



J R C T E C H N I C A L R E P O R T S

SETIS expert workshop on the assessment of the potential of pumped hydropower storage

Petten, the Netherlands, 2nd and 3rd April 2012

Organised on behalf of SETIS by the Energy Systems Evaluation Unit, Institute for Energy and Transport, Joint Research Centre.

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2012

Report EUR 25367 EN

Joint
Research
Centre

European Commission
Joint Research Centre
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JRC71928

EUR 25367 EN

ISBN 978-92-79-25151-1 (print)
ISBN 978-92-79-25150-4 (pdf)

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

doi:10.2790/53924 (online)

Luxembourg: Publications Office of the European Union, 2012

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1 Introduction

Energy storage is one of three main options to enable a higher share of variable renewable electricity such as wind and solar, in the energy system the other two being improved interconnections and more flexible conventional power generation plants. Pumped hydropower storage (PHS) is currently the only storage technology able to provide the large storage needed for accommodating renewable electricity under the 2020 EU energy targets. Moreover, the transformation of an existing water reservoir into a PHS facility has a much smaller environmental and social impact compared with most new hydropower plant in Europe.

During last year, the JRC collaborated with University College Cork (UCC) in Ireland to develop a GIS-based tool that can be used to identify the potential for transforming single reservoirs into PHS systems, and the associated benefits in terms of energy storage of the identified PHS facilities.

This GIS-based tool has the potential for effective and efficient identification of both national and EU-wide potentials (which is of interest to policy makers and to the scientific community) and of individual candidate sites (of interest to project developers and national authorities). Once the model is set up, improvements, e.g. allowing better sensitivity analysis, could be effectively applied with minimum effort. The methodology has been published as a JRC report¹ and already been applied to Croatia and Turkey as case studies.

As a follow-up to the report, the JRC organised an expert workshop whose main objectives were to:

- Validate the JRC methodology and model by a multi-disciplinary expert group. An expected outcome was a set of recommendations for the improvement of the effectiveness and efficiency of the methodology, focusing on the approach followed, software used and data sources, multi-criteria elements, costing methodology, sensitivity analysis and envisaged output.
- Address the issue of data availability in the Member States and their collection, since the JRC intention is to apply the methodology to the EU, Norway and Switzerland, once validated.
- Share and disseminate the methodology among relevant stakeholders, such as policy makers, industry, research, etc.

The workshop addressed the following:

- Presentations of five relevant studies followed by discussion:
 - [*The JRC/UCC methodology*](#) by Dr. Paul Leahy
 - [*Locating sites for PHEs*](#) by Dr. David Connolly
 - [*Identification of potential PHS sites in large areas based on a multi-criteria GIS-model*](#) by Dr. Peter Vennemann
 - [*GIS-based, small-size PHS potential in the French department Alpes Maritimes*](#), by Mr. Matthieu Pauwels
 - [*Site assessment for the German region of Thuringia*](#), by Dr. Stefan Schmid
 - [*Principles and issues to incorporate a costing methodology*](#) by Mr. Roberto Lacal Arántegui
- Discussions covering the following topics:
 - Energy, methodological aspects
 - GIS aspects
 - Environmental, social, spatial planning aspects
 - Economic aspects

¹ “Pumped-hydro energy storage: potential for transformation from single dams” JRC scientific and technical report EUR 25239 EN, ISBN 978-92-79-23182-7, available at <http://setis.ec.europa.eu/newsroom-items-folder/report-pumped-hydro-energy-storage-potential-for-transformation-from-single-dams>

This report is a summary of the discussions which took place during the workshop, of the opinions and proposals put forward by the experts. It also includes recommendations and sources of data which could be used by any individual or organisation aiming at assessing the potential for pumped hydropower storage by using a GIS-based approach.

The following experts took part in the SETIS expert workshop:

- Dr Manjola Banja, Detached National Expert, Renewable Energy Unit, Institute for Energy and Transport, Joint Research Centre, European Commission.
- Dr Andrei Bocin-Dumitriu, GIS expert, Energy Systems Evaluation Unit, Institute for Energy and Transport, Joint Research Centre, European Commission.
- Mr Emmanuel Branche, Senior Engineer Economist, Generation & Engineering, EDF.
- Dr David Connolly, Assistant Professor, Department of Development and Planning, Aalborg University.
- Mr Luigi Debarberis, Scientific Officer, Energy Security Unit, Institute for Energy and Transport, Joint Research Centre, European Commission.
- Dr Neven Duic, Head of Power Engineering and Energy Management Chair, Department of Energy, Power Engineering and Environment, University of Zagreb.
- Mr Gregory Fayet, Research Project Manager on the economics of storage, EDF R&D.
- Mr Gianluca Fulli, Scientific Officer, Energy Security Unit, Institute for Energy and Transport, Joint Research Centre, European Commission.
- Dr Hans-Christoph Funke, Head of Development International & Engineering, Hydro Power & New Technologies, RWE Innogy GmbH.
- Mr François Halgand, Project Director, TRACTEBEL Engineering / GDF Suez.
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- Dr Andreas Hutarew, CEO, Dr. Hutarew & Partner International.
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- Mr Roberto Lacal Arantegui, Scientific Officer, Energy Systems Evaluation Unit, Institute for Energy and Transport, Joint Research Centre, European Commission.
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- Dr Paul Leahy, Lecturer in Wind Energy, School of Engineering, University College Cork.
- Mr Xavier Mayau, Project Director, ISL Ingénierie.
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- Mr Markus Pflieger, Technical Planning and Operational Control, Verbund Hydro Power, Verbund.
- Dr Patrick Schaefer, Project Manager, Renewable Energies and Environment, Fichtner GmbH & Co. KG.
- Dr. Stefan Schmid, GIS expert, Hydraulic Engineering Unit, Hydroprojekt Ingenieurgesellschaft mbH.
- Dr Klaus Schneider, Technische Grundsatzfragen, Schluchseewerk AG.
- Mr Olivier Teller, Product Director Pumped (Hydro) Storage Plants, Renewable Power – Hydro Global R&D and Product Management, Alstom.
- Mr Vangelis Tzimas, Action Leader, Energy Systems Evaluation Unit, Institute for Energy and Transport, Joint Research Centre, European Commission.
- Dr Constantinos Varnavas, Assistant Manager, Generation, Electricity Authority of Cyprus.
- Dr Peter Vennemann, Head of Hydropower Mechanical & Electrical Engineering, RWE Power AG.
- Ms Annicka Wänn, Researcher – stoRE project, University College Cork.
- Dr Alyona Zubaryeva, GIS expert, Energy Systems Evaluation Unit, Institute for Energy and Transport, Joint Research Centre, European Commission.

2 Area 1: methodological aspects

Summary of the “Energy” group² discussions

The effectiveness of an assessment of the potential for PHS of a certain area is considered to be intrinsically linked to a definition of “potential”. Experts agreed that the broad definition of a theoretical PHS potential for a site should be expressed in terms of storage volume and head. Generally, two types of PHS potential could be defined: storage capacity potential (as proposed by JRC-IET), expressed as the gigawatt-hours that would be produced from using only once the maximum water stored in the upper reservoir; and annual storage potential or the result of assuming a number of full pump/storage cycles throughout the year in the identified site. In terms of the former one, in addition to the topologies (A and B) chosen for the assessment by the JRC-IET model, the recommendation is to include not only existing or partly existing sites, but also extend the methodology for the identification of new ones. The evaluation of a potential within the methodology proposed by JRC-IET should follow a 3-step procedure³: i) selection based on the topography of an area; ii) screening based on a list of criteria; iii) assessment of an economic potential.

The first step of broad site **selection** (theoretical potential assessment) could be based on *topography* via usage of digital elevation model data. In this case, experts commented that flatness criteria were too restrictive within the JRC model if the model is going to detect depressions and valleys, while they felt that such an important criterion should not be included in the list of no-go criteria. Other parameters to be included at an initial evaluation stage are the *distance between the two reservoirs, head (or elevation difference between the reservoirs), head/distance ratio, water availability and storage volume*.

The second step of the assessment methodology – **screening** – should include a list of criteria. “No-go” criteria or the areas which could be excluded from further analysis should at least include residential areas; however, a common opinion was that there should not be many restrictive criteria as for example flatness, geology of an area or nature protected areas as based on regional conditions all of them can be considered for the further PHS potential analysis. The recommendation of experts was to include a system of ranking or filtering for *environmental, geological, inflow analysis, flatness, and social* (i.e. risk assessment, drinking water reservoirs) criteria, where based on expert judgement and regional conditions each of these criteria would obtain a certain weighting. Examples were given for the areas where the predominant geological type is for instance karst formations. While in many models this type of formation would be given a no-go status due to the heavy financial commitments necessary to develop PHS in such areas, experts recommended not to exclude them but to assign them with a low weighting in the filtering process.

The third step of proposed methodological improvements would include evaluation of **economic** considerations linked to energy potential. These among others would include the cost thresholds (i.e. next technology available). This was also addressed in a dedicated group for economic aspects. Energy group experts proposed to include in this step the recommendations given by the economics experts group.

Overall, it was suggested to develop different scenarios: most restrictive scenario, where all possible restrictions and no-go areas are employed, least restrictive and medium restrictive. Care should be taken so that steps 1 and 2 are not too restrictive as to leave room for only extremely costly sites. This approach would assist in taking into account of regional differences both in physical potential and regulatory framework.

² Group 1 “Energy”: Michael Heiland (chair), Markus Pflieger, Neven Duic, Gregory Fayet, François Halgand, Eppie Pelgrum, Peter Vennemann, Alyona Zubaryeva (rapporteur)

³ Aspects of each step are present in the others. For example, a multi-criteria table comparing head and distance between reservoirs already takes into account that the higher the head and the shorter the distance the cheaper the cost of energy (through less round-cycle losses)

Step 1 - site selection

The topologies of PHS whose potential can be assessed include:

- Topology 1 - linking two existing reservoirs with a penstock, and add a powerhouse to transform them to a PHS scheme.
- Topology 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 area (by digging or building shallow dams), on a depression or on a valley.
- Topology 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.
- Topology 4 - a greenfield PHS that uses the sea as the lower reservoir and a new nearby reservoir.
- Topology 5 - multi-reservoir systems including both PHS and conventional hydropower.
- Topology 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.
- Topology 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 case. An example is the old coal mine of As Pontes, in Spain⁴.

It was recommended that the JRC methodology should not focus only on topologies 1 and 2 because “the impact of a pumped storage scheme on existing reservoirs is often more difficult to handle than the impact of building new reservoirs. Upgrade sites with existing reservoirs shall be considered by means of a weighed secondary criterion, so that they move up in the ranking”

Four different scopes of the assessment were identified: (a) national/supranational; (b) region; (c) county; and (d) electricity system. A brief description follows:

- a) A national/supranational scope aims at assessing the potential of a country or group of countries. Its purpose tends to be scientific research and/or support to the policy decision-making processes.
- b) A region/province scope aims at identifying sites and their potential energy storage in an area which is under a single spatial planning authority, and for the purpose of spatial planning. Note that the term “regional” is not used in order to avoid confusion with “a cluster of neighbouring countries”.
- c) A county (or similar) scope is a detailed assessment of a part of a region/province which aims at identifying the most suitable site for a given project or a cluster of projects. It can be used for site assessment as part of a single PHS project design.
- d) An electricity-system scope assesses the electricity system seeking to identify where storage (PHS in this case) is or will be needed for grid management purposes.

The boundaries between scopes are not rigid.

The methodology proposed for the national and region scope is based on a GIS application digital elevation model (DEM, see below) one of whose main characteristic, resolution, should depend on the scope. To this DEM other elements (e.g. a GIS layer containing the description of the use of the land or where human populations are located) could be added either in all cases, or in some cases

⁴ See <http://www.endesa.com/es/conoceendesa/lineasnegocio/principalesproyectos/Paginas/AsPontes.aspx>

depending on the scope. For the county and electricity-system scopes other software than GIS-based might be more appropriate. Because the assessment of PHS potential depends on the topology under study, in all cases the topology influences the decision on which geographical, physical or social elements could or should be added as GIS layers.

The assessment should provide figures of storage volume in terms of energy, e.g. in GWh. Depending on the scope it should also provide capacity-time information i.e. the sum of MW of turbine capacity of the proposed sites and the number of hours that would take to empty the proposed sites. In all cases an attempt should be made to take adequate account of the non-usable water volume (because of an existing dam having another use such as irrigation, because of environmental considerations –minimum water levels-, etc.), net head (as opposite to gross head)

Step 2 - screening

The screening step needs to be flexible to account for national and regional differences, ranges of power and other aspects. This could be achieved through a menu allowing the user to assign the different criteria as “exclusion” (also called “no-go”) areas, or “ranking”, which will not exclude sites but rank them according to the criteria.

The distance between both reservoirs and the head difference should be used as a single parameter (multi-criteria) for site selection.

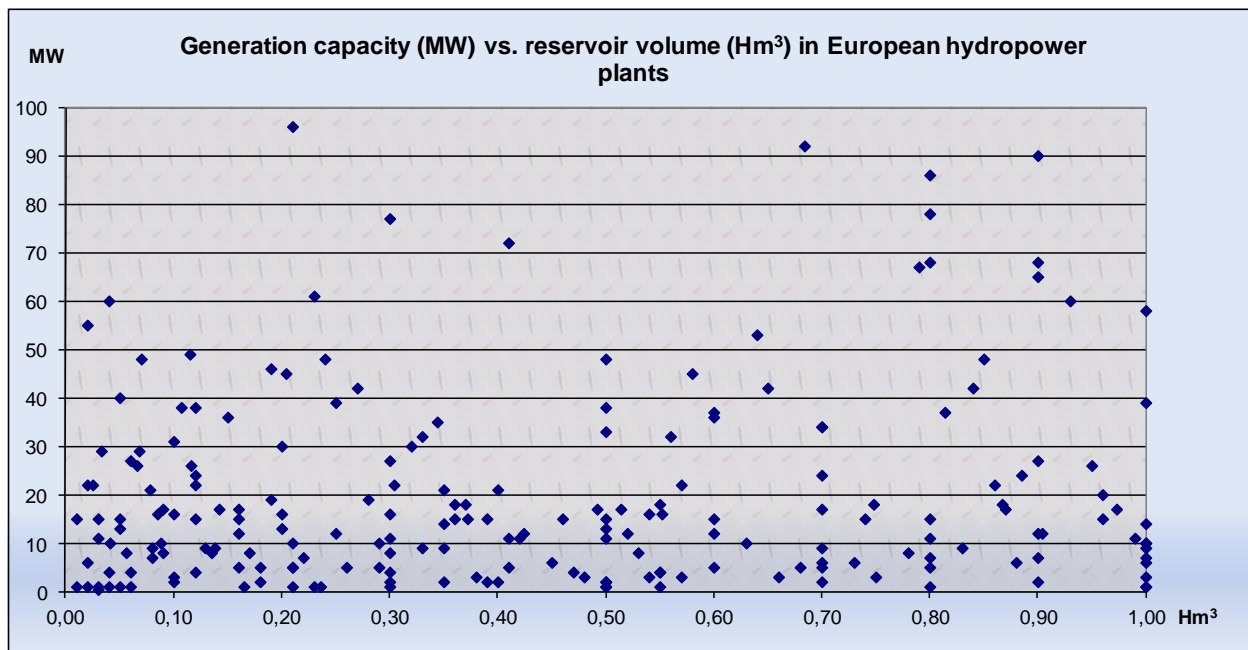


Figure 1: Comparison of hydropower generation capacity vs. reservoir capacity in European hydropower plant below 1 Hm³. Source: JRC.

The following criteria were discussed:

- 1) Minimum size of existing reservoir. The equivalence of a reservoir capacity of one million m³ (1 Hm³) or 1 MW of hydropower installed capacity as the threshold for inclusion of existing reservoirs under topologies 1 and 2 was considered inappropriate. In effect, many reservoirs with less than 1 Hm³ of water capacity yield much higher hydropower capacities than 1 MW, as shown in figure 1. Therefore it is proposed that initial thresholds should be variable depending on the scope, and generally from 0.05 to 1 Hm³ and from 1 to 10 MW”.
- 2) Maximum size of the new reservoir. When the new reservoir is the upper reservoir, its usable volume is limited by the usable water in the lower reservoir. If the latter is an existing reservoir, water currently used for other purposes should be taken into account as well as the environmental impact of a changing shore level.

This could be remedied by importing ICOLD's "reservoir purpose" field into the GIS and taking it into appropriate consideration. A maximum draw-down limit could be imposed on drinking water and irrigation reservoirs.

- 3) Distance between the two reservoirs. A 5-km horizontal distance between the two reservoirs is too restrictive and 20 km is a more sensible figure depending on the difference in elevation. Those distances could be measured as from the coordinates of the dam. See the GIS section below.
- 4) Head. It was proposed to use a minimum head between 20 and 200 m depending on the scope of the assessment. The head range could extend from 20 to 1500 m in order to avoid excluding any possible sites. For example, the recent PHS project Baixo Sabor Jusante in Portugal has a minimum head of only 26 m.

Box 1: the view of the designers.
- 5) Surface gradient. The evaluation of the surface gradient is made e.g. through the slope function of a GIS application, and depends on the scope of the assessment. An alternative approach is the assessment of elevation difference (or maximal surface gradient) in a radius of some hundred meters. By this, the criteria can be adapted to the type of terrain and the type of dam intended (e.g. dam in valley). This criterion can be strongly affected by the type of terrain/rock as excavation costs can be prohibitive in certain types of rock).

A storage volume of 10,000 m³ would correspond to a discharge of less than 1 m³/s, if one plans 4 hours of turbine operation. Typically designers plan at 6 or 8 hours of operation, the flow would be reduced accordingly. If we used the flow of 1 m³/s with a head of 100 m, the power would be less than 1 MW. This level of installation is unlikely to contribute much to a European potential
- 6) Distance to the electricity grid. Large facilities, most likely to be found in the national or region scopes, are likely to be connected to the high-voltage (or transmission) grid, whereas small schemes could be connected to the medium-voltage (or distribution) grid. The increasing difficulty to deploy new electricity transmission suggests that the criterion of distance to the electricity grid is as much as an environmental and social criterion as it is an economic one.

The reservoir volumes do not give information about the volume of it that can actually be used: All reservoirs are designed for a certain live volume (available between minimum and maximum reservoir levels) according to their purpose. If the current use of a reservoir should be maintained, then this live volume will not be available for the pumped-storage scheme. To gain live volume, the dam would need to be raised. The variables you then need for calculating this additional volume are: 1.) reservoir area (in m²), and 2.) possible amount of heightening (in m). This is where it becomes very site specific: there may be buildings on the banks, a harbours etc.

If that specific information for the available volume is not available, it is recommended to use reservoir areas instead, to get an idea of what is available.
- 7) Populated areas should be excluded unless they are isolated houses. The reasoning is that a large project for the interest of the society can to a certain extent trigger adequate compensation for a single house affected negatively, but social issues would prevent the same for a more populated zone.
- 8) National monuments such as UNESCO-listed world heritage sites should be excluded.
- 9) Existing infrastructure in general should not be excluded but ranked. The reasoning is that e.g. a regional road can be slightly moved at a reasonable cost if the energy storage potential affected is large enough. In addition, regional and cultural differences play a role in this kind of decision.
- 10) Nature conservation areas, including Natura 2000, should not be generally excluded at a national or region scope, but the choice of exclusion or ranking should be allowed. RAMSAR convention wetlands should be excluded in principle. Different countries treat these areas differently and only the detailed site assessment of a county scope could determine whether the conservation area should be excluded.

- 11) The geology heavily determines the risks and costs involved in the construction of a pumped storage plant. The effort needed to dig a reservoir, excavate a tunnel or build a dam is determined by size/distance/volume as well as the geology. Examples include: limestone terrain being very difficult to dig, a pool could be built on it instead; the cost of two tunnels with the same geometrical characteristics but excavated in different geological context can vary from 1 (good terrain) to 4 (bad terrain) and even to 10 (faults); finally, costs for sealing to avoid water losses can be high and this need depends on geology.

For reservoirs some of the parameters are: stability for the foundation of the dam and sensitiveness of the foundation to possible leakages. The tunnelling would require support during construction. The end impact is on the specific project/reservoir structure and on costs.

- 12) Water availability is a ranking criterion because the amount of water available is variable, not a yes/no parameter. However, the absence of adequate water supply for filling, filling up and re-filling a PHS would exclude the potential site. For the region and county scopes the models should evaluate the distance to the available water or the extent of the catchment area. Of not less importance, from a social and environmental point of view, is the assessment of the flow remaining after the PHS has covered its water needs – but this criterion is not adequate when the scope of the assessment is national/supranational.
- 13) Social acceptance is a ranking criterion that is difficult to implement in the model. Social acceptance is determined, among others, by:
- a) the previous situation (e.g. if the water course was heavily modified the addition of a new reservoir would not significantly deteriorate the nature of the river)
 - b) the future use of the new reservoir – experience has shown that it may become a tourist attraction, improve flood protection or reinforce the water supply of an area,
- 14) Economic criteria include both costs and revenue. However, the inclusion of the latter criterion is considered not possible in a methodology to assess the potential among other reasons because the legislative and regulatory context changes from country to country. The inclusion of costs is evaluated under area 4 below.
- 15) Definitions of potential. Different steps in the assessment process yield different levels of potential: theoretical, technical, environmental, economic... It is necessary to group the methodological steps so that a definition of the different potentials can be applied that is consistent with international scientific practice.
- 16) For any medium-detail scope (e.g. for region/county) checking the site in Google Earth or OpenStreetMap is convenient as it might yield surprises such as that the site already is non-compatible. For any more detailed scope expert's opinion on every proposed site is necessary and a visit to the site strongly recommended by experience.
- 17) Different forms of land use should find different fits within the model according to the scope of the assessment and cultural and local conditions. For example, agricultural land should be excluded from the assessment in countries with such a legal requirement for a national scope, and this exclusion should be explicit in the results⁵ (linked with Area 3).
- 18) Buffer distances. Buffer distances should be considered differently for each of the criteria and in a flexible way. Buffer distance to infrastructure (e.g. a road) can be reduced to zero in most cases, whereas that one to a city or world heritage site should be much larger.
- 19) The main multi-criteria is the distance between reservoirs vs. head. The group strongly supported the approach first presented by the RWE/Fichtner study of linking these two elements. The approach is shown in a table in the GIS section below.

⁵ Notwithstanding this, given the changing nature of laws, it is recommended that a national scope assessment meant for a supranational contexts disregards this kind of legislation and includes e.g. agricultural land as usable for PHS.

- 20) The assessment could distinguish between short-term storage (6 - 10 hours), medium-term (up to 15 days) and long-term (beyond)
- 21) The potential installed power could only be estimated in very broad terms. It depends on the plant equipment and how it would be used. An average of 10-hour storage could be assumed, the power could be estimated as the storage capacity (in MWh) divided by those 10 hours.

The following values are recommended for the different criteria:

Criteria	Scope			
	National	Region	County	Grid
Max distance between reservoirs (km)	20	20	20	20
Minimum head (m)	50 – 200	25 – 200	15 – 200	50 – 200
Topologies 1 & 2: minimum usable volume of existing reservoir (Hm ³), or hydropower installed capacity (MW)	1 Hm ³ / 10 MW	0.1 Hm ³ / 5 MW	0.05 Hm ³ / 1 MW	1 Hm ³ / 10 MW
Topology 2, assumed new reservoir size (m ²)	1 000	700	700	1 000
Topology 2, assumed new reservoir average depth (m)	10	7	7	10
Minimum distance to inhabited sites (m)	2 000	1 000	200	2 000
Minimum distance to existing transportation infrastructure (m)	100	100	0	100
Distance to national parks	2 000	1 000	500	2 000
Distance to Natura 2000 sites	200	100	50	200
Distance to special protection areas	200	100	50	200
Minimum distance to a UNESCO site (m)	2 000	1 000	500	2 000
Maximum distance to suitable grid connection (km)	20	20	10	20

Table 1: Proposed values for some of the criteria described, depending on the scope of the assessment. Minimum distances are between the new reservoir under assessment and the given feature⁶.

The required deliverables of the model depend on the scope, as shown in table 2, and in some cases on the user.

Deliverables/results	Scope	National	Region	County	Grid
Energy storage capacity potential, in GWh		X	X	X	X
Indicative power considering 10- hour storage ⁷		X	X	X	X
List of assumptions used		X	X	X	X
Split of potential between short-, medium- and long-term		X			X
Detailed list of potential sites				X	
Per selected potential site a list of assessed second-reservoir sites				?	
Sensitivity analysis (to be defined) on demand				X	

Table 2: selection of deliverables related to the scope

Reservoirs not used anymore for their original purpose (e.g. water supply) present an opportunity for a new use such as PHS.

Sensitivity analysis should be included in the presentation of results. The latter could include GWh of storage capacity in total, percentage of that in Natura 2000 areas, percentage with new reservoirs, percentage below 50 MW at five hours full load pumping duration, etc.

⁶ Given the subjective nature of some of the values proposed above it is recommended that the values can be adjusted by the analyst taking into account cultural and local conditions.

⁷ 10 hours of storage is an arbitrary figure, other periods might be necessary depending on the scope.

Matching the head and distance criteria.

	Distance between reservoirs [km]																				
	0,5	1	2	3	4	6	8	10	12	14	16	18	20	22	25	28	31	34	37	40	
25																					
50																					
100																					
150	2,0	1,0																			
200	3,6	1,8																			
250	5,6	2,8	1,4																		
300	8,0	4,0	2,0	1,3	1,0																
350	11	5,4	2,7	1,8	1,4																
400	14	7,1	3,6	2,4	1,8	1,2															
450	18	9,0	4,5	3,0	2,3	1,5	1,1														
500	22	11	5,6	3,7	2,8	1,9	1,4	1,1													
550	27	13	6,7	4,5	3,4	2,2	1,7	1,3	1,1												
600	32	16	8,0	5,3	4,0	2,7	2,0	1,6	1,3	1,1	1,0										
650	38	19	9,4	6,3	4,7	3,1	2,3	1,9	1,6	1,3	1,2	1,0									
700	44	22	11	7,3	5,4	3,6	2,7	2,2	1,8	1,6	1,4	1,2	1,1								
750	50	25	13	8,3	6,3	4,2	3,1	2,5	2,1	1,8	1,6	1,4	1,3	1,1	1,0						
800	57	28	14	9,5	7,1	4,7	3,6	2,8	2,4	2,0	1,8	1,6	1,4	1,3	1,1	1,0					
850	64	32	16	11	8,0	5,4	4,0	3,2	2,7	2,3	2,0	1,8	1,6	1,5	1,3	1,1	1,0				
900	72	36	18	12	9,0	6,0	4,5	3,6	3,0	2,6	2,3	2,0	1,8	1,6	1,4	1,3	1,2	1,1			
950	80	40	20	13	10	6,7	5,0	4,0	3,3	2,9	2,5	2,2	2,0	1,8	1,6	1,4	1,3	1,2	1,1	1,0	
1000	89	44	22	15	11	7,4	5,6	4,4	3,7	3,2	2,8	2,5	2,2	2,0	1,8	1,6	1,4	1,3	1,2	1,1	
1100	108	54	27	18	13	9,0	6,7	5,4	4,5	3,8	3,4	3,0	2,7	2,4	2,2	1,9	1,7	1,6	1,5	1,3	
1200	128	64	32	21	16	11	8,0	6,4	5,3	4,6	4,0	3,6	3,2	2,9	2,6	2,3	2,1	1,9	1,7	1,6	
1300	150	75	38	25	19	13	9,4	7,5	6,3	5,4	4,7	4,2	3,8	3,4	3,0	2,7	2,4	2,2	2,0	1,9	
1400	174	87	44	29	22	15	11	8,7	7,3	6,2	5,4	4,8	4,4	4,0	3,5	3,1	2,8	2,6	2,4	2,2	
1500	200	100	50	33	25	17	13	10	8,3	7,1	6,3	5,6	5,0	4,5	4,0	3,6	3,2	2,9	2,7	2,5	

Table 3 : weighting the two criteria against each other. Different values might be appropriate for different topologies.

Table 3 reflects an empirical relationship between head and distance in which the former gets a significantly higher weight than the latter (“as a first rule costs relative to power are declining with head in square”). Ranges of head in existing plant extent from 20 m to 1500 m. Both head and distance ranges (as well as the ranking from the empirical relationship between them) probably will need to be readjusted after results are obtained (trial and error), and differentiated according to the scope of the assessment and the country/region considered. In a real example for a new design, the choice between 160 m head / 800 m distance and 270 m head / 3 500 m distance, the latter was chosen with (among others) more favourable cost calculations.

Any screening criteria should be tested against the existing PHS fleet and PHS projects under development. There exists several hundreds of existing PHS plants. If the screening criteria exclude a few existing sites, it would mean that they are too restrictive.

A contentious issue is whether a very unfavourable head/distance relationship should lead to exclusion (no-go), i.e. whether all sites for which this ratio is below a value to be determined should be eliminated in the first step. Against this argument is the fact that some of the existing PHS plant would fail this no-go test e.g. Waldshut, Häusern and Wiznau in Germany and Le Cheilas in France.

Step 3 - economic considerations

The economic aspects were discussed in a separate group, see section 4 below.

3 Area 2: GIS aspects

Summary of the GIS group⁸ discussions

The GIS aspects workshop group addressed two key questions: “*where can we build storage?*” and “*where do we⁹ need storage?*” Group members with GIS expertise addressed mostly the former question whereas those with TSO expertise addressed mostly the latter aspect. Further, the GIS group expanded the discussions focusing on six major topics: A) software, plug-ins and tools; B) alternative elevation data sources; C) recommendations for additional layers; D) economics and tools for cost estimation; E) environmental criteria (layer) and GIS databases; and F) hydrology criteria (layer).

The JRC/UCC team used ArcGIS, a commercial application from Esri¹⁰. The experts highlighted that ArcGIS is not compatible to any other GIS application and thus it is not inter-operable with open-source tools. On the positive side ArcGIS has become some kind of industry standard.

GIS has been used for identifying potential sites, geographical data (storage volume, elevation, difference between higher and lower basins) and the potential conflicts (i.e. overlapping with protected areas and infrastructure). The implementation of the multi-criteria-approach was performed outside GIS in Excel, based on GIS-Data. The same is valid for sensitivity analysis.

The implementation of a multi-criteria approach starts with listing all the input criteria to explore their dependency with the model output. A problem is to combine and integrate map criteria according to their weights. As it was explained previously a lot of parameters are really dependent on the local acceptance and on national legal and regulatory considerations. A general and global weighted matrix for the EU is really difficult to assess, but national and even regional matrices can be drawn up separately. This kind of tool can be developed and implemented “easily” on ArcGIS software through an ArcGIS plug-in developed in Python programming language.

The detailed results of the national or European assessments, in the form of potential storage at specific sites, could feed into the process of new grid design, e.g. the 10-year ENTSO-e research and development plan¹¹.

For validating the assessment model both existing and proposed PHS could be used. The model should capture those PHS schemes at least in a 90 % of the cases.

It was noted that GIS-based tools will always have to take local specificities into account.

Software, plug-ins and tools

The computational needs can be an issue as shown in one of the projects presented. Computational speed can be increased by using fast modelling methods / algorithms / software such as certain fast GIS plug-ins using directional analysis to identify surface depressions. In addition, faster computation is also acquired by using raster data instead of irregular terrain data (e.g. TIN data).

Overall, finding suitable PHS sites is subject to numerous debatable assumptions which are based more on perspective than any rigid requirements. Therefore, by creating a tool which can scan a terrain very quickly, it will be possible to assess the sensitivity of the results to numerous different assumptions very quickly. Almost always in modelling there is a trade-off between speed and detail, so the point here is to remember that a quick tool with less detail may be more useful than a slow tool with a lot of detail, particularly when considering the variety of assumptions that can be made in this study.

⁸ Group 2 “GIS”: Paul Leahy (chair), Manjola Banja, David Connolly, Martin Le Blanc, Mathieu Pauwels, Stefan Schmid, Andrei Bocin-Dumitriu (rapporteur).

⁹ “We” refers, in this case, to the European society in order to achieve the European Union 20/20/20 goals.

¹⁰ The use of ArcGIS by the authors does not imply that the JRC endorses this commercial application over any other.

¹¹ Available at <https://www.entsoe.eu/rd/rd-plan/>

Other methods to automate tasks include non-GIS tools such as MATLAB¹², ANSYS¹³ and others already available, which are customisable and can be developed for PHS assessment. Plug-ins can be created in Python programming language¹⁴.

Alternative sources for DEMs

The digital elevation model (DEM) is the basis for the map. The DEM used by the UCC/JRC team, SRTM, has as main limitation its coarse resolution outside the United States, 90 x 90 m, and at high latitudes. For county scope it would be necessary to find alternative sources with a finer resolution, and this might be convenient as well for other scopes.

Sources from where an alternative DEM include:

- national geodetic services;
- military geodetic maps and data;
- LIDAR surveys. In some countries the data are the propriety of a governmental agency;
- SRTM/non-SRTM data cost ration;
- Japan Space Systems (see box 2)
- other, non-SRTM remote sensing data sources.

However, these DEMs may be expensive. For example in France a 40 000-km² topographical map from IGN with a resolution of 25 x 25 m would cost 5000 €. In Ireland, 10-m horizontal, ±2.5 m vertical resolution data are available from Ordnance Survey Ireland at a cost of (at the time of writing) approximately €800 per 400 km² tile, although academic institutions have an 80% discount at €165/400 km² tile.

Box 2: The JSS is another source of remotely sensed digital elevation information: ASTER GDEM

<http://www.jspacesystems.or.jp/ersdac/GDEM/E/>

It appears to be better than SRTM in

* spatial coverage at northern/southern latitudes to 83 degrees N/S

* horizontal resolution (30m)

* vertical resolution (<~ 10m)

However, it is newer than SRTM and not as widely used, so perhaps it is not as well validated.

Source: Paul Leahy

Sources for data on lakes and reservoirs

In addition to the ICOLD database of major dams, which is not geo-referenced, and to the GRanD database, which geo-references 15 – 20 % of the ICOLD dams, the following sources are available:

- The JRC's Catchment Characterisation and Modelling (CCM).
- The European Environmental Agency's (EEA) ECRINS (European Catchments and Rivers Network System)
- The EEA's Eldred ("European Lakes, Dams and Reservoirs Database")
- EuroGlobalMap (EGM).

The annex to this document contains a summary of what each of those sources contain.

Recommendations for additional layers

Additional layers could be included to refine the model, here are some recommendations:

- Geology. A number of sources could provide a GIS geological layer including the European Scale Geological Map (One Geology project) and the Member States geological surveys (see resources in the annex).

¹² MATLAB is available at <http://www.mathworks.nl/products/matlab/>

¹³ ANSYS is available at <http://www.ansys.com/>

¹⁴ [http://en.wikipedia.org/wiki/Python_\(programming_language\)](http://en.wikipedia.org/wiki/Python_(programming_language))

- Geological data could include other items that need to be checked and considered: tunnels in the area, possibility of mines, whether it is a volcanic area, seismic hazards, etc.
- Land-use. In addition to CORINE available sources include MODIS, a high-resolution product or upon-request free low-resolution data from ESA, LANDSAT, and others.
- Electricity grid layer including both transmission and distribution networks. The level of detail would depend on the scope of the assessment and could include available grid capacity data from TSOs – but it is difficult to get those data. This difficulty to access electricity grid data depends on the voltage of the transmission line: high-voltage (transmission) network data are available; but access to GIS-format data on the medium voltage (distribution) network is not obvious.
- The necessity for creating/accessing a layer with electricity production and demand (variable and baseload) for creating “density” maps. For demand a proxy usable for GIS computation could be population density.

The European Environmental Agency has developed GIS layers and databases which could be available for PHS assessment.

Economics and tools for cost estimation

The model could export specific results that would enable further cost estimation in a separate tool, normally a spreadsheet.

There is a need to limit the number of parameters in order to obtain cost estimations. There were indicated a number of classification features for developing a ranking methodology for parameters:

- The most significant contributors to project costs, e.g. building a reservoir, a tunnelled penstock, the power house.
- The most significant contributors to cost uncertainty.
- Whether the penstock is in a tunnel or on-surface.

A first estimate of cost needs to be performed before developing any ranking methodology for the major costs contributors. This could start with a rough estimate of the costs based on head and reservoir volume using stepwise improvement. Although this estimate could take into account transmission network cost, the costs of wall dam sizes, volume of the material to be moved, and area to be lined, this group of costs are too detailed for any scope other than project level.

Environmental criteria (layer) and GIS databases

The experience of one of the assessments presented, for the land of Thuringia in Germany, suggests that sites with the highest ratio volume x head squared ($V \times h^2$) to land needed (surface of new reservoir) are more valuable. The assessment of potential could include some way to incorporate this point in the GIS model although it is easier (and current practice) to evaluate this point outside GIS, in a spreadsheet.

Hydrology criteria (layer)

GIS sources available on hydrology include CCM and ECRINS (see above). The suitability of these sources to provide the information needed for an advanced screening step was not assessed.

4 Area 3: environmental, social and spatial planning (E, S, SP)

Summary of the E, S, SP group¹⁵ discussions

The environmental impacts depend on the way the PHS scheme interferes with natural environments. Three kinds of PHS systems can be described from a water management perspective:

- Closed-loop system: neither reservoir is part of a river course and contact with a natural water course is only for filling, topping up and refilling the system. A new project of this kind might not affect significantly any river ecosystem.
- Semi-open system: one of the reservoirs (normally the lower one) is part of a river course.
- Open system: both reservoirs are part of a river course which can be the same river or not. The most common type of open system is the pump-back PHS which is also the most similar to a regular hydropower plant.

According to Wänn et al. (2012) the environmental impacts of each type will differ. The study is based on 5 case studies of existing PHS of which the environmental performance was assessed. Results show that the extent of environmental impact is largely determined by the status of the (pre-) existing environment. As can be seen in Figure 2 the main environmental impact that all three types have in common is impact on biodiversity and hydrology and hydrogeology. Thissavros is a good

		CAES	Pump-back PHEs	Semi-open PHEs			Closed-loop PHEs
Potential Issues/EIA terms of reference		Huntorf	Thissavros	Kopswerk2	Goldisthal	Bolarque2	Turtough Hill
Human Impact	Population	L	L	L	L	L	L
	Traffic	L	L	L	L	L	L
	Cultural Heritage	L	L	L	L	L	L
	Material Assets	L	L	L	L	L	L
Natural	Biodiversity	L	H	L	H	L	H
	Fisheries	L	H	L	M	L	M
Ecology and Systems	Air and Climate	L-H*	L-H*	L-H*	L-H*	L-H*	L-H*
	Landscape and Visuals	L	M	L	M	M	M
	Water Resources & Quality	L	H	L	M	L	M
Physical Environment	Noise & Vibration	L	L	L	L	L	L
	Soils, Geology & Sediment Transport	L	H	L	M	L	L
	Hydrology & Hydrogeology	L	H	M	H	L	H

- Recommended to review each individual case study
- Inclusion of combined impacts with existing land uses and pressures
- Limited raw data

Figure 2: Summary of negative environmental impact during operation highlighted by case studies. Source: Wänn et al.

¹⁵ Group 3 “E, S, SP”: Andreas Hutarew (chair), Emmanuel Branche, Goran Krajacic, Sergio Olivero, Constantinos Varnavas, Annicka Wänn, Klaus Schneider, Roberto Laca Arántegui (rapporteur)

example as it was constructed into a relatively unmodified environment as both hydro and pump-back at the same time. This means that Thissavros shows the environmental impacts that are likely to occur if a developer is constructing a completely new hydropower dam (and facility) with or without the pump. The construction of the dam is the most important factor which means that if a hydropower plant is already in place then retrofitting the facility would have much less environmental impact at this later stage. Turlough Hill and Goldisthal represent new builds for the closed-loop and semi-open PHS systems respectively. Both types highlight similar environmental issues. However, PHS projects are very site specific which means that all potential issues need to be considered as in any environmental impact assessment (EIA) terms of reference. It also means that any list of possible impacts have to be considered in a generic way and thus they might not be applicable to all cases.

The need for water is limited to the first filling, to topping up and to re-filling when full release is necessary. This can be very problematic in dry climates or if the river flow is low compared to the flow needed to fill up the PHS in a reasonable time. Design filling time could be from less than half a year and up to two years, but sometimes filling can start before construction is complete.

It was noted that the impact of evaporation in Cyprus was estimated at 10-15% of water evaporated from a reservoir in one year. This element is difficult to evaluate, and presents significant differences from one country to another.

Regional and cultural differences affect environmental and social perceptions, and spatial planning. Adequate compensation and mitigation measures, mostly as economic benefits, helps reaching consensus and shorten the permitting process. A proactive approach by developers helps too, and could include the following elements: (a) identify all stakeholders; (b) approach the local community and authorities very early in the planning and design process; (c) give them alternatives, i.e. different sites/designs, etc.; (d) describe the economic and social benefits that each alternative could contribute to the local community. Social and environmental issues should be discussed with three categories of stakeholders: public authorities, investors and the local community. In this context, it was mentioned that a “soft” reality is that a person’s support for new schemes depends on whether s/he is directly affected, his/her point of view might change in this case.

Environmental issues linked to transmission lines should not be tackled in PHS assessment.

Legal aspects have a strong impact on a specific project proposal, but should not be taken into account or, at most, should only be flagged at the assessment of national scope. This is because laws change and the assessment of national and/or European potential is mostly a technical issue with long-term implications. Incidentally, it was noted that depending on national legislation there can be a significant gap between legal requirements and environmental concerns.

The definitions of the different potentials have to be clear (see Area 1).

The International Hydropower Association published a [hydropower sustainability assessment protocol](#) some suggestions of which might be applicable for PHS.

Implementation

National, region and grid scope assessments

Environmental, social and spatial planning aspects can be subject alternatively to a no-go or flagged for the user to determine whether an aspect is weighted (ranked) negatively, e.g. the vicinity of a given Natura 2000 area. Given the cultural differences and those in the treatment of environmental protection areas, most parameters should be subject to the more flexible “flag” approach. Generally but depending on the country, both national parks and inhabited sites beyond a standalone house are recommended to be no-go, and all the other protected areas to be flagged. Suggested implementation of environmental, social and spatial planning aspects were incorporated to table 1.

County scope assessment

An advanced model with a county scope should be more detailed than for the other scopes. It should detect water flows into the existing reservoir and the prospective sites under analysis. It should include the river flow and should calculate the levels of water extraction that are possible for each topology, and the effect in downstream water resources of the flow reduction caused by the PHS project. Water used for non-hydropower uses in the existing reservoir should be discounted from the total water storage capacity, thus giving its “active” or “available” reservoir capacity, because this water would not be available for pumping. Other future uses, compatible with the PHS scheme, should be explored e.g. irrigation, tourism...

Land uses should be analysed with more detail than in the higher-level assessments, other used should be included.

Legal issues, whereas not applicable or only “flagged” if the scope is national, should be taken into account at the detailed assessment level. In the example of Cyprus, where farmland use change is forbidden by law, this should be a no-go at the county assessment unless the law permits the change of use for public-interest reasons.

It would be necessary to develop a system for the rating/ranking of river disturbance and apply it to show what the state of the river was before any proposed project has any effect. Pristine areas should be identified and separated from those with current human/industrial activity. This could be done based on other land uses that disturb the river and by taken into account the EU Water Framework Directive.

The visual impact of the proposed sites should be presented e.g. in Google Earth.

Area 3 references.

Wänn, A.; Leahy, P.; Reidy, M.; Doyle, S.; Dalton, H.; Barry, P.; and McKeogh, E.: *Environmental performance of existing energy storage installations*. Deliverable 3.1 of the European Union-supported research project stoRE, available at www.store-project.eu, accessed April 2012.

5 Area 4: economic aspects

Summary of the cost group¹⁶ discussions

The assessment of the economics of PHS projects is considered as valuable complementary information to the assessment of the physical potential in order to facilitate decision making. In principle, for the business case, economic assessment should be performed following a 3-step process: (i) the evaluation of capital (and operating) costs, (ii) the estimation of revenues, and (iii) their combination to assess project profitability. The experts at the workshop however considered that initially work should be focused on the estimation of capital costs only, even if a PHS is always site specific. Revenue estimation would require a more in-depth analysis and assumptions regarding regulation, market functioning and an overall system approach, which is site- and country-specific and hence could not be part of a universal methodology aimed at evaluating potentials for large regions or countries.

The development of a methodology for the assessment of the capital costs, which could lead to an economic module operating in tandem with the JRC tool for the estimation of the physical potential, is feasible, however not easy to implement. While the JRC approach presented at the workshop was considered best for larger feasibility studies at project level, the workshop participants agreed that it would be too complex to be applied for pre-screening purposes. Instead, the best way forward would be a simplistic approach, which could be followed by an engineering analysis on the project level by project developers.

¹⁶ Group 4 “Costs”: Wolfgang Hamelmann (chair), Hans-Christoph Funke, Xavier Mayau, Juergen Krenn, Patrick Schaefer, Olivier Teller, Vangelis Tzimas (rapporteur)

The simplistic approach would necessarily be based on a number of assumptions, like whether or not grid connection costs are included, if limestone formations should have a cost correction coefficient, or about the typical operation of the project, e.g. daily or weekly. Furthermore, a model project should be developed and used (e.g. number of penstocks, type of turbine, etc.) for all projects of the same topology. Capital costs should be related to key physical parameters, which will be outputs of the GIS physical potential calculation model, such as horizontal distance of reservoirs, volume of reservoirs, length of reservoir perimeter, length-to-head ratio etc. The most suitable parameters should be identified based on a statistical analysis of real costs of existing projects (or at least the most recent ones) and the potential physical parameters identified above. The aim of the statistical analysis would be to identify statistical relationships between these parameters and actual costs, which would lead to the development of cost diagrams, which in turn could be used for the estimation of costs of potential sites. This approach would be helpful especially for the civil works, which generally account for 50 - 75% of total costs. The expected accuracy would fall in the range of -25% to +70 % which is considered satisfactory for the sake of this exercise. Furthermore, cost curves for the machinery are available, which offer accuracy of $\pm 20\%$. It was stressed that such an analysis is not available, and hence, it would be a major contribution to PHS technology deployment once made. A potential difficulty would be access to real cost data. The workshop participants were not aware of a single source of information on PHS project costs and suggested the use of recent open literature, including magazines, newsletters and company reports.

The outcome of such an analysis could be used to compare costs with the next lower cost storage technology (e.g. CAES), alternative technologies for RES integration (such as gas turbines, demand side management, new transmission lines), or costs of other more expensive projects, taking into account the accuracy of the calculated results.

Implementation

Table 4 represents how the different costs could be estimated:

Empirical formula	Rough estimate
<ul style="list-style-type: none"> • water flow diversion • excavation and fill, lining (upper reservoir) • tunnelling and cavern • excavation and fill, lining (lower reservoir) • concrete dam construction (if applicable) • amount of tunnel lining (penstock and reservoir) 	<ul style="list-style-type: none"> • water intake • penstock installation • other electrical equipment
Information from suppliers	Share of initial investment
<ul style="list-style-type: none"> • steel price (penstocks and steel liners) • pumps + turbines or pump-turbines • transformers • transport + installation of equipment 	<ul style="list-style-type: none"> • project assessment • O&M costs • engineering, design and construction supervision

Table 4: split of works in a PHS project and basis for their cost assessment

A top-down approach (cost estimation by empirical comparison with existing plants) should reduce the workload and it is preferable to a bottom-up approach (cost estimation by means of individual design elements).

After the economic module has been established and has been applied, it may be useful to select a number of assessed projects randomly, and review them manually in terms of a) technical layout; and b) estimated costs. This will help to assess the confidence that can be given both to the technical, and to the economic modules.

6 Conclusions

The assessment of the potential for pumped hydropower storage may have two main purposes: site assessment within a project proposal, or country/region/county assessment for policy planning and decision-making. The use of geographical information systems models is effective, efficient and convenient for both purposes: what differs is the intensity of the use of the tools, the detail of the data needed and the assumptions behind the model and methodology.

The restriction to PHS development imposed by the different types of nature protection areas (NPA) is different in different countries. Also, laws and perceptions change with time according to the needs of the societies. PHS projects take a long time to realise, ten years is normal. Therefore, the scientific assessment of European or national potential cannot take current NPAs and laws into account with the same weight as the site assessment for a proposed PHS project has.

Country and European assessment is heavily dependent on the assumptions taken. For example, sensitivity analysis showed that enlarging the maximum distance between two reservoirs from 5 to 20 km multiplies the theoretical potential for Croatia by a factor of 10.

A significant part of the effort of this kind of assessment is needed for obtaining data of adequate quality and detail.

7 Abbreviations and acronyms

DEM – digital elevation model

E, S, SP – environment, social, spatial planning issues

PHS – pumped hydropower (energy) storage

NPA – nature protection area

ANNEX - RESOURCES

This is a list of resources available, free and commercial, for a GIS-based assessment. The list is not comprehensive, nor the authors endorse any of those which are commercial applications, their inclusion here is as a reference only.

1. GIS applications and plugs-in

- ArcGIS is available at <http://www.esri.com/software/arcgis/index.html> .
- QGIS (QuantumGIS), an open source GIS application: <http://www.qgis.org>
- GRASS, an open-source GIS application, can be downloaded from <http://freegis.org/database/?cat=0& ZopeId=77989294A5Xxl7tDnDM>
- DIVA, an open source GIS application: www.diva-gis.org

2. Alternative sources for DEM

Worldwide: The JSS (Japan Space Systems) is another source of remotely-sensed digital elevation information:

- ASTER GDEM: http://gds.aster.ersdac.jspacesystems.or.jp/gds_www2002/index_e.html

Ireland: Ordnance Survey Ireland provides 10-m horizontal, ± 2.5 m vertical resolution data for approximately €800 per one 400-km² tile, although academic institutions have an 80% reduction at €165/400 km² tile.

- Ordnance Survey Ireland: <http://www.osi.ie/Home.aspx>

Also in Ireland Geological Survey Ireland offers digital data free of charge:

- <http://www.gsi.ie/Publications+and+Data/Digital+Data/Available+Digital+Data.htm>

France:

BRGM is the *Bureau de Recherches Géologiques et Minières* of France. France's leading public institution in Earth science applications for the management of surface and subsurface resources and risks, the BRGM plays 4 key roles: scientific research, support to public policy development, international cooperation and mine safety.

- BRGM at <http://www.brgm.fr>

IGN is the *Institut national de l'information géographique et forestière* of France.

- IGN: <http://www.ign.fr/>

Germany: Geological data of the German federal states are available for a small fare, see i.e. Thuringia.

- Thuringia geological data: www.tlug-jena.de

3. Lakes and reservoirs data

The following sources are available:

- The JRC's Catchment Characterisation and Modelling (CCM) is a pan-European database of river networks and catchments, public, free for non-commercial use, and GIS-based. One of its modules is dedicated to lakes. The updated version (CCM2.1) is available at <http://ccm.jrc.ec.europa.eu/php/index.php?action=view&id=23>
- The European Environmental Agency's (EEA) ECRINS (European Catchments and Rivers Network System) is a fully connected system of watersheds, rivers, lakes, monitoring stations, dams which originated in the JRC CCM2.1 and was then completed with data from other sources.

Compared to CCM, ECRINS is smaller: (138,000 instead of >2,000,000 elementary catchments), only the main drainage system has been kept, which makes ECRINS more usable, and has many CCM errors corrected resulting in an improvement of the CCM lakes layer, which is now better documented. Moreover, ECRINS is more DCE-compatible since the rivers are organised as main / non main and water bodies snapped. Over the ECRINS, under the water accounts, the river segments with monthly discharge are documented. This is a not-CCM-compatible data set since CCM IDs had to be changed fully for making ECRINS. ECRINS is available at <http://projects.eionet.europa.eu/ecrins>

- Eldred is acronym for “European Lakes, Dams and Reservoirs Database”, it is the internal EEA database for managing dams, artificial lakes that go with and to some extent natural lakes if related with a dam. Dams may have two classes of sources: (a) ICOLD for the larger dams containing ~7000 plus more recent ones from the Member States; (b) any other source of non-large (as ICOLD defines them) lakes and reservoirs, it includes many sites but it is not completely updated.

Compared to ICOLD (the main source or homogeneous layer of dams) EEA mainly added two important sets of information: (a) exact placement of dam thus more accurate than ICOLD’s very vague “next city”, “in region XXX”, that is supported by a restricted access Web tool, Dampos, to place the dams exactly, helped by Google Earth images; and (b) relation with ECRINS. The latter is due to a special table in ECRINS which contains dams information (those not to be hidden under ICOLD’S rules) and the relationship between those dams actually matched to i) ECRINS lakes and ii) ECRINS segment (i.e. “river” for the lay person). It is now coupled with ECRINS.

Eldred is available from EEA on demand for specific institutions in the Member States.

- EuroGlobalMap (EGM). This is a 1:1-million scale topographic dataset covering 38 countries in the European region. Our analysis of EGM suggested that it has good geographical coordinates but they do not cover all the large dams. For example for Spain, the Spanish national databases contain 1300+ dams and the EGM version explored contains only 477. EGM is available from Eurogeographics at <http://www.eurogeographics.org/products-and-services/euroglobalmap>

4. Other software/data

- Refined CORINE Land Cover data. Additional information at <http://www.tandfonline.com/doi/abs/10.1080/1747423X.2012.667450>. The refinement process involved mainly the artificial classes of Corine, by using ancillary data, such as the Urban Atlas layers available by then and the Soil Sealing layer. The linked paper explains the details. The dataset is not available on-line: entities interested need to address the authors (JRC), briefly explaining for which purposes the dataset is needed.
- Electricity network data: GENIE. Free but accuracy might not be at the required level.
- A simple tool for the evaluation of capital and operating costs is available at <http://www.dconnolly.net/calculator.html>

Appendices: summary of the projects presented

A. Pumped-hydro energy storage: potential for transformation from single dams

Dr. Paul Leahy, Lecturer in Wind Energy, School of Engineering, University College Cork. Roberto Lacal Arántegui, Scientific Officer, Joint Research Centre, European Commission.

Compared with the high environmental and social impact of most new hydropower plant in Europe, the transformation of an existing reservoir into a PHS system offers the prospects of a much smaller environmental and social impact. On this basis, the authors developed a geographical information system (GIS) -based methodology and a model to identify the potential for transforming single reservoirs into PHS systems, and to assess the additional energy storage which these new PHS could contribute to the electricity systems. The methodology was applied as case studies to Croatia and Turkey.

GIS-based tools have the potential for effective and efficient identification of both national/EU potentials (of policy and scientific-interest) and individual site candidates for transformation (pre-feasibility, project-level). Once the model is set up, improvements to such tools, e.g. allowing better sensitivity analysis, can be effectively applied to the whole of the EU with minimum effort.

This paper first summarises the methodology and tool used, then presents the sources of data, and finally applies the model to the cases of Croatia and Turkey and presents the results. These results limit the assessment to potential sites within 5 km of one existing reservoir (TA) or of one another (TB), and a minimum 150 m of head.

In the case of Croatia, it was found that at least a potential of 60 GWh is possible for which can be compared with the existing 20 GWh of storage capacity at its PHS plants. In the case of Turkey a potential of 3 800 GWh was assessed mostly under TA, with two potential TB sites providing three additional GWh of storage potential.

B. Development of a computer program to locate potential sites for pumped hydroelectric energy storage

Dr. David Connolly, Assistant Professor, Department of Development and Planning, Aalborg University, Denmark.

Pumped hydroelectric energy storage (PHES) is the largest and most mature form of energy storage currently available. However, the capital costs required for PHES are extremely large and the availability of suitable sites is decreasing. Therefore, identifying the remaining sites available for PHES is becoming vital so that the most beneficial location is chosen: in terms of capacity and economics.

As a result, the aim of this work is to develop a computer program that will scan a terrain and identify if there are any feasible PHES sites on it. In this paper, a brief description of the program is provided, including the limitations identified during the initial development. Also, the program was used to evaluate a 20 km x 40 km area in the South West of Ireland so the results obtained from this study are discussed.

Finally, future improvements to advance the program's capabilities are identified. The program has proven to date that it can identify feasible locations for PHES, however, further investigation is necessary to improve the site selection.

The tool developed is able to rearrange the terrain which it is assessing. In other words, it can move the earth around as it wishes. The model builds a 3D landscape with the terrain data given and then afterwards, the landscape can be modified. This was important in our study as this was the method we used to define whether or not a site was acceptable. We told the model that a site was acceptable

it the amount of earth which needed to be moved around to make a site perfectly flat was below a value we specified.

This facility could potentially be used in many other ways, especially when trying to evaluate how existing terrain could be used to make reservoirs. However, although this can be done we didn't have the funding to support this development.

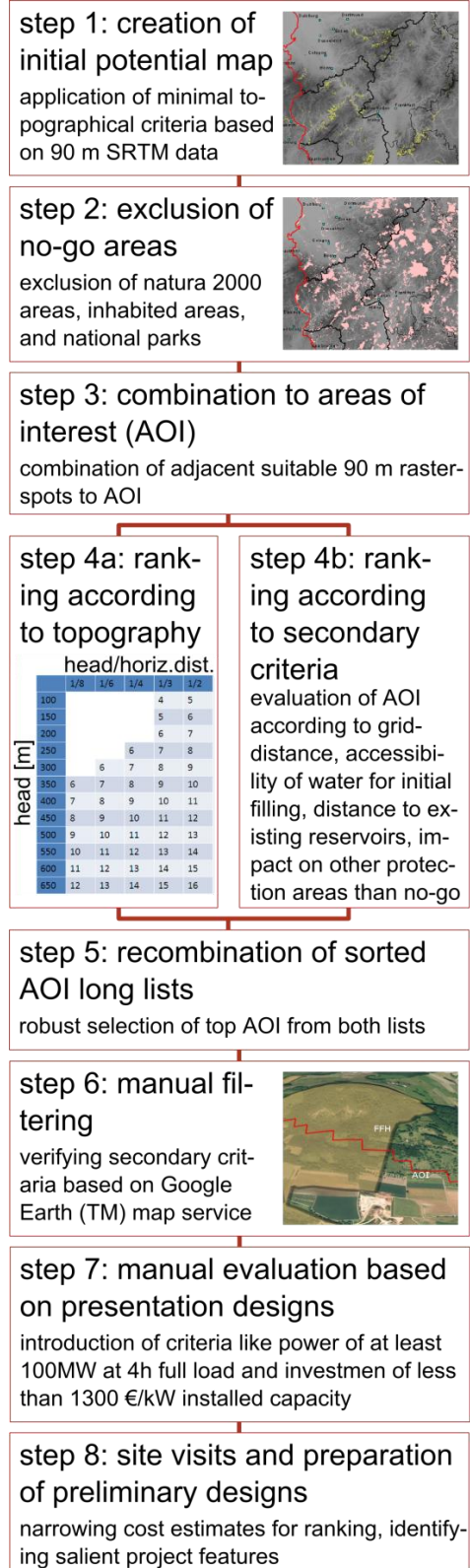
C. Multi-criteria, GIS-based screening of pumped hydro potential in Germany

Dr. Patrick Schäfer (Fichtner GmbH), Dr. Peter Vennemann (RWE Power AG)

The identification of potential projects and the estimate of the capacities were accomplished in a top-down process, as shown in the figure. The chosen method allows to screen large areas throughout their extents and select the most attractive projects using documented parameters. The GIS-model utilized for the pre-selection of potential sites is based on a number of geo-information, such as topography and protected areas. The software used (ESRI ArcView 3.3 and ArcGIS 9.2) is equipped with different algorithms and filters, however some additional algorithms were developed, to make a selection according to defined properties. The GIS-model is based on the topographical information received from the Shuttle Radar Topography Mission (SRTM) in its Version 4.

The no-go areas, such as SPA, were available in shape files. Every cell of the 90m x 90m grid was tested whether it lies inside one of the no-go areas or not. Similarly to the removal of no-go areas, the GIS-software tested for each cell whether it is located inside one of the remaining protected areas, such as conservation areas and biosphere reserves, in order to mark the corresponding cells accordingly. In order to evaluate the favourable criteria, the GIS-software calculated the distance to certain shape files, for instance to the transmission lines or existing reservoirs. For the topographic criteria, the algorithm checks for each cell of the model, whether a defined difference in elevations of the cells surrounding it inside a defined radius is available, and if yes, marks the cell positive. Neighbouring marked cells were united in polygons, named Areas-of-Interest (AOIs).

The ranking was based on two types of criteria: the geometric criteria (head and ratio of head and length of waterway); and secondary criteria like distance to grid, existing infrastructure, etc. A project with perfect geometrical topographical conditions but, e.g. lacking a grid connection, or water for the first filling will not be attractive - same as the other way around, while it yet may be an interesting project. Therefore, both groups of criteria must be considered. The results of the geometrical and soft



criteria were combined and applied to each cell of the model. In order to assess the AOIs, the value of the best cell within was attached to the corresponding AOIs.

The resulting AOIs were exported to the Google Earth software, which permits easy navigation. Furthermore all shape files from the GIS-Model could be transferred and visualized in Google Earth, including no-go areas, transmission lines, etc.. In this environment, the general feasibility of the selected AOIs was checked. Based on Google Earth, charts were prepared indicating the main parameters of each project.

The best 20 sites identified in the course of the study were visited on site in order to confirm the boundary conditions of the corresponding sites. Three of the sites turned out to be unsuitable for the development of pumped storage schemes, thus 17 projects remained. Preliminary drafts were prepared for the 17 projects, based on 1:25.000 topographical maps.

The finally identified potential in the considered area in the Western part of Germany, consists of 17 sites with 2,500 MW installed capacity. This is 1,000 MW less than identified based on after inspection with the help of Google Earth. The manual screening for feasible projects resulted in 7,500 MW installed capacity, however, there were multiple counts for several 500 MW projects all using the same existing lower reservoir.

D. Prediagnostic cartographique du potentiel de développement de micro station de transfert d'énergie par pompage-turbinage dans les Alpes Maritimes

Mathieu Pauwels, Project Engineer, Renewable energies - Hydro, Hydrowatt - UNIT^e

The possibility of storing and recovering a large amount of energy very quickly is one of the main challenges for the management of electricity at the present time. Today, pumped hydro energy storage power plants is the most technologically and economically mature solution to respond to these criteria. Pumped hydro energy storage has grown in the 1970th to manage the production of non-flexible energy sources such as nuclear power plants. The massive development of intermittent renewable energies in the recent decades, such as wind and solar energies has changed this approach and increased the need for additional energy storage capacities.

Despite the importance of pumped storage, its development becomes increasingly difficult in OECD countries due to a lack of geographical sites with important energy potentials. The combination of small hydro power plant with the advantages of limiting the impacts on the environment and pump storage technologies could be an issue for the development of intermittent renewable energies.

Prospecting and prefeasibility studies for new small pumped hydro storage sites are complex, entailing significant input of time and energy. This paper proposes a general and universal methodology to assess the feasible energy storage potential of a region ($\approx 40\,000\text{ km}^2$) using the most pertinent site characteristics. This approach is based on geographical information system (GIS) technologies.

The identification of a potential site depends on a few relevant parameters which come in three varieties: site topography (storage volume available, head of the site...), environmental restriction and technical and economic constraints. GIS tools are particularly adapted to merging these restrictions and finding favourable sites. A methodology developed in collaboration with ADEME (French Environment and Energy Management Agency), Mines Paristech and HYDROWATT for identifying reservoirs has been integrated with GIS software and tested in the South East Province of France. The methodology developed identify to type of reservoirs: existing reservoirs such as lakes, ponds and the sea or natural depression that could be seal and fill with water to build a new reservoir. After identifying the searching reservoirs, criteria for land occupation and environmental constraints and their relative weight are determined. Finally site are selected regarding their characteristics (head and distance between two reservoirs) and, technical and

economic criteria such as the distance to electrical substation. The goal of this methodology is to provide a rapid idea of the feasibility of a project and is well adapted for a global approach to analysis on a regional scale.

This methodology has been applied on a case study, the French Alpes-Maritimes department. Field measurements have been performed to validate both reservoirs (depth, area, width, length) and sites (distance to the grids, water resources, distance between reservoirs) characteristics. Considering only new reservoirs (natural depression) with a storage volume of 10 000m³ to 1 300 000m³, a head of 50 to 800m and a horizontal distance between the two reservoir of 20 to 2000m, a feasible potential of 107 MWh was assessed.

E. Pumpspeicherkataster Thüringen. Ergebnisse einer Potenzialanalyse.

Hydroprojekt undertook a study for the regional government of the state of Thuringia, Germany, to identify new sites for PHS. The basic requirements for a greenfield site or a site based on an existing reservoir to be chosen included:

A	No existing reservoir	Existing reservoir
Minimum head	180 m	100 m
Maximum horizontal distance	5 km	5 km
Minimum installed capacity	200 MW	50 MW
Minimum operating time under full load	8 hours	6 hours

The full report is available at www.thueringen.de/de/publikationen/pic/pubdownload1272.pdf

European Commission

EUR 25367 EN – Joint Research Centre – Institute for Energy and Transport

Title: SETIS expert workshop on the assessment of the potential of pumped hydropower storage

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Luxembourg: Publications Office of the European Union

2012 – 29 pp. – 21.0 x 29.7 cm

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

ISBN 978-92-79-25151-1 (print), 978-92-79-25150-4 (pdf)

doi:10.2790/53924 (online)

Abstract

Energy storage is an important option to enable a higher share of variable renewable electricity such as wind and solar, in the energy system. Pumped hydropower storage (PHS) is currently the only storage technology able to provide the large storage needed for accommodating renewable electricity under the 2020 EU energy targets. Moreover, the transformation of an existing water reservoir into a PHS facility has a much smaller environmental and social impact compared with most new hydropower plant in Europe.

The JRC collaborated with University College Cork (UCC) in Ireland to develop a GIS-based methodology and model to assess the potential for transforming single reservoirs into PHS systems. Then the JRC organised a multi-disciplinary expert workshop to validate the methodology and model, provide a set of recommendations for the improvement of the effectiveness and efficiency of the methodology, address the issue of data availability in the Member States, and share and disseminate the methodology among relevant stakeholders, such as policy makers, industry, research, etc.

This report presents the results of the workshop which concluded that the assessment of the potential for PHS is different when its purpose is site assessment or policy planning and decision-making; and that the use of geographical information systems models is effective, efficient and convenient for both purposes whereas what differs is the intensity of the use of the tools, the detail of the data needed and the assumptions behind the model and methodology.

The restriction to PHS development imposed by the different types of nature protection areas (NPA) is different in different countries. Also, laws and perceptions change with time and as PHS projects take a long time to realise the scientific assessment of European or national potential cannot take current NPAs and laws into account with the same weight as the site assessment for a proposed PHS project. Country and European assessment is heavily dependent on the assumptions taken. For example, sensibility analysis showed that enlarging the maximum distance between two reservoirs from 5 to 20 km increased the theoretical potential for Croatia from 60 GWh to nearly 600 GWh.

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.