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GIS-based assessment of the European potential for pumped hydropower energy storage

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Resumen

Este artículo presenta los resultados de la evaluación del potencial almacenamiento de energía hidráulica por bombeo en Europa bajo determinadas topologías y escenarios. Los resultados muestran que el potencial teórico en Europa es significativo. Se estudiaron dos topologías diferentes. Bajo la topología 1, la energía potencial teórica almacenado alcanza 54 TWh para una distancia de 20 km entre dos embalses existentes; de este potencial de aproximadamente 11 TWh corresponden a la UE y 37 TWh a otros países europeos. Bajo topología 2, el potencial teórico europeo alcanza 123 TWh cuando la distancia entre el embalse existente y la nueva localización propuesta es de hasta 20 km. A diferencia de la topología 1, en la topología 2 la mitad este potencial se establece dentro de la UE. El potencial realizable tiene en cuenta centros de población, espacios naturales protegidos e infraestructuras de transporte para la eliminación de nuevos embalses situados demasiado cerca. Para la Topología 1 y escenario 20 kilómetros el potencial realizable se reduce a la mitad, 29 TWh; mientras que la topología 2 está ligeramente menos afectada y finalmente alcanza 80 TWh de los que 33 TWh pertenecen a la UE.

Palabras clave: SIG; planificación estratégica; hidráulica de bombeo

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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 European energy and climate policies have as one of their targets 20% of 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 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 Commission, 2009; 2012), will require even higher share of renewables in the electricity mix.

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 & Keil, 2012).

The objective of this work is to assess the potential for energy storage in pumped hydropower schemes in Europe focusing on two topologies: T1 when two reservoirs exist already with the adequate difference in elevation and close enough so that they can be connected, and T2 based on one existing reservoir, when there is a suitable site close enough for a second reservoir.

2. Application of the methodology and issues

The methodology is based on a GIS model, built in *ArcGIS Model Builder*, mainly fed with a digital elevation model and with data of existing reservoirs including 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.

Table 1: List of data needed to run the model

Data	Description
Digital Elevation Model (DEM)	SRTM 90 m (GMTED2010 250 m for Scandinavian countries)
Reservoirs	ECRINS database (EEA, 2012)
Political borders	DIVA GIS shapefile (www.diva-gis.org)
Corine Land Cover	For extracting inhabited areas and rivers
Nature protected areas	Natura 2000
Culture protected areas	UNESCO georreferenced dots
Transport infrastructure	DIVA GIS shapefile (www.diva-gis.org)
Electricity grid infrastructure	PLATTS (2012)

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; Lacal-Arántegui et al, 2011).

There are different potentials depending on the depth of the analysis and the constraints included in each analysis. The two energy storage potentials described in this modelling exercise are the theoretical and realisable ones.

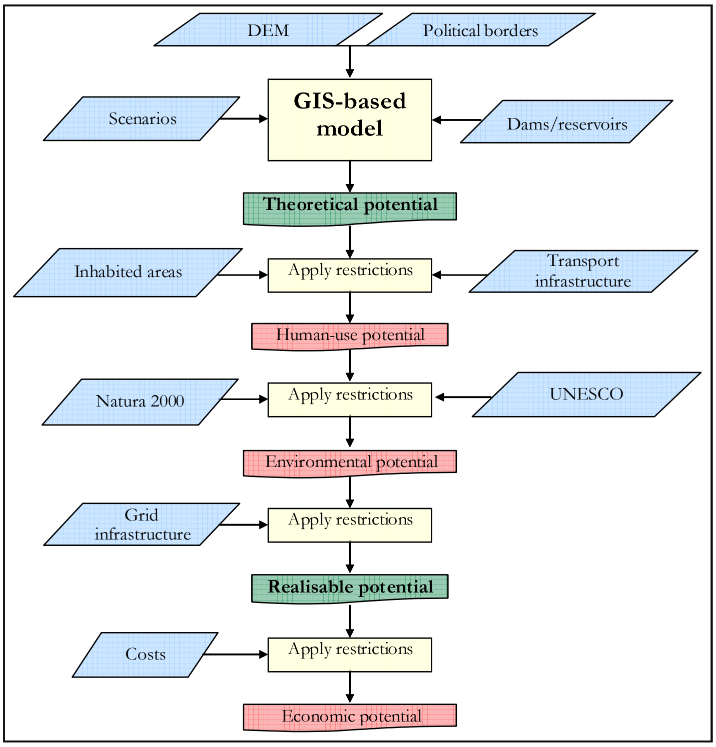

Figure 1: Methodological flowchart with the inclusion of mid-stage potentials (red colour)

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, and scenarios for the parameters head and maximum distance between reservoirs. Realisable potential is the result of applying to the theoretical potential a series of social, infrastructure and environmental constraints.

Prospective second-reservoir sites under T2 are defined as flat or non-sloping areas (slope lower than 5%) in the vicinity 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 m3) 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.

Table 2: Constraints and values applied in T1 and T2.

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 (only 5-km) and 150 m
Assumed minimum new reservoir capacity	100 000 m3	100 000 m3
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

It could 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 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.

2.1. Validation and comparison with existing PHS 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 has a contributing flow and more flexibility for releasing or accumulating water.

We explored how the energy storage calculated by the model compares to data from external sources.

Table 3: comparison between external and JRC storage data. Sources: (1) Wänn (2013); (2) DENA (2008); (3) Martínez Campillo (2010); (4) Ursat et al. (2011); (5) Sallaberger (2010); (6) Hartmann et al., (2012). *DENA (2008) does not contain head information, Hartmann et al., (2012) does. **Storage hours calculated from storage capacity and installed electrical capacity.

Country	PHS	Capacity upper reservoir m3	Head*	Generation capacity (MW)	Storage from source (MWh)	JRC model storage (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	2,6
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	2,6
DE	Langenprozelten	1 500 000	297	168	950	990	6	2,6
DE	Makersbach	6 300 000	285	1 050	4 018	3 989	4	2
DE	Niederwartha	1 981 000	143	120	591	629	5	2,6
DE	Rönkhausen	1 000 000	265	140	690	590	4	6
DE	Säckingen	2 100 000	400	353	2 064	1 866	5	2
DE	Waldeck I	700 000	296	140	487	461	3	6
DE	Waldeck II	4 400 000	324	440	3 428	3 167	7	2
DE	Waldshut	1 350 000	160	176	476	480	3	6
DE	Wendefurth	1 970 000	126	80	523	551	7	2
DE	Witznau	1 300 000	250	220	642	722	3	6
ES	Guillena	2 330 000	217	210	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

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 2 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.

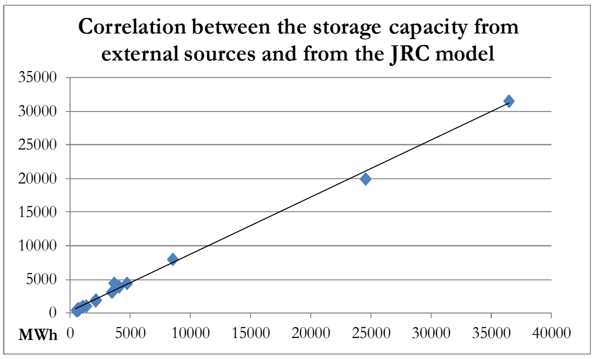

Figure 2: correlation on PHS storage capacity data from external sources and from the JRC model.

3. Results: The European PHS potential

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.

Table 4 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.

Table 4: number of potential sites found and stored energy associated.

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

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

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 5 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.

Table 5: number of potential sites found and stored energy associated.

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

Linked with the strong reduction in the number of prospective sites are the very low capacities found in scenarios 1- to 10-km. For example, the maximum potential reached in the 5-km scenario is 0.20 TWh, 0.63 TWh less than its theoretical potential. The relative reduction reaches its maximum at the 10-km scenario, where only 16% of the theoretical potential, i.e. 1.32 TWh passes the restrictions. The largest scenario show a significant reductions in absolute terms as it loses more than 25 TWh. Overall, the realisable potential is still significant at a 20-km distance.

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 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.

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.

Table 6: number of theoretical potential sites found under T2 and stored energy associated.

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

The maximum European T2 realisable potential reaches 80 TWh, from 4 600 available sites, as shown in table below.

Table 7: number of potential sites found and stored energy associated under T2 (realisable).

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

The reduction in potential as a result of applying constraints is significantly lower under T2 than under T1: around 65% of the theoretical potential made it into realisable under the 20-, 10- and 5-km scenarios, 60% under the 3- and 2-km scenarios and 50% under the 1-km scenario. For T1 those figures were 53%, 16%, 24%, 21%, 26% and 83% respectively.

4. Conclusions

This assessment estimates the potential for pumped storage capacity in Europe under the assumptions and topologies considered.

There are no official figures reported to Eurostat for the existing pumped storage capacity in Europe, nor in the EU. A comparison for some countries (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 (see Annex A for further details on each country studied).

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.

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.

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Appendix A.

Potential PHS energy storage capacity per country under the two topologies, in GWh for 1, 5 and 20-km 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
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
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
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
Europe	**4**	**831**	**54 309**	**3**	**198**	**28 627**	**366**	**15 313**	**122 874**	**180**	**10 214**	**79 758**