat data for 2011	GWh
Net electricity production	70 389
Net production natural hydro	12 278
Net production from PHS	0
Net production from wind	481
Net production from solar	5
Total variable RES electricity	486
PHS generation capacity (MW)	0
Conventional hydro generation capacity (MW)	3 156

Total PHS energy storage capacity	*0*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	56
Of which capacity is inc.	53
Total capacity (Hm^3)	19 048
No. of reservoirs selected	53
Capacity of selected reservoirs (Hm^3)	19 048

Finland



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	1
Average head (m)	0	0	0	0		0	152
Average energy storage (GWh)	0	0	0	0		0	12
Total energy storage (GWh)	0	0	0	0		0	12

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	1
Average head (m)	0	0	0	0		0	152
Average energy storage (GWh)	0	0	0	0		0	12
Total energy storage (GWh)	0	0	0	0		0	12

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0	2	0	4
Average head (m)	0	0	0	0	66	0	179
Average energy storage (GWh)	0	0	0	0	6	0	8
Total energy storage (GWh)	0	0	0	0	12	0	33

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0	0	0	1
Average head (m)	0	0	0	0	0	0	160
Average energy storage (GWh)	0	0	0	0	0	0	2
Total energy storage (GWh)	0	0	0	0	0	0	2

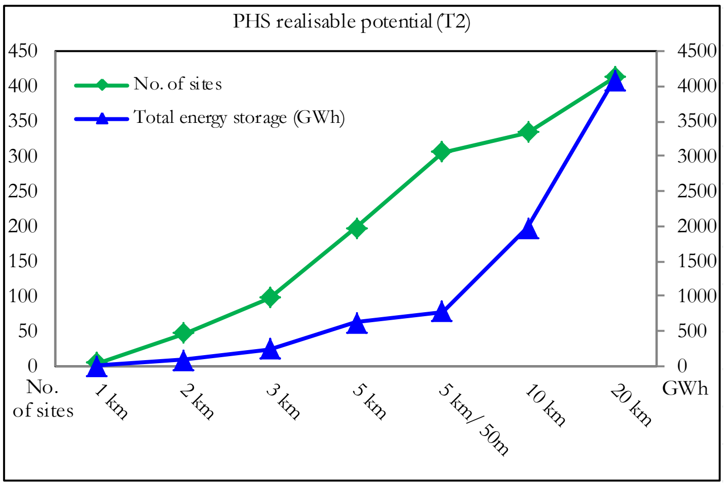
Eurostat data for 2011	GWh
Net electricity production	537 510
Net production natural hydro	49 671
Net production from PHS	5 074
Net production from wind	12 235
Net production from solar	2 050
Total variable RES electricity	14 285
PHS generation capacity (MW)	6 985
Conventional hydro generation capacity (MW)	25 332

Total PHS energy storage capacity	*184*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	715
Of which capacity is inc.	567
Total capacity (Hm^3)	24 531
No. of reservoirs selected	550
Capacity of selected reservoirs (Hm^3)	24 530

France



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	3	9	20		91	298
Average head (m)	0	308	332	425		384	414
Average energy storage (GWh)	0	2	2	3		4	4
Total energy storage (GWh)	0	6	20	54		409	1 184

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	2	4		20	124
Average head (m)	0	0	514	373		382	435
Average energy storage (GWh)	0	0	2	1		5	4
Total energy storage (GWh)	0	0	4	5		93	506

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	6	72	135	245	358	371	427
Average head (m)	180	239	277	353	268	464	614
Average energy storage (GWh)	1	3	3	3	3	7	14
Total energy storage (GWh)	9	180	374	811	967	2 591	6 118

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	5	47	98	198	306	334	413
Average head (m)	183	230	268	341	251	430	571
Average energy storage (GWh)	1	2	2	3	3	6	10
Total energy storage (GWh)	1	90	242	631	778	1 984	4 090

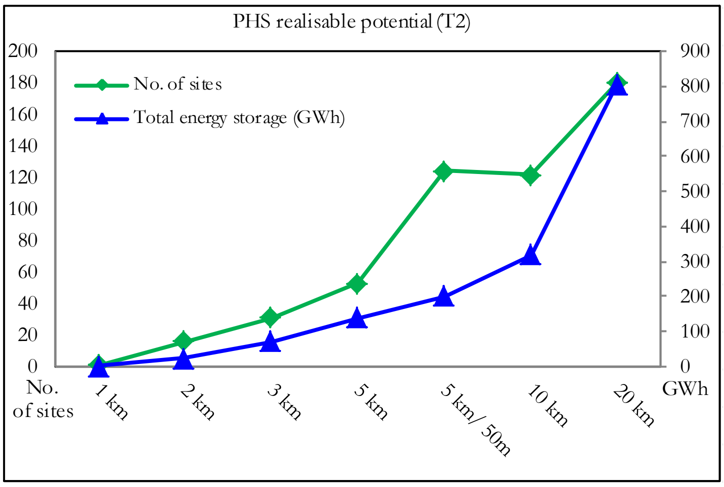
Eurostat data for 2011	GWh
Net electricity production	572 887
Net production natural hydro	23 038
Net production from PHS	6 099
Net production from wind	48 883
Net production from solar	19 340
Total variable RES electricity	68 223
PHS generation capacity (MW)	6 777
Conventional hydro generation capacity (MW)	11 562

Total PHS energy storage capacity	*39*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	246
Of which capacity is inc.	236
Total capacity (Hm^3)	3 658
No. of reservoirs selected	235
Capacity of selected reservoirs (Hm^3)	3 658

Germany



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		9	51
Average head (m)	0	0	0	0		190	201
Average energy storage (GWh)	0	0	0	0		2	2
Total energy storage (GWh)	0	0	0	0		19	89

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		1	5
Average head (m)	0	0	0	0		153	189
Average energy storage (GWh)	0	0	0	0		5	3
Total energy storage (GWh)	0	0	0	0		5	14

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	3	30	43	78	145	138	189
Average head (m)	159	200	217	228	166	271	317
Average energy storage (GWh)	1	1	3	3	2	4	7
Total energy storage (GWh)	2	43	113	232	301	566	1 291

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	16	31	53	124	122	180
Average head (m)	161	190	205	209	146	247	276
Average energy storage (GWh)	1	1	2	3	2	3	4
Total energy storage (GWh)	1	23	71	139	201	320	804

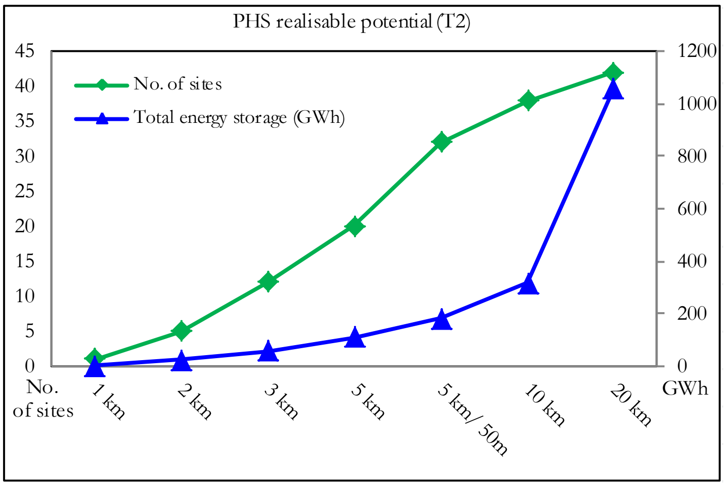
Eurostat data for 2011	GWh
Net electricity production	53 913
Net production natural hydro	4 262
Net production from PHS	264
Net production from wind	3 315
Net production from solar	610
Total variable RES electricity	3 925
PHS generation capacity (MW)	699
Conventional hydro generation capacity (MW)	3 224

Greece

Total PHS energy storage capacity	*21*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	59
Of which capacity is inc.	51
Total capacity (Hm^3)	13 347
No. of reservoirs selected	51
Capacity of selected reservoirs (Hm^3)	13 347



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		1	3
Average head (m)	0	0	0	0		151	442
Average energy storage (GWh)	0	0	0	0		28	56
Total energy storage (GWh)	0	0	0	0		28	168

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	7	18	31	44	46	47
Average head (m)	256	248	259	311	238	465	668
Average energy storage (GWh)	1	4	5	6	6	11	41
Total energy storage (GWh)	1	26	84	171	277	519	1 920

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	5	12	20	32	38	42
Average head (m)	256	280	265	287	211	421	613
Average energy storage (GWh)	1	5	5	6	6	8	25
Total energy storage (GWh)	1	24	59	110	182	318	1 062

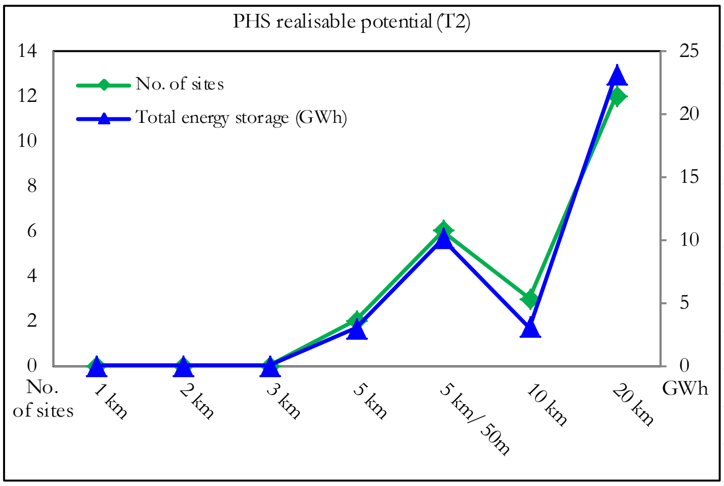
Eurostat data for 2011	GWh
Net electricity production	33 500
Net production natural hydro	216
Net production from PHS	0
Net production from wind	610
Net production from solar	1
Total variable RES electricity	611
PHS generation capacity (MW)	0
Conventional hydro generation capacity (MW)	55

Hungary

Total PHS energy storage capacity	*0*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	15
Of which capacity is inc.	15
Total capacity (Hm^3)	62
No. of reservoirs selected	15
Capacity of selected reservoirs (Hm^3)	62



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	1		3	9
Average head (m)	0	0	0	181		192	243
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	4

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	2	2	7	10	13	15
Average head (m)	0	219	291	282	235	362	433
Average energy storage (GWh)	0	1	2	1	2	2	4
Total energy storage (GWh)	0	1	3	9	15	30	59

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	2	6	3	12
Average head (m)	0	0	0	219	150	181	243
Average energy storage (GWh)	0	0	0	1	2	1	2
Total energy storage (GWh)	0	0	0	3	10	3	23

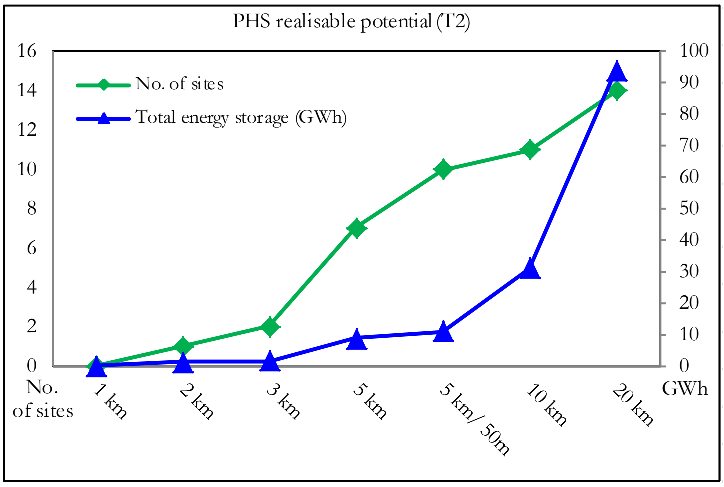
Ireland

Eurostat data for 2011	GWh
Net electricity production	26 369
Net production natural hydro	699
Net production from PHS	0
Net production from wind	4 380
Net production from solar	0
Total variable RES electricity	4 380
PHS generation capacity (MW)	292
Conventional hydro generation capacity (MW)	529

Total PHS energy storage capacity	*2*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	16
Of which capacity is inc.	16
Total capacity (Hm^3)	970
No. of reservoirs selected	16
Capacity of selected reservoirs (Hm^3)	970



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	2	3	8	11	12	15
Average head (m)	0	194	249	222	189	369	407
Average energy storage (GWh)	0	1	1	1	1	4	24
Total energy storage (GWh)	0	3	3	10	12	52	355

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	2	7	10	11	14
Average head (m)	0	173	255	220	184	303	280
Average energy storage (GWh)	0	1	1	1	1	3	7
Total energy storage (GWh)	0	1	1	9	11	31	94

[22]

[22] The only PHS in Ireland was down for refurbishment during the entire year 2011, therefore the lack of 2011 generation

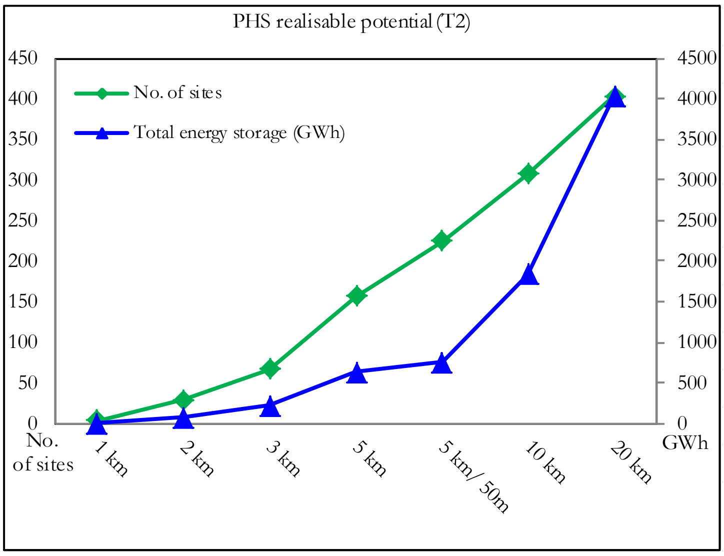
Italy

Eurostat data for 2011	GWh
Net electricity production	291 441
Net production natural hydro	47 201
Net production from PHS	2 539
Net production from wind	9 775
Net production from solar	10 668
Total variable RES electricity	20 443
PHS generation capacity (MW)	7 544
Conventional hydro generation capacity (MW)	21 737

Total PHS energy storage capacity	*No data*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	502
Of which capacity is inc.	462
Total capacity (Hm^3)	61 414
No. of reservoirs selected	436
Capacity of selected reservoirs (Hm^3)	61 413



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	2	10	27	54		179	497
Average head (m)	225	301	397	424		470	565
Average energy storage (GWh)	2	1	3	4		4	4
Total energy storage (GWh)	3	11	85	218		661	1 867

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	3	7	17		48	225
Average head (m)	292	557	375	446		456	589
Average energy storage (GWh)	3	2	1	2		2	3
Total energy storage (GWh)	3	5	6	35		99	670

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	7	53	113	240	320	381	428
Average head (m)	184	255	335	422	332	558	807
Average energy storage (GWh)	1	2	3	5	4	9	16
Total energy storage (GWh)	9	118	382	1 183	1 345	3 280	6 846

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	4	29	67	157	225	307	404
Average head (m)	192	266	306	355	269	465	670
Average energy storage (GWh)	1	3	3	4	3	6	10
Total energy storage (GWh)	1	78	213	633	758	1 833	4 034

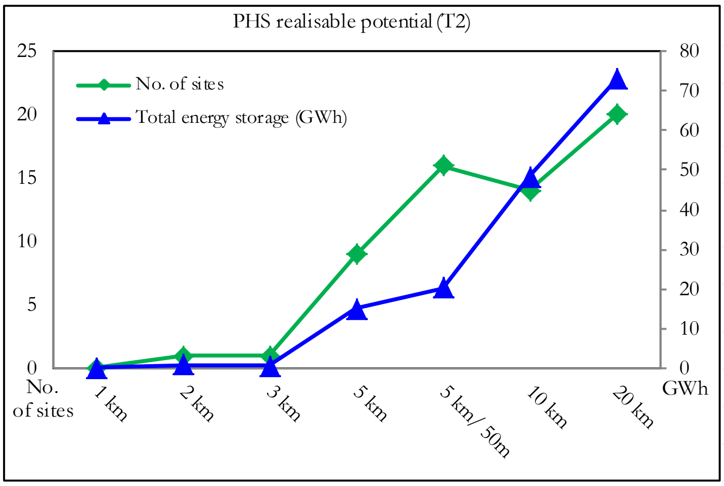
Eurostat data for 2011	GWh
Net electricity production	148 891
Net production natural hydro	2 735
Net production from PHS	422
Net production from wind	3 205
Net production from solar	0
Total variable RES electricity	3 205
PHS generation capacity (MW)	1 406
Conventional hydro generation capacity (MW)	2 346

Poland

Total PHS energy storage capacity	*11*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	41
Of which capacity is inc.	41
Total capacity (Hm^3)	2 980
No. of reservoirs selected	41
Capacity of selected reservoirs (Hm^3)	2 980



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	2	5	12	20	20	28
Average head (m)	0	173	191	238	166	251	415
Average energy storage (GWh)	0	1	1	2	2	6	13
Total energy storage (GWh)	0	2	6	19	47	111	350

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	1	9	16	14	20
Average head (m)	0	175	153	252	183	238	240
Average energy storage (GWh)	0	1	1	2	1	3	4
Total energy storage (GWh)	0	1	1	15	20	48	73

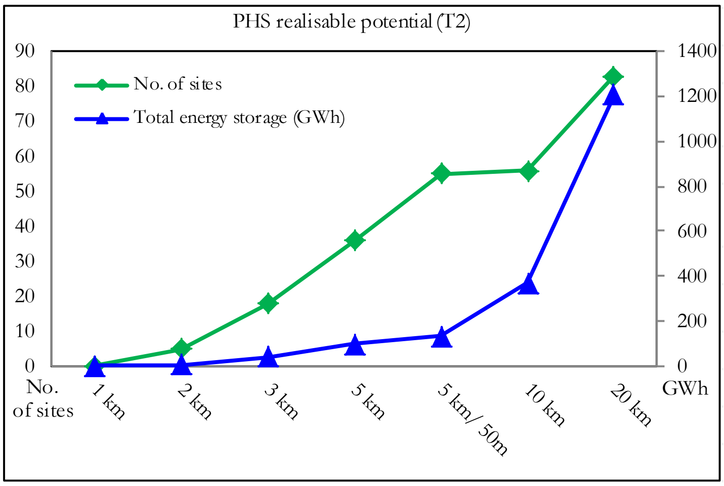
Portugal

Eurostat data for 2011	GWh
Net electricity production	51 124
Net production natural hydro	11 987
Net production from PHS	564
Net production from wind	9 102
Net production from solar	277
Total variable RES electricity	9 379
PHS generation capacity (MW)	1 029
Conventional hydro generation capacity (MW)	5 551

Total PHS energy storage capacity	*107*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	107
Of which capacity is inc.	103
Total capacity (Hm^3)	11 885
No. of reservoirs selected	102
Capacity of selected reservoirs (Hm^3)	11 885



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	3		15	40
Average head (m)	0	0	0	258		260	365
Average energy storage (GWh)	0	0	0	2		8	14
Total energy storage (GWh)	0	0	0	7		118	542

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		5	12
Average head (m)	0	0	0	0		214	302
Average energy storage (GWh)	0	0	0	0		6	5
Total energy storage (GWh)	0	0	0	0		29	60

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	16	33	55	75	68	87
Average head (m)	0	244	263	322	248	397	492
Average energy storage (GWh)	0	3	5	3	3	9	17
Total energy storage (GWh)	0	54	173	151	192	594	1 472

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	5	18	36	55	56	83
Average head (m)	0	218	250	303	228	372	438
Average energy storage (GWh)	0	2	2	3	2	7	15
Total energy storage (GWh)	0	8	43	99	133	372	1 209

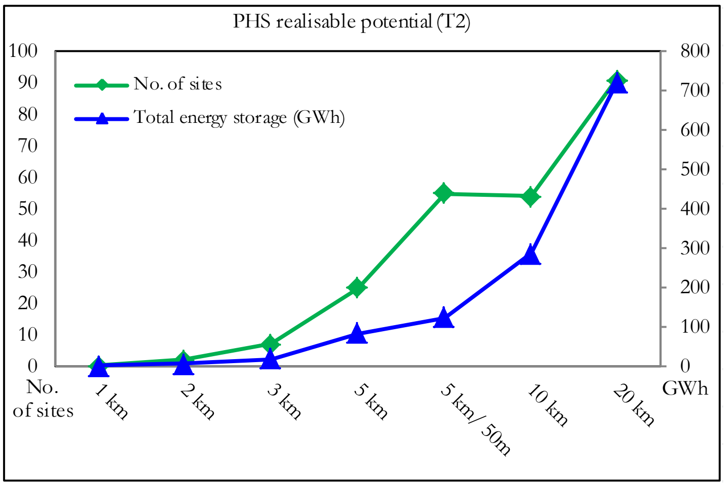
Eurostat data for 2011	GWh
Net electricity production	56 491
Net production natural hydro	14 788
Net production from PHS	218
Net production from wind	1 390
Net production from solar	0
Total variable RES electricity	1 390
PHS generation capacity (MW)	92
Conventional hydro generation capacity (MW)	6 483

Total PHS energy storage capacity	***No data***

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	126
Of which capacity is inc.	126
Total capacity (Hm^3)	7 264
No. of reservoirs selected	125
Capacity of selected reservoirs (Hm^3)	7 264

Romania



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		2	11
Average head (m)	0	0	0	0		226	331
Average energy storage (GWh)	0	0	0	0		2	4
Total energy storage (GWh)	0	0	0	0		3	44

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	4	13	41	74	73	103
Average head (m)	0	225	245	255	170	318	426
Average energy storage (GWh)	0	3	3	4	3	8	14
Total energy storage (GWh)	0	11	38	165	226	556	1 429

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	2	7	25	55	54	91
Average head (m)	0	295	217	245	154	258	327
Average energy storage (GWh)	0	3	3	3	2	5	8
Total energy storage (GWh)	0	7	18	83	124	286	719

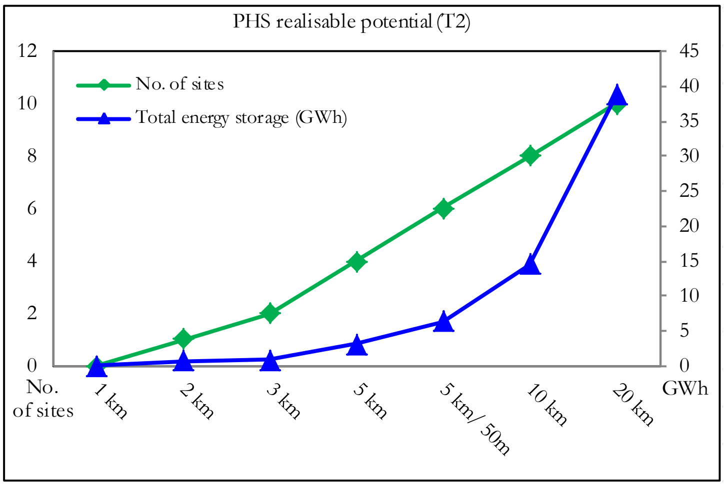
Eurostat data for 2011	GWh
Net electricity production	26 090
Net production natural hydro	3 579
Net production from PHS	368
Net production from wind	5
Net production from solar	397
Total variable RES electricity	402
PHS generation capacity (MW)	916
Conventional hydro generation capacity (MW)	2 523

Total PHS energy storage capacity	*4*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	11
Of which capacity is inc.	11
Total capacity (Hm^3)	266
No. of reservoirs selected	10
Capacity of selected reservoirs (Hm^3)	266

Slovakia



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	3	5	8	9	10
Average head (m)	0	169	192	206	151	352	496
Average energy storage (GWh)	0	1	1	1	1	3	5
Total energy storage (GWh)	0	1	4	6	11	23	46

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	2	4	6	8	10
Average head (m)	0	169	183	206	168	227	353
Average energy storage (GWh)	0	1	0	1	1	2	4
Total energy storage (GWh)	0	1	1	3	6	15	39

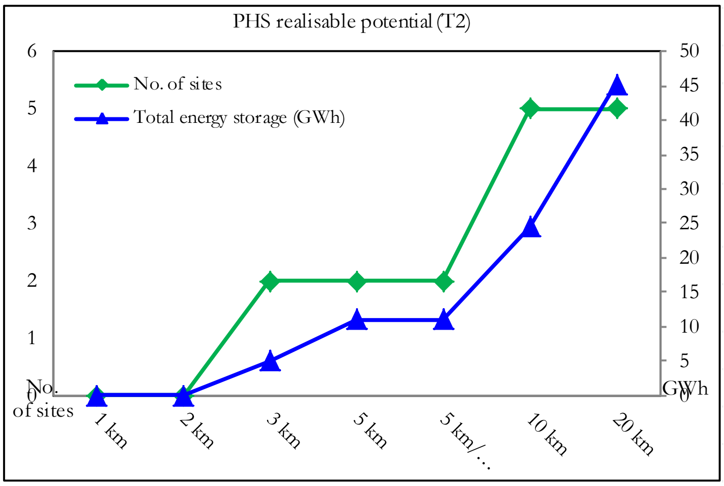
Eurostat data for 2011	GWh
Net electricity production	14 998
Net production natural hydro	3 646
Net production from PHS	143
Net production from wind	0
Net production from solar	66
Total variable RES electricity	66
PHS generation capacity (MW)	180
Conventional hydro generation capacity (MW)	1 253

Total PHS energy storage capacity	*No data*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	7
Of which capacity is inc.	6
Total capacity (Hm^3)	33
No. of reservoirs selected	6
Capacity of selected reservoirs (Hm^3)	33

Slovenia



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	2	3	4	5	6
Average head (m)	0	0	361	421	332	788	988
Average energy storage (GWh)	0	0	2	4	3	9	13
Total energy storage (GWh)	0	0	5	12	13	47	77

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	2	2	2	5	5
Average head (m)	0	0	361	512	512	575	642
Average energy storage (GWh)	0	0	2	5	5	5	9
Total energy storage (GWh)	0	0	5	11	11	25	45

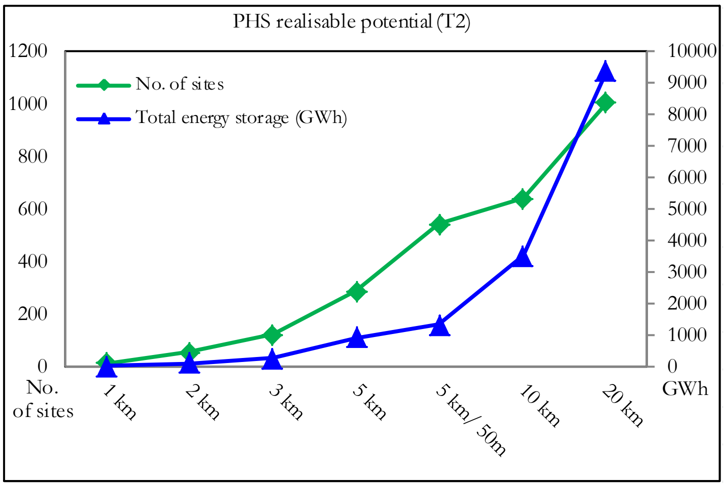
Eurostat data for 2011	GWh
Net electricity production	281 304
Net production natural hydro	32 345
Net production from PHS	2 275
Net production from wind	41 398
Net production from solar	8 561
Total variable RES electricity	49 959
PHS generation capacity (MW)	5 260
Conventional hydro generation capacity (MW)	18 540

Total PHS energy storage capacity	*1 530*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	1 425
Of which capacity is inc.	1 320
Total capacity (Hm^3)	64 718
No. of reservoirs selected	1 230
Capacity of selected reservoirs (Hm^3)	64 715

Spain



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	2	24	70	175		652	2 912
Average head (m)	181	263	276	293		371	513
Average energy storage (GWh)	0	1	2	2		2	2
Total energy storage (GWh)	0	34	132	292		1 182	5 788

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	3	9	32		165	1 305
Average head (m)	0	310	271	323		370	531
Average energy storage (GWh)	0	4	3	3		2	1
Total energy storage (GWh)	0	12	23	93		362	1 894

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	21	122	256	523	847	865	1 080
Average head (m)	204	256	271	323	230	435	618
Average energy storage (GWh)	1	2	3	4	4	8	16
Total energy storage (GWh)	28	264	676	2 096	3 192	7 235	17 596

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	11	54	121	286	544	639	1 005
Average head (m)	221	260	251	275	186	330	456
Average energy storage (GWh)	1	2	2	3	2	5	9
Total energy storage (GWh)	1	96	263	915	1 329	3 507	9 363

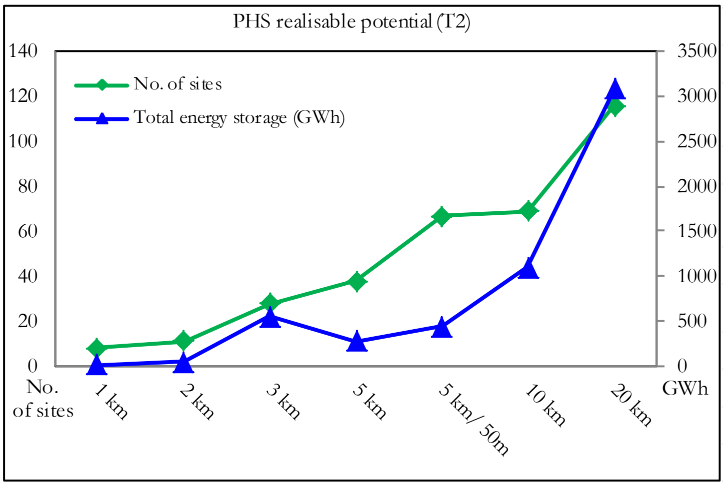
Eurostat data for 2011	GWh
Net electricity production	146 936
Net production natural hydro	66 169
Net production from PHS	122
Net production from wind	6 078
Net production from solar	11
Total variable RES electricity	6 089
PHS generation capacity (MW)	99
Conventional hydro generation capacity (MW)	16 478

Total PHS energy storage capacity	*No data*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	193
Of which capacity is inc.	182
Total capacity (Hm^3)	40 518
No. of reservoirs selected	148
Capacity of selected reservoirs (Hm^3)	40 518

Sweden



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		1	6
Average head (m)	0	0	0	0		222	209
Average energy storage (GWh)	0	0	0	0		22	8
Total energy storage (GWh)	0	0	0	0		22	51

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	1
Average head (m)	0	0	0	0		0	188
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	20	18	53	54	86	86	127
Average head (m)	301	199	292	237	175	317	493
Average energy storage (GWh)	14	5	28	12	15	46	80
Total energy storage (GWh)	278	84	1 468	661	1 319	3 963	10 160

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	8	11	28	38	67	69	116
Average head (m)	294	200	289	221	164	316	493
Average energy storage (GWh)	16	4	20	7	7	16	27
Total energy storage (GWh)	16	47	557	283	440	1 102	3 081

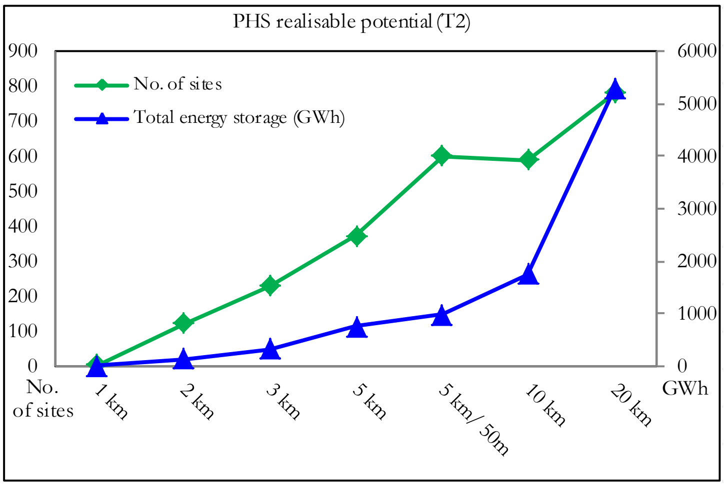
Eurostat data for 2011	GWh
Net electricity production	351 347
Net production natural hydro	8 545
Net production from PHS	2 895
Net production from wind	15 497
Net production from solar	252
Total variable RES electricity	15 749
PHS generation capacity (MW)	2 744
Conventional hydro generation capacity (MW)	4 420

Total PHS energy storage capacity	*33*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	1 528
Of which capacity is inc.	1 236
Total capacity (Hm^3)	8 256
No. of reservoirs selected	915
Capacity of selected reservoirs (Hm^3)	8 238

United Kingdom



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	5	16	68		561	3 264
Average head (m)	0	205	199	195		189	193
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	2	4	23		199	994

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	3	21		166	805
Average head (m)	0	0	226	192		197	201
Average energy storage (GWh)	0	0	0	0		1	1
Total energy storage (GWh)	0	0	0	4		106	501

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	10	185	330	457	648	633	804
Average head (m)	181	203	215	237	193	290	377
Average energy storage (GWh)	1	1	2	3	2	4	8
Total energy storage (GWh)	7	248	580	1 144	1 397	2 399	6 120

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	5	121	228	372	601	590	781
Average head (m)	186	201	213	228	176	255	391
Average energy storage (GWh)	1	1	1	2	2	3	7
Total energy storage (GWh)	1	141	330	750	981	1 749	5 292

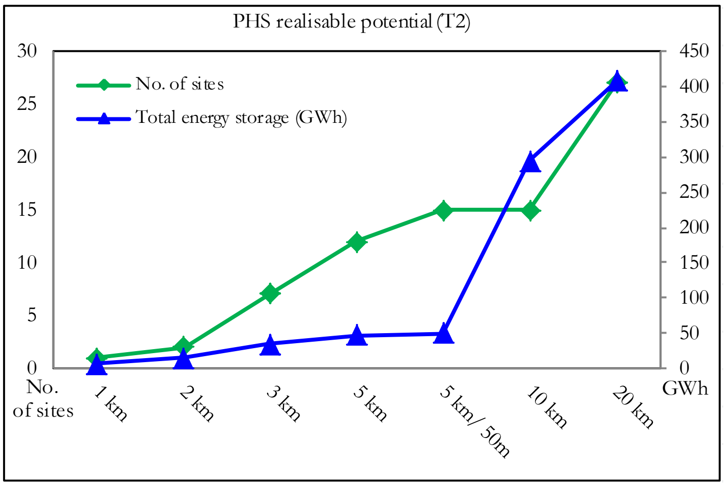
Eurostat data for 2010	GWh
Net electricity production	13 635
Net production natural hydro	8 325
Net production from PHS	106
Net production from wind	139
Net production from solar	0
Total variable RES electricity	139
PHS generation capacity (MW)	293
Conventional hydro generation capacity (MW)	2 141

Total PHS energy storage capacity	***No data***

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	29
Of which capacity is inc.	26
Total capacity (Hm^3)	1 014
No. of reservoirs selected	26
Capacity of selected reservoirs (Hm^3)	1 014

Croatia



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	1
Average head (m)	0	0	0	0		0	543
Average energy storage (GWh)	0	0	0	0		0	2
Total energy storage (GWh)	0	0	0	0		0	2

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	6	13	16	21	21	29
Average head (m)	159	188	222	310	241	452	581
Average energy storage (GWh)	6	3	3	4	8	23	25
Total energy storage (GWh)	6	18	42	64	160	486	719

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	2	7	12	15	15	27
Average head (m)	159	183	240	273	220	332	465
Average energy storage (GWh)	6	8	5	4	3	20	15
Total energy storage (GWh)	6	15	34	47	50	294	408

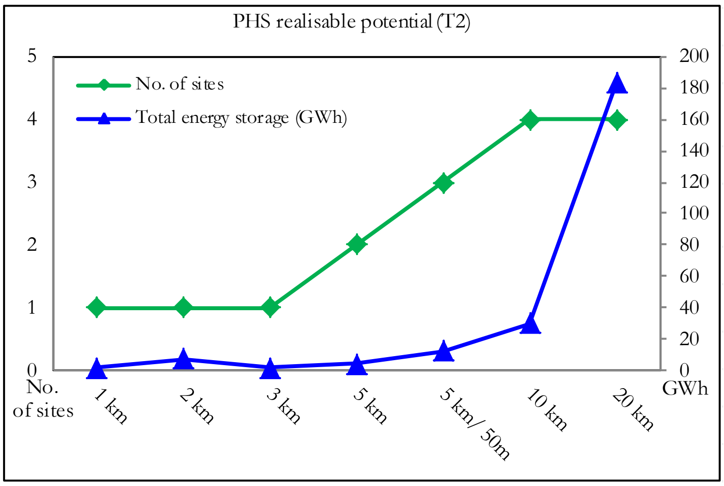
Eurostat data for 2011	GWh
Net electricity production	No data
Net production natural hydro	No data
Net production from PHS	No data
Net production from wind	No data
Net production from solar	No data
Total variable RES electricity	No data
PHS generation capacity (MW)	No data
Conventional hydro generation capacity (MW)	No data

Total PHS energy storage capacity	***No data***

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	9
Of which capacity is inc.	6
Total capacity (Hm^3)	921
No. of reservoirs selected	6
Capacity of selected reservoirs (Hm^3)	945

Iceland



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	1	1	2	4	6	6
Average head (m)	304	168	264	244	145	345	485
Average energy storage (GWh)	2	7	2	2	6	61	36
Total energy storage (GWh)	2	7	2	4	25	367	218

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	1	1	2	3	4	4
Average head (m)	304	168	264	244	144	376	624
Average energy storage (GWh)	2	7	2	2	4	7	46
Total energy storage (GWh)	2	7	2	4	12	30	183

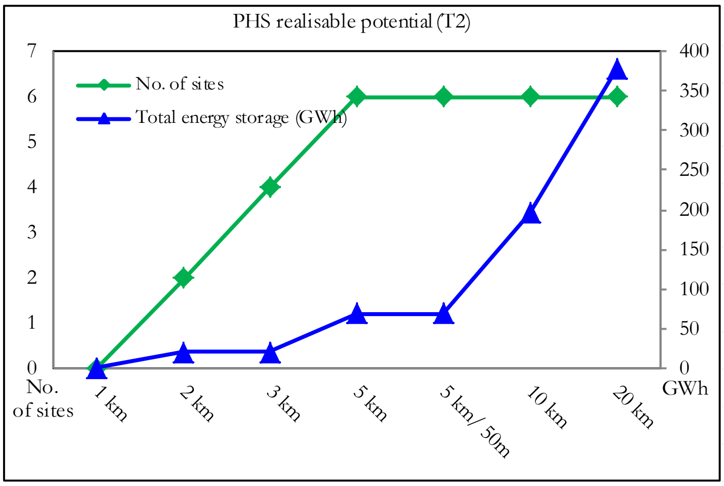
Eurostat data for 2011	GWh
Net electricity production	No data
Net production natural hydro	No data
Net production from PHS	No data
Net production from wind	No data
Net production from solar	No data
Total variable RES electricity	No data
PHS generation capacity (MW)	No data
Conventional hydro generation capacity (MW)	No data

Montenegro

Total PHS energy storage capacity	***No data***

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	6
Of which capacity is inc.	6
Total capacity (Hm^3)	1 052
No. of reservoirs selected	6
Capacity of selected reservoirs (Hm^3)	1 052



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	2	4	6	6	6	6
Average head (m)	0	552	338	428	428	558	734
Average energy storage (GWh)	0	10	6	32	32	105	161
Total energy storage (GWh)	0	20	25	190	190	633	966

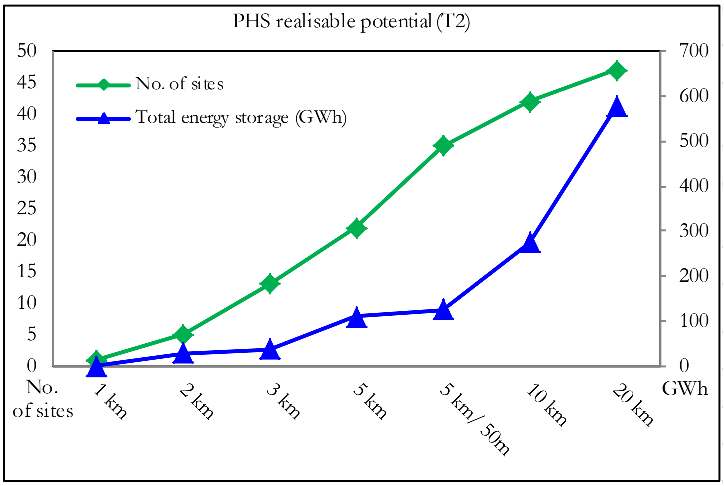
T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	2	4	6	6	6	6
Average head (m)	0	552	403	439	439	563	715
Average energy storage (GWh)	0	10	5	11	11	33	63
Total energy storage (GWh)	0	20	21	69	69	196	377

Eurostat data for 2011	GWh
Net electricity production	No data
Net production natural hydro	No data
Net production from PHS	No data
Net production from wind	No data
Net production from solar	No data
Total variable RES electricity	No data
PHS generation capacity (MW)	No data
Conventional hydro generation capacity (MW)	No data

Serbia

Total PHS energy storage capacity	***No data***

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)



Reservoir data (ECRINS)	
No. of reservoirs	69
Of which capacity is inc.	68
Total capacity (Hm^3)	7 778
No. of reservoirs selected	67
Capacity of selected reservoirs (Hm^3)	7 778

JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		1	15
Average head (m)	0	0	0	0		645	344
Average energy storage (GWh)	0	0	0	0		1	22
Total energy storage (GWh)	0	0	0	0		1	327

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	4
Average head (m)	0	0	0	0		0	414
Average energy storage (GWh)	0	0	0	0		0	66
Total energy storage (GWh)	0	0	0	0		0	265

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	7	17	26	39	46	51
Average head (m)	181	302	296	335	245	416	500
Average energy storage (GWh)	1	5	3	5	4	7	13
Total energy storage (GWh)	1	32	50	131	157	323	638

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	1	5	13	22	35	42	47
Average head (m)	181	309	299	352	247	405	486
Average energy storage (GWh)	1	6	3	5	4	7	12
Total energy storage (GWh)	1	29	37	109	125	274	577

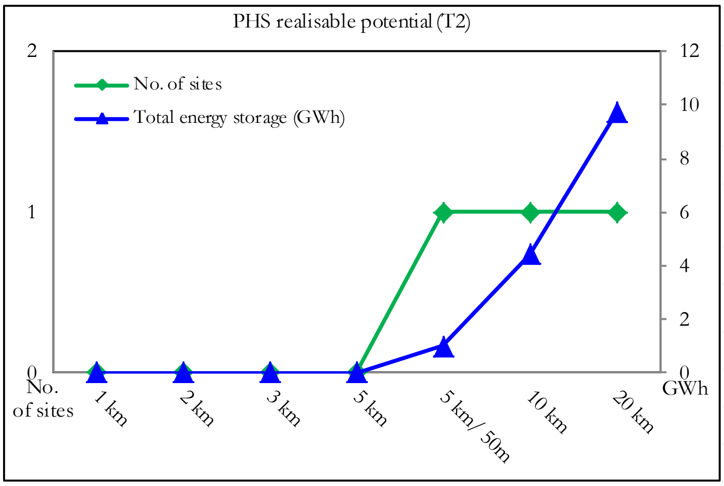
FYROM

Eurostat data for 2010	GWh
Net electricity production	6 827
Net production natural hydro	2 424
Net production from PHS	0
Net production from wind	0
Net production from solar	0
Total variable RES electricity	0
PHS generation capacity (MW)	0
Conventional hydro generation capacity (MW)	556

Total PHS energy storage capacity	*0*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	1
Of which capacity is inc.	1
Total capacity (Hm^3)	8
No. of reservoirs selected	1
Capacity of selected reservoirs (Hm^3)	8



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0	1	1	1
Average head (m)	0	0	0	0	82	331	492
Average energy storage (GWh)	0	0	0	0	1	4	10
Total energy storage (GWh)	0	0	0	0	1	4	10

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0	1	1	1
Average head (m)	0	0	0	0	82	331	492
Average energy storage (GWh)	0	0	0	0	1	4	10
Total energy storage (GWh)	0	0	0	0	1	4	10

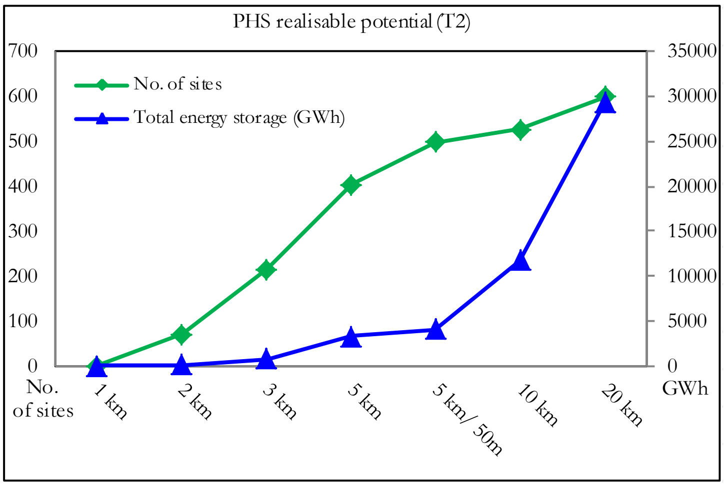
Turkey

Eurostat data for 2010	GWh
Net electricity production	203 046
Net production natural hydro	51 423
Net production from PHS	0
Net production from wind	2 908
Net production from solar	0
Total variable RES electricity	2 908
PHS generation capacity (MW)	0
Conventional hydro generation capacity (MW)	17 137

Total PHS energy storage capacity	*0*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	198
Of which capacity is inc.	194
Total capacity (Hm^3)	101 268
No. of reservoirs selected	193
Capacity of selected reservoirs (Hm^3)	101 268



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	1	1	5		37	188
Average head (m)	0	193	193	277		267	276
Average energy storage (GWh)	0	24	24	7		117	196
Total energy storage (GWh)	0	24	24	36		4 319	36 793

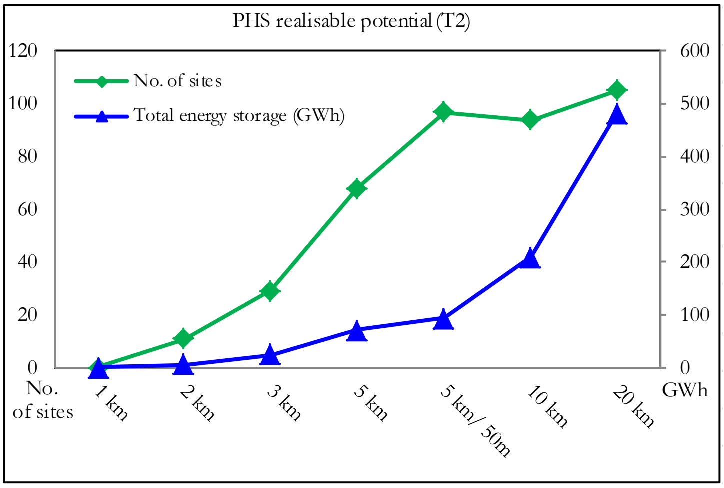
T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	3		9	86
Average head (m)	0	0	0	344		288	254
Average energy storage (GWh)	0	0	0	1		1	228
Total energy storage (GWh)	0	0	0	4		13	19 631

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	2	88	256	449	551	565	607
Average head (m)	163	207	227	284	219	385	483
Average energy storage (GWh)	1	2	4	9	9	26	68
Total energy storage (GWh)	3	154	901	3 936	5 055	14 821	41 412

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	2	72	216	404	498	527	600
Average head (m)	163	204	231	285	227	393	485
Average energy storage (GWh)	1	2	4	8	8	22	49
Total energy storage (GWh)	1	130	783	3 338	4 105	11 811	29 319

Eurostat data for 2011	GWh
Net electricity production	No data
Net production natural hydro	No data
Net production from PHS	No data
Net production from wind	No data
Net production from solar	No data
Total variable RES electricity	No data
PHS generation capacity (MW)	No data
Conventional hydro generation capacity (MW)	No data

Albania



Total PHS energy storage capacity	***No data***

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	205
Of which capacity is inc.	204
Total capacity (Hm^3)	4 442
No. of reservoirs selected	196
Capacity of selected reservoirs (Hm^3)	4 441

JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	10		65	422
Average head (m)	0	0	0	259		309	383
Average energy storage (GWh)	0	0	0	1		1	7
Total energy storage (GWh)	0	0	0	11		47	3 152

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	5		46	339
Average head (m)	0	0	0	260		317	374
Average energy storage (GWh)	0	0	0	2		1	8
Total energy storage (GWh)	0	0	0	8		37	2 580

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	11	34	68	98	94	105
Average head (m)	0	240	313	396	298	625	1 014
Average energy storage (GWh)	0	1	1	1	1	2	6
Total energy storage (GWh)	0	6	26	72	117	220	651

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	11	29	68	97	94	105
Average head (m)	0	240	294	377	288	617	1 010
Average energy storage (GWh)	0	1	1	1	1	2	5
Total energy storage (GWh)	0	6	24	71	93	210	481

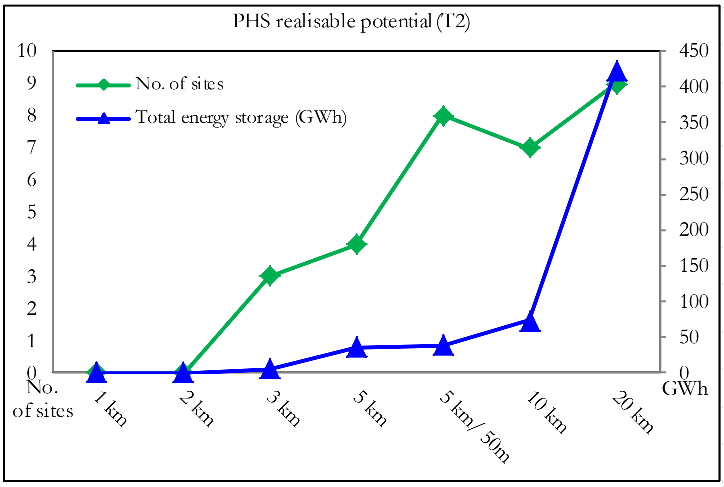
Bosnia and Herzegovina

Eurostat data for 2011	GWh
Net electricity production	No data
Net production natural hydro	No data
Net production from PHS	No data
Net production from wind	No data
Net production from solar	No data
Total variable RES electricity	No data
PHS generation capacity (MW)	No data
Conventional hydro generation capacity (MW)	No data

Total PHS energy storage capacity	***No data***

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	9
Of which capacity is inc.	9
Total capacity (Hm^3)	1 314
No. of reservoirs selected	9
Capacity of selected reservoirs (Hm^3)	1 314



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	1
Average head (m)	0	0	0	0		0	185
Average energy storage (GWh)	0	0	0	0		0	1
Total energy storage (GWh)	0	0	0	0		0	1

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	3	4	8	7	9
Average head (m)	0	0	317	656	379	665	769
Average energy storage (GWh)	0	0	2	9	5	10	48
Total energy storage (GWh)	0	0	6	36	39	73	430

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	3	4	8	7	9
Average head (m)	0	0	317	656	379	665	722
Average energy storage (GWh)	0	0	2	9	5	10	47
Total energy storage (GWh)	0	0	6	36	39	73	424

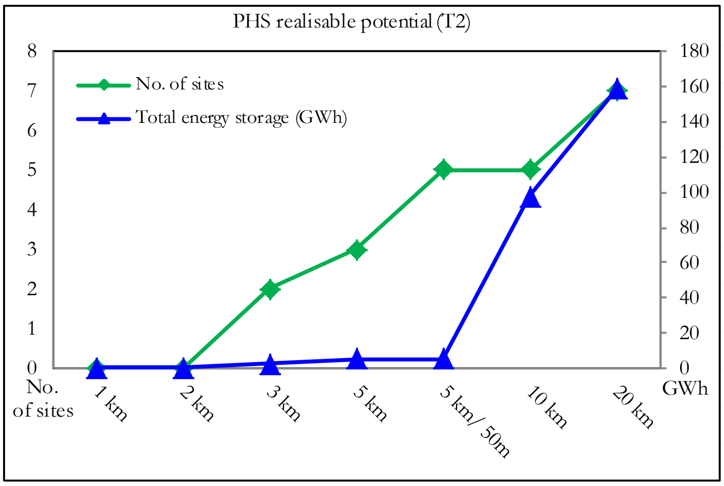
Eurostat data for 2011	GWh
Net electricity production	No data
Net production natural hydro	No data
Net production from PHS	No data
Net production from wind	No data
Net production from solar	No data
Total variable RES electricity	No data
PHS generation capacity (MW)	No data
Conventional hydro generation capacity (MW)	No data

Kosovo

Total PHS energy storage capacity	***No data***

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	7
Of which capacity is inc.	7
Total capacity (Hm^3)	556
No. of reservoirs selected	7
Capacity of selected reservoirs (Hm^3)	556



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	0	0		0	0
Average head (m)	0	0	0	0		0	0
Average energy storage (GWh)	0	0	0	0		0	0
Total energy storage (GWh)	0	0	0	0		0	0

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	2	3	5	5	7
Average head (m)	0	0	273	236	189	409	508
Average energy storage (GWh)	0	0	1	2	1	21	23
Total energy storage (GWh)	0	0	2	6	7	107	159

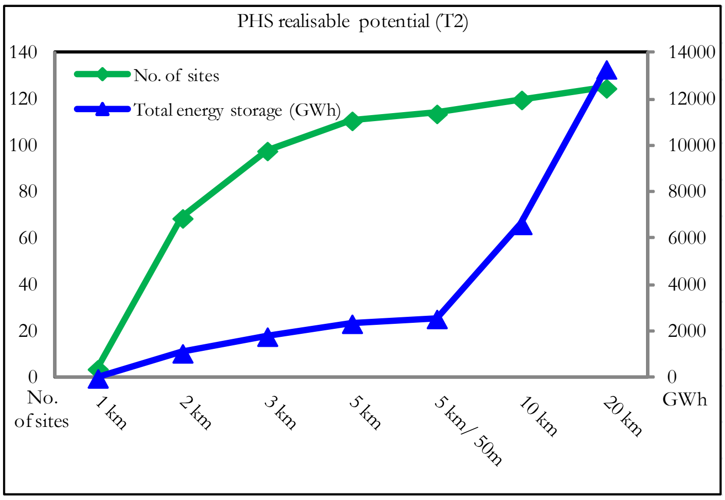
T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	2	3	5	5	7
Average head (m)	0	0	273	241	177	426	500
Average energy storage (GWh)	0	0	1	2	1	19	23
Total energy storage (GWh)	0	0	2	5	6	97	158

Eurostat data for 2010	GWh
Net electricity production	123 071
Net production natural hydro	116 946
Net production from PHS	406
Net production from wind	895
Net production from solar	0
Total variable RES electricity	895
PHS generation capacity (MW)	1 326
Conventional hydro generation capacity (MW)	29 693

Total PHS energy storage capacity	*11 000*

(Source: personal communication from SINTEF Energy Research)

Norway



Reservoir data (ECRINS)	
No. of reservoirs	141
Of which capacity is inc.	129
Total capacity (Hm^3)	15 305
No. of reservoirs selected	127
Capacity of selected reservoirs (Hm^3)	15 305

JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	1	6		29	81
Average head (m)	0	0	188	251		301	348
Average energy storage (GWh)	0	0	5	6		11	12
Total energy storage (GWh)	0	0	5	33		332	991

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	0	1	2		24	62
Average head (m)	0	0	188	240		290	324
Average energy storage (GWh)	0	0	5	8		9	12
Total energy storage (GWh)	0	0	5	17		212	747

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	6	89	111	123	125	126	126
Average head (m)	183	350	383	421	401	582	763
Average energy storage (GWh)	3	19	24	26	27	68	132
Total energy storage (GWh)	18	1 702	2 621	3 218	3 398	8 578	16 597

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	4	69	98	111	114	120	125
Average head (m)	177	340	387	411	385	560	718
Average energy storage (GWh)	3	16	18	21	23	55	107
Total energy storage (GWh)	3	1 084	1 802	2 356	2 566	6 616	13 315

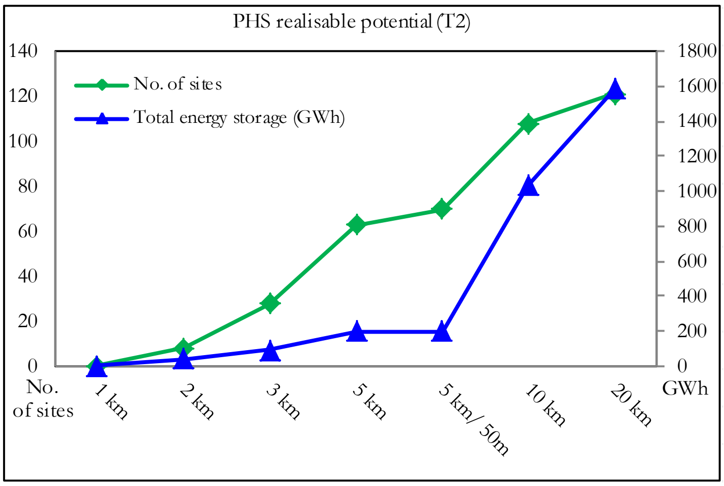
Switzerland

Eurostat data for 2010	GWh
Net electricity production	66 137
Net production natural hydro	37 450
Net production from PHS	1 746
Net production from wind	37
Net production from solar	83
Total variable RES electricity	120
PHS generation capacity (MW)	1 817
Conventional hydro generation capacity (MW)	13 720

Total PHS energy storage capacity	*369*

(Source: Eurelectric's *Hydro in Europe: Powering renewables*)

Reservoir data (ECRINS)	
No. of reservoirs	159
Of which capacity is inc.	148
Total capacity (Hm^3)	3 738
No. of reservoirs selected	124
Capacity of selected reservoirs (Hm^3)	3 737



JRC assessment

T1 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	4	8	22		66	243
Average head (m)	0	331	379	498		502	521
Average energy storage (GWh)	0	5	4	2		7	7
Total energy storage (GWh)	0	18	31	42		431	1 656

T1 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	2	6	12		38	185
Average head (m)	0	340	398	536		515	536
Average energy storage (GWh)	0	5	4	2		7	8
Total energy storage (GWh)	0	10	23	28		256	1 437

T2 - theoretical potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	11	34	68	76	109	121
Average head (m)	0	340	428	583	526	806	1 024
Average energy storage (GWh)	0	4	4	3	3	10	14
Total energy storage (GWh)	0	48	128	226	232	1 060	1 645

T2 - realisable potential	1 km	2 km	3 km	5 km	5 km/ 50m	10 km	20 km
No. of sites	0	8	28	63	70	108	121
Average head (m)	0	344	418	581	529	796	1 009
Average energy storage (GWh)	0	5	3	3	3	10	13
Total energy storage (GWh)	0	42	94	197	202	1 034	1 583

European Commission
EUR 25940 – Joint Research Centre – Institute for Energy and Transport

Title: Assessment of the potential for European pumped hydropower storage

Authors: Marcos Gimeno Gutiérrez and Roberto Lacal Arántegui

Luxembourg: Publications Office of the European Union

2013 – 74 pp. – 21.0 x 29.7 cm

EUR – Scientific and Policy Reports series - ISSN 1831-9424 (online), ISSN 1018-5593 (print)

ISBN 978-92-79-29511-9 (pdf)
ISBN 978-92-79-29512-6 (print)

doi:10.2790/86815

Abstract

This report presents the results of the assessment for PHS in Europe under certain topologies and scenarios. The results show that the theoretical potential in Europe is significant. We studied two different topologies. Under topology 1 the theoretical potential energy stored reaches 54 TWh for a maximum of 20 km between existing reservoirs; of this potential approximately 11 TWh correspond to the EU and 37 TWh to candidate countries. Under topology 2 the European theoretical potential reaches 123 TWh when the distance between the existing reservoir and the prospective site is up to 20 km. Unlike topology 1, in topology 2 the majority of this potential (50%) lays within the EU.
The realisable potential accounts for reduced potential sites too close to a centre of population, protected natural areas or transport infrastructure. For topology 1 and scenario 20 km the realisable potential is halved to 29 TWh, whereas topology 2 is slightly less affected and still reaches 80 TWh of which 33 TWh in the EU.

LD-NA-25940-EN-N

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new standards, methods and tools, and sharing and transferring its know-how to the Member States and international community.

Key policy areas include: environment and climate change; energy and transport; agriculture and food security; health and consumer protection; information society and digital agenda; safety and security including nuclear; all supported through a cross-cutting and multi-disciplinary approach.

Publications Office

ISBN 978-92-79-29511-9

9 789279 295119