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

Analysis of the potential for transformation of non-hydropower dams and reservoir hydropower schemes into pumping hydropower schemes in Europe

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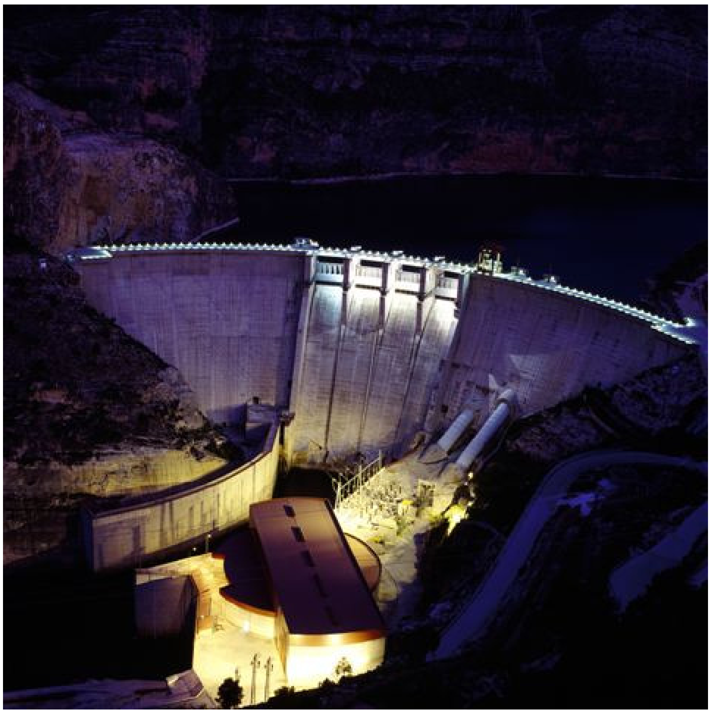

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Introduction

Electricity supply and demand has to be balanced for the system to work smoothly and for achieving this balance systems use demand-, supply- and system-based elements and measures. In modern electricity grids electricity storage is a major system resource to keep that balance, and currently the only widespread, large-scale electricity storage installed are reservoir-based hydropower and pumped hydropower storage (PHS) [1]. One difference between both is that PHS can act as load when electricity is spare in the system thus absorbing the excesses.

The decarbonisation of electricity systems requires increased use of renewable energies, the fastest-growing of those, solar and wind, are dependent on natural resources that are not necessarily available when electricity is most demanded. Increased penetration of wind and solar electricity is therefore dependent, among other factors, on electricity systems developing larger storage capacities. The problem is compounded by the effects of climate change on the availability of rain and thus hydropower generation.

The potential for further conventional hydropower in Europe is limited because of environmental considerations, lack of adequate sites and certain social acceptance issues. New PHS schemes are subject to similar limitations, but this is likely not to be the case for PHS resulting from the transformation of existing hydropower and non-hydropower reservoirs. Reasons include that an existing reservoir, candidate for transformation to PHS, already caused effects (e.g. environmental) long time ago and currently forms part of a more stable system where –hopefully- those problems have been alleviated. The two-dam system PHS is, in this context, a closed-circuit whose PHS-related impact is unlikely to significantly spread beyond the system. The transformation of single reservoirs to PHS therefore becomes the simplest way to add electricity storage capacity, has lower costs than new PHS and lower environmental impact than new reservoir hydropower.

A PHS scheme, while not necessarily adding more electricity of renewable origin (PHS electricity is as renewable as the electricity that was used to pump the water up in the first time, minus the cycle efficiency losses of 15-30 %), would allow the integration of more renewable variable electricity [2]. Other system benefits include the replacement of expensive peak-serving power plants fuelled by oil or natural gas and, beyond electricity production, the contribution to flood control and water supply that are typical of any reservoir-based hydropower plant.

The analysis of hydropower potential has been widely explored. For example, the European Environmental Agency commissioned AEA to define a methodology to estimate the European environmentally compatible potential for small hydropower (SHP) [3]. However, a literature search exercise showed that the PHS potential has hardly been analysed. The analysis of the potential for PHS -or for transformation to PHS for this matter- was carried out in Europe at project level by private companies (e.g. RWE), at regional (e.g. Canary Islands) and national (e.g. Ireland) levels, but a similar analysis was never carried out for the whole of Europe.

The objective of this report is to define a methodology for finding the potential for transformation to pumped hydro schemes (PHS) under two given topologies, and to test this methodology in two cases, Croatia and Turkey. The methodology uses a geographical information system (GIS) tool and a purposely-developed database of European reservoirs.

Section 1 of this report develops the methodology under two different topologies. Section 2 defines the database of hydropower and non-hydropower reservoirs on which the methodology is based, and how it was created. Section 3 applies the methodology to the data in the database and describes and quantifies the potential for transformation to PHS for the two case studies. Section 4 then identifies barriers to the realisation of this potential whereas Section 5 identifies topics for future research and Section 6 summarises the findings.

1 Definition of a methodology for transformation

1.1 Diversity of topologies for PHS transformation

A PHS scheme requires the existence of an upper and a lower reservoir between which water is pumped up –mostly in off-peak periods- to store hydraulic potential energy and then released down through a turbine –mostly in peak periods- to produce electricity. One or two penstocks join the two reservoirs and a power house, often built inside the mountain, contains the pumping and generation as well as any ancillary equipment. A dynamic representation of how a PHS works is available at Verbund's web site [5].

The following topologies for transformation would be possible.

- **Topology A (TA):** when a reservoir exists already TA consists of adding a second reservoir, normally at a higher elevation, plus penstock and equipment. The Dinorwig PHS plant project in Gwynedd, North Wales, UK, is an example of TA.
- **Topology B (TB):** when two reservoirs already exist and are within suitable distance and difference in elevation, TB consists of adding generation and pumping equipment between them. Existing natural lakes can also be considered one of the two reservoirs in this topology, and these dams might be in the same river or in parallel valleys. Limberg II PHS plant in Kaprun, Salzburg, Austria, a 480-MW plant due for completion in 2011, is an example of a TB PHS transformation [5].

This research develops those two topologies, but it would be possible to analyse the potential for transformation under the following three more topologies:

- **Topology C:** when an old, abandoned pit or quarry is available this one could take the role of the existing reservoir in TA above, or used as new (e.g. upper) reservoir if geography so permits.
- **Topology D:** "pump-back" in an existing 2-dam system a penstock and a pump are added to send water back from the lower reservoir to the upper one.
- **Topology E:** the lower reservoir is the sea and the upper reservoir is build above cliffs close to the sea. This topology was implemented for the first time in Okinawa, Japan [52].

This paper will not extent on the latter three topologies nor in other ideas proposed by researchers.

Throughout this document the terms "dam" and "reservoir" are used as equivalents.

1.2 Introduction to countries selected as case studies

Turkey and **Croatia** were selected as the countries that will be analysed for the potential transformation of dams to PHS using the methodology defined in Section 0.

1.2.1 Croatia

The total average electricity generation in Croatia is 12 500 GWh per year, of which hydropower plants contribute 5 700 GWh (Eurostat average from 2005 to 2009[1]), and account for 2 076 MW of installed power. Total annual consumption reaches around 18 000 GWh and therefore local hydropower plants supply 31 % of Croatian consumption. Croatia currently has 3 PHS plants in operation: RHE Velebit [7] (generation capacity 276 MW (2x138), pumping

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[1] Calculation from Eurostat tables nrg_105a and nrg_1072a in Energy Statistics (nrg_10) - supply, transformation, consumption [6]

capacity 240 MW (2x120)), Fužine (generation capacity 4.6 MW, pumping capacity 4.8 MW) and Lepenica [8] (generation capacity 1.14 MW, pumping capacity 1.25 MW).

Croatia has set a target to increase the share of electricity from renewable energy sources, and this includes 1200 MW of wind by 2020. For the purpose of providing incentives, Croatia does not take into account RES electricity from large hydropower (capacity of 10 MW or more) [9].

The high penetration of hydropower in Croatia and their commitment to a 20 % share of renewable energy in its total consumption by 2020 [10], along with its numerous electricity interconnections, make Croatia a suitable candidate for this study. Croatia is directly interconnected to Slovenia, Bosnia and Herzegovina, Serbia and Hungary, which creates the potential to store surplus wind generation from these neighbouring countries.

1.2.2 Turkey

The total average electricity generation in Turkey is 195 000 GWh per year, of which hydropower plants contribute 38 000 GWh (Eurostat average from 2005 to 2009[1]) and account for 14 550 MW [11] of installed power at the end of 2009, thus hydropower plants supply 20 % of Turkish demand. DSI [12] suggests that only 35 % of estimated economic potential for hydropower is utilised in Turkey, and the Turkish government hopes that hydropower capacity will expand to 35 000 MW by the year 2020 [13]. Table 1 presents a broad overview of dam projects in operation and under construction.

Projects	In operation	Under construction	Planned
Large dams	260	63	
Small dams	413	83	
Hydroelectric plants (no.)	172	148	1 418
Hydroelectric capacity (MW)	13 700	8 600	22 700
Annual average generation (GWh/yr)[2]	48 000	20 000	72 000

Table 1: list of existing dams and dams under construction in Turkey in 2008 [61]

Turkey is a suitable country for this study due to the large number of dam sites, and thus the large number of potential transformation sites, and of its target to increase the country's installed wind power capacity to 20 000 MW by the year 2023 [14]. Both factors make of the Turkish case representative of the potential transformation of dams to PHS in some other European countries.

1.3 Methodology for transformation

The methodology for the transformation of existing reservoirs into PHS, under both TA and TB, is set out below. A high level methodology flow chart is described in Figure 1 which shows the flow of decisions which need to be implemented. In the subsequent sections each stage of the methodology is described and implementation details are provided.

Initial physical characteristics for transformation[3]	Value
Minimum size of existing reservoir (m^3)	1 million
(or) minimum hydropower capacity (MW)	1
Max distance between reservoirs (dams) (km)	5
Minimum head (m)	150
Topology A, assumed new reservoir surface (m^2)	70 000
Minimum distance from inhabited sites to new dam infrastructure (m)	200
Minimum distance from existing transportation infrastructure to new dam infrastructure (m)	100
Minimum distance to a UNESCO site (km)	5
Potential site should not be in a Natura 2000 area	
Maximum distance to suitable grid connection (km)	20

Table 2: summary of parameters used for analysing the potential

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[2] Note the discrepancies with Eurostat data for generation

[3] It has to be noted that the final parameters used were even more restrictive, see e.g. Table 10

1.3.1 Transformation topography, physical characteristics and assumptions

First, the topography and physical characteristics for transformation must be defined, and assumptions must be made on distances to key features (e.g. inhabited sites), sources of data, etc. Each site can then be assessed in a consistent and uniform manner. An overview of the physical characteristics and assumptions is presented in Table 2, where the values were derived from experience and from examination of existing schemes.

The study concentrates on the major dams and therefore excludes all dams and hydropower schemes that have a water storage capacity less than 1 million m³ and have a nominal electricity capacity of less than 1 MW. The existing reservoir can either be the upper or the lower reservoir of a potential transformation site under TA. In the case of topology B both reservoirs have to already exist and the assumption is that the penstock, generation and pumping equipment must be added.

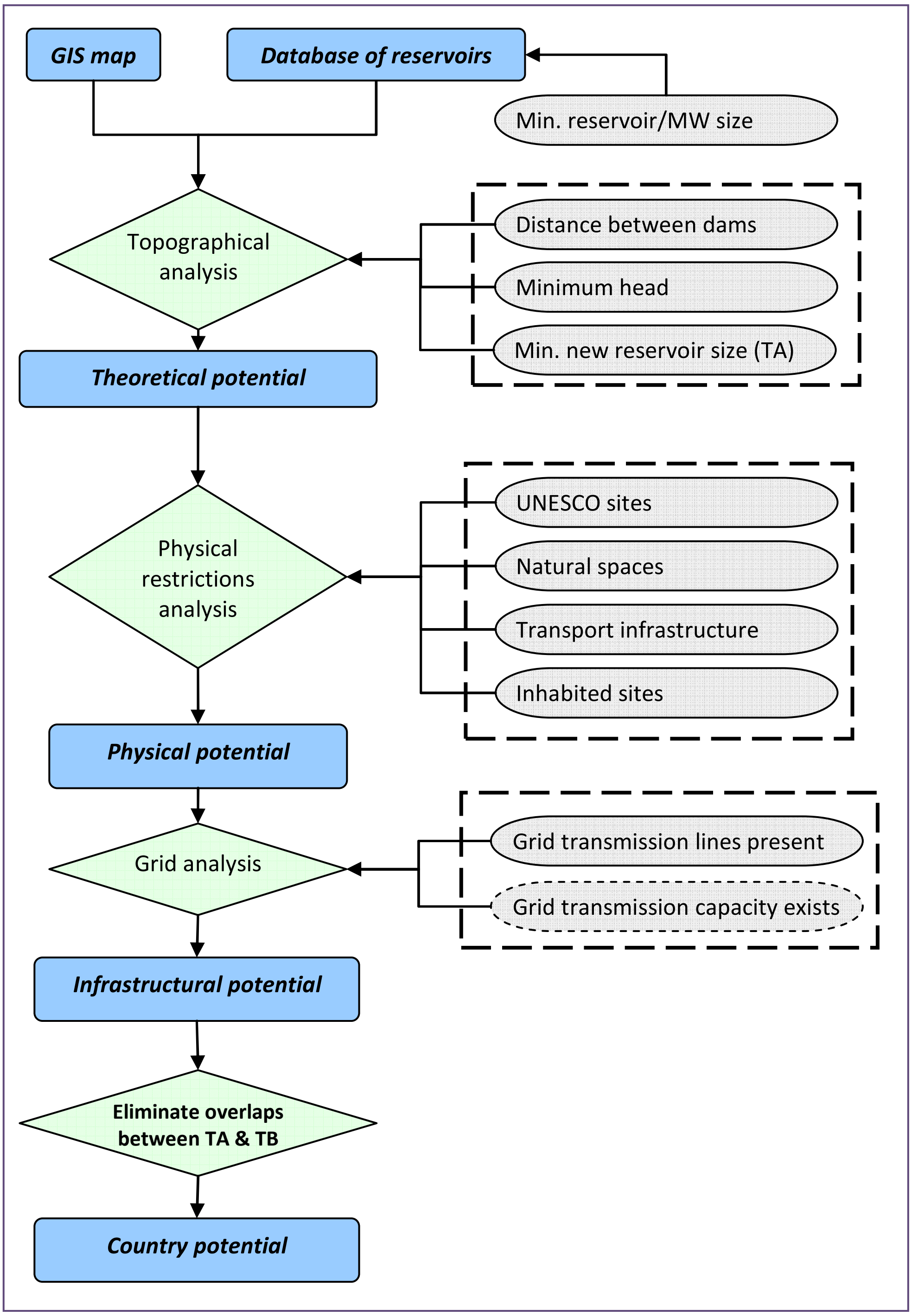

Figure 1: methodology flow chart. The dashed line at ***grid transmission capacity exists*** indicates elements not applied because of lack of appropriate data

- ***Dam types***. It was assumed that all types of dams are suitable for transformation regardless of the dam construction type (rock-fill, concrete etc.).

- The ***distance between the existing and the prospective reservoirs*** under TA, or between the two reservoirs under TB, must not be greater than 5 km. If greater, the transformation to PHS will be deemed not viable. This distance is normally measured between their dams.
- ***Head***. The head for a transformation to PHS should be 150 m or greater, if not then the transformation to PHS will be deemed to be not viable.
- ***Volume and surface of a new reservoir***. The analysis must assume a standard area for the size of a prospective new reservoir in order for constraints to be applied. Based on the requirement of a minimum volume of 1 million m^3, and on an indicative reservoir depth of 20 m, the resulting minimum indicative reservoir surface is 50 000 m^2. In order to take into account embankments and other infrastructure, a minimum indicative size of any prospective reservoir site for TA should be 70 000 m^2.
- ***Human presence***. The restriction on inhabited sites is that if there is an inhabited area within 200 m of a new construction, either a new reservoir or the corresponding penstock, in a transformation site then the transformation to PHS will be deemed to be not viable. Figure 2 illustrates this restriction for TA.

  Both the dams already exist for TB so the inhabited constraint is that there should be no generation, pumping and penstock placed on or within 200 m of an inhabited site.

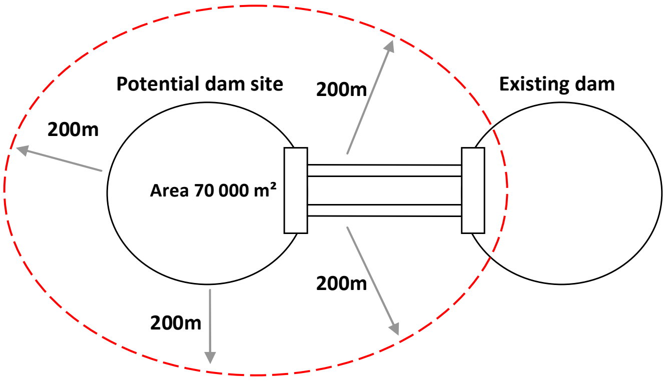

Figure 2: Topology A – minimum distance to inhabited sites

- ***Transport infrastructure***. If there is transport infrastructure within 100 m of a transformation site then the transformation to PHS will be deemed to be not viable. Transportation infrastructure refers to public roads, train lines and bridges (road or rail bridges).
- ***Grid infrastructure***. If the transformation site is a no hydro-dam then there must be suitable grid infrastructure within 20 km, if not the transformation to PHS will be deemed to be not viable. Application of this constraint will be subject to public availability of data, which may not be the case due to security or other considerations.

1.3.2 Energy storage

The potential energy storage will be analysed for each potential site, but it will also be used when merging the results of TA and TB into a global country potential to eliminate overlaps.

The theoretical energy storage available from a reservoir can be expressed as:

$$E = \frac{\rho * g * h * V * \eta}{3600}$$

where:

E = energy storage capacity in Wh
η = efficiency (in general ranging 0.75 to 0.80)
ϱ = density (kg/m^3) (~ 1000 kg/m^3 for water
g = acceleration of gravity (9.81 m/s^2)
h = falling height, head (m)
V = Volume of water in the upper reservoir (m^3)

1.3.3 Methodology definition

For each of topology A and B the following steps and definitions apply to a database of reservoirs above the minimum size as in Table 2:

Theoretical potential: the theoretical potential is the result of applying in the GIS programme the restrictions of minimum reservoir size, maximum distances between reservoirs, and minimum head to every reservoir in the database.

Physical potential: the theoretical potential will be filtered for distances to UNESCO sites, to natural reserves, to transport infrastructure and to inhabited sites to eliminate any sites which do not meet the defined specification for a site to be suitable for transformation to PHS. The result will be the physical potential for both TA and TB.

Infrastructural potential: when grid maps are available the filter of distance to the grid connection will be applied to obtain the "Infrastructural" potential. For the time being it was not possible to obtain data on capacity of the power grid and thus this aspect was not analysed.

Country potential: both infrastructural potentials (TA and TB) will be analysed to eliminate overlaps to realise each country potential. The rules of how the global country potential will be reached will be defined in section 1.4.

Each dam/reservoir in the country being analysed will be given a unique ID, henceforth termed "Dam ID", used to identify each dam during the analysis.

1.3.4 Filters

Topography. The topographical analysis is the first stage of filtering down the potential transformation sites, and uses the distance between dams and minimum head filters. Each of the reservoirs will be analysed under TB to find out whether another dam is within 5 km of the Dam ID and whether the head is greater than 150 m. For TA the GIS analysis will check whether there is a suitable plateau within 5 km of Dam ID and at least 150 m above Dam ID's elevation.

Dam ID sites passing this phase will have one or more potential *second reservoir* associated, which will constitute the theoretical potential for transformation. Then all Dam IDs having passed this topography filter will have the following listed constraints applied to them.

Inhabited sites. For TA if there is any inhabited site within 200 m of the potential site for a second reservoir or of the direct penstock link between it and Dam ID, this potential reservoir is considered unsuitable for transformation and the potential site is dropped. The question is then repeated for any subsequent potential second-dam site for the same Dam ID, then for all the other Dam IDs. For TA the filter is applied to the direct penstock link between two Dam IDs making up a potential site for transformation.

The final application of this constraint will depend on the public availability of detailed information on settlements, but the presence of settlement cluster(s), rather than an individual dwelling, will be deemed to constitute a sufficient level of habitation to apply the constraint in any particular case.

Transport infrastructure. This part analyses whether there is any transport infrastructure site within 100 m of the potential site for a second reservoir or of the direct penstock link between it and Dam ID, as in the inhabited sites case for TA and TB.

Transport infrastructure here refers to public roads, bridges and railways. As in the previous case if the answer is yes the potential site is dropped. The question is then repeated for any subsequent potential site for the same Dam ID, then for all the other Dam IDs.

UNESCO and natural spaces. This aspect of the analysis focuses on nature conservation sites and archaeological and historic location sites[4] and more concretely Natura 2000 areas, those associated to the EUROPARC federation [15], included in UNESCO Biosphere Reserve [16] or World Heritage lists [17], special areas of conservation (SAC), or national parks -most of which are already included in the Biosphere Reserve or EUROPARC lists.

Grid infrastructure. Suitable grid infrastructure must be within 20 km of Dam ID. When Dam ID is an existing hydropower reservoir the answer is already yes – however, this approach obviates whether the existing hydropower site could be enlarged as a result of this analysis because then a higher-capacity export line could be needed. For non-hydropower reservoirs this constrain is most relevant. When suitable GIS-shaped information on the capacity of the grid transmission lines becomes available, this filter could be applied at this stage thus improving the quality of the infrastructural potential.

1.4 Country potential

It is assumed that when both generation and pumping equipment is required this will be in the form of pump-turbines. Then only one penstock will be required.

Transformation following TA will always require the construction of a new reservoir, pumping, equipment and the associated penstock(s) and normally, unless it is a pump-back PHS (not analysed here), the installation of generation equipment. Transformation following TB will not require the construction of a second reservoir but will require the installation of generation and pumping equipment and the associated penstocks. Table 3 below illustrates the required modification needed to the existing reservoirs, whether a no-hydro or hydro reservoir, under TA and TB.

Required modification	**Topology A**		**Topology B**	
	No-hydro reservoir	**Hydro reservoir**	**No-hydro reservoir**	**Hydro reservoir**
Add new reservoir	Yes	Yes	No	No
Add generation	Yes	Yes[note]	Yes	Yes[note]
Add pumping	Yes	Yes	Yes	Yes
Add penstock	Yes	Yes	Yes	Yes

Table 3: matrix analysis of the modifications needed for the different conversion options

Note: - The existing generation equipment installed at a hydropower reservoir would not be suitable, in most cases, to be used for transformation to PHS. The reason is that existing generation equipment was designed for the head of the existing hydro scheme. In TA the new reservoir will normally be the upper reservoir, thus new generation equipment is required. In TB existing generation equipment will never be suitable given the difference in heads, flows and capacities. One case under TA where existing generation equipment may be used is for pump-back PHS (topology D). In this case, the new reservoir is constructed directly below the existing reservoir, thus the head will be the same as the existing hydropower scheme. For pump-back PHS the generation equipment may be replaced with pump turbines[5]. Another scenario is to install a separate pump unit and related penstock, which would reduce the impact on the current generation unit while the transformation is occurring.

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[4] This list of constraints is from the UK Environmental Agency, good practice guidelines to the environmental agency handbook, The environmental assessment of proposed low head hydropower developments, http://publications.environment-agency.gov.uk/pdf/GEHO0310BSCT-E-E.pdf

[5] Pump-turbines refer to a unit which is reversible so it can both generate and pump and share the same penstock. Further analysis of each individual hydropower dam transformation site would be required in order to access the potential to replace current generation equipment with pump turbine equipment for a pump-back PHS.

1.4.1 Merging topologies A and B

The process of merging topologies A and topology B results into an overall country potential and must eliminate overlaps. The level of modification detailed above to transform to PHS will be taken into account in selecting the preferred option for each site. In this study and at this stage this is done by giving TB a higher priority than TA when a given Dam ID results in both options. The reason for this choice is that TB being based in two existing dams/reservoirs, it will only be necessary to add generation and pumping equipment, see note in Table 3 and the difference in cost that is discussed in section 4.2.4.

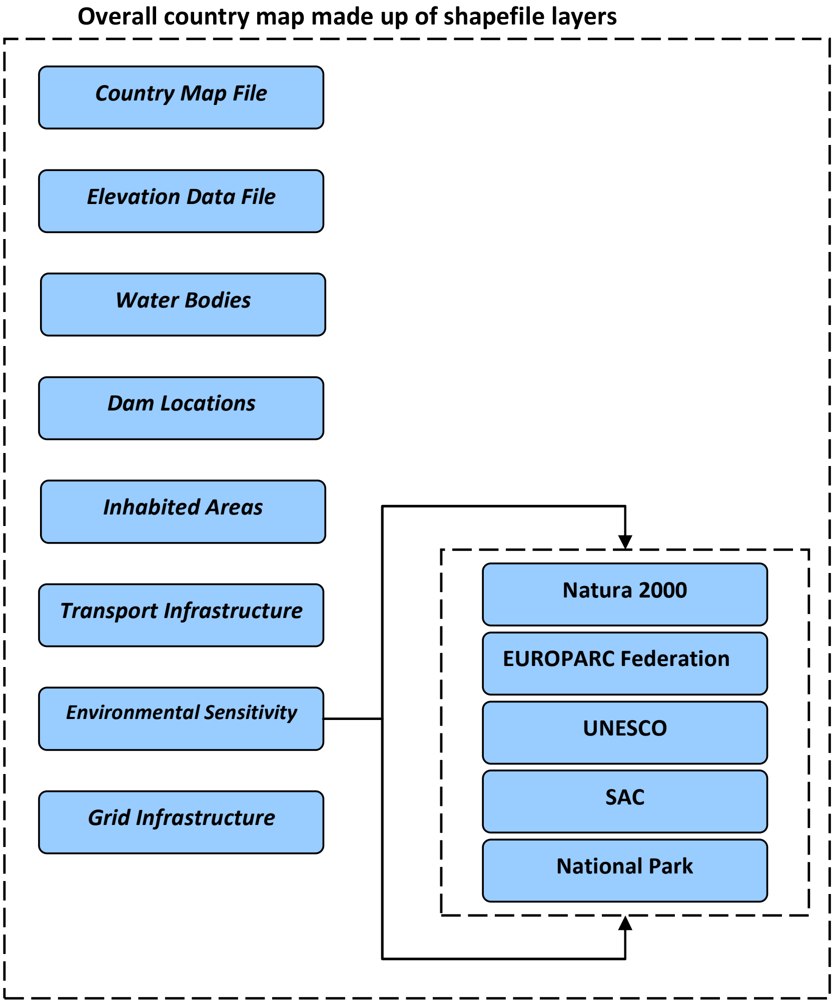

Figure 3: GIS shapefile layers to form an overall country map

1.5 GIS implementation

GIS shapefiles (layers) will be required to build up a full country map for each of the proposed countries. Digital terrain maps will be used to provide topographic information.

Additional data will include: country maps (rivers, water bodies), topography layer (elevation data), inhabited sites, environmental sensitivity (Natura 2000, EUROPARC, UNESCO, SAC, and national parks), and electricity grid both at distribution and transmission level.

2 Database of dams and hydropower schemes

A suitable database of dams with or without a linked hydropower scheme was necessary for finding the potential for transformation. Initial screening of public and private databases showed that none of them included the full range of details needed for this project, the most problematic of which were the geographical coordinates and elevation, and the reservoir capacity. In this assessment is included a focus on reservoirs that either have a water storage capacity larger than 1 million m^3 or have a turbine capacity of 1 MW and a geographical coverage including the members of the European Union (EU) [18], the European Free Trade Area [19], the Western Balkans, EU candidate countries and EU potential candidate countries [20].

This section describes the sources and methodology used to build the database and discusses the reasons why some data were unavailable. The fields in the database are also explained.

2.1 Countries included in database

Country	Status
Albania	Potential Candidate Country
Austria	Member State of EU
Belgium	Member State of EU
Bosnia-Herzegovina	Potential Candidate Country
Bulgaria	Member State of EU
Croatia	Candidate Countries
Cyprus	Member State of EU
Czech Republic	Member State of EU
Denmark	Member State of EU
Estonia	Member State of EU
Finland	Member State of EU
Former Yug. Rep. Of Macedonia	Candidate Countries
France	Member State of EU
Germany	Member State of EU
Greece	Member State of EU
Hungary	Member State of EU
Iceland	Candidate Countries
Ireland	Member State of EU
Italy	Member State of EU
Kosovo (Under Unscr 1244)	Potential Candidate Country
Latvia	Member State of EU
Liechtenstein	European Free Trade Area
Lithuania	Member State of EU
Luxemburg	Member State of EU
Malta	Member State of EU
Montenegro	Potential Candidate Country
Netherlands	Member State of EU
Norway	European Free Trade Area
Poland	Member State of EU
Portugal	Member State of EU
Romania	Member State of EU
Serbia	Potential Candidate Country
Slovakia	Member State of EU
Slovenia	Member State of EU
Spain	Member State of EU
Sweden	Member State of EU
Switzerland	European Free Trade Area
Turkey	Candidate Countries
Ukraine	Other European Country
United Kingdom	Member State of EU

Table 4: list of countries included in the database and their EU status

Country	Hydropower generation (GWh)	Total gross electricity generation (GWh)	Hydropower Percentage	Source
Albania	4 200	4 250		EIA
Austria	36 347	65 500	55 %	Eurostat
Belgium	362	86 577	0 %	Eurostat
Bosnia-Herzegovina	5 050	12 260	41 %	EIA
Bulgaria	3 568	44 636	8 %	Eurostat
Croatia	5 446	12 365	44 %	Eurostat
Cyprus	0	4 745	0 %	Eurostat
Czech Republic	2 261	84 664	3 %	Eurostat
Denmark	25	39 349	0 %	Eurostat
Estonia	21	10 677	0 %	Eurostat
Finland	14 142	77 884	18 %	Eurostat
Former Yug. Rep. Of Macedonia	1 240	6 250	20 %	EIA
France	57 973	574 150	10 %	Eurostat
Germany	20 339	632 803	3 %	Eurostat
Greece	4 242	62 014	7 %	Eurostat
Hungary	203	37 900	1 %	Eurostat
Iceland	7 156	9 308	77 %	Eurostat
Ireland	748	27 840	3 %	Eurostat
Italy	36 875	312 709	12 %	Eurostat
Kosovo (Under Unscr 1244)				
Latvia	2 966	4 960	60 %	Eurostat
Liechtenstein				
Lithuania	418	13 796	3 %	Eurostat
Luxemburg	113	4 007	3 %	Eurostat
Malta	0	2 140	0 %	EIA
Montenegro	1 640	2 740	60 %	EIA
Netherlands	101	102 855	0 %	Eurostat

Country	Hydropower generation (GWh)	Total gross electricity generation (GWh)	Hydropower Percentage	Source
Norway	132 057	134 862	98 %	Eurostat
Poland	2 187	158 551	1 %	Eurostat
Portugal	8 156	47 210	17 %	Eurostat
Romania	17 931	62 185	29 %	Eurostat
Serbia	10 090	34 610	29 %	EIA
Slovakia	4 382	29 960	15 %	Eurostat
Slovenia	3 584	15 419	23 %	Eurostat
Spain	24 044	303 075	8 %	Eurostat
Sweden	67 441	150 205	45 %	Eurostat
Switzerland	33 368	65 146	51 %	Eurostat
Turkey	38 232	182 058	21 %	Eurostat
Ukraine	11 590	180 940	6 %	EIA
United Kingdom	4 943	395 501	1 %	Eurostat

Table 5: overview of the percentage of hydropower generation. Sources: Eurostat [6], EIA [21]

Table 5 presents an overview of the percentage of electricity generated by hydropower, on average 2005 to 2008 when the source is Eurostat [6], in the countries included in the database. Data from EIA [21] is 4- or 5-yr average and total generation is net instead of gross, and the percentages are therefore calculated on a different basis yet they all are representative. It is clear from this table that hydropower plays an important role in the electricity generation portfolios of most countries in Europe.

2.2 Data sources

As pointed out above, error-free global data sets describing reservoir characteristics and geographical distribution are largely incomplete. The best and most comprehensive global dam database, the World Register of Dams, is compiled by the International Commission on Large Dams (ICOLD) [22] and currently lists more than 33 000 records of large reservoirs and their attributes. However, this database is not geo-referenced thus its use is limited for this project. Despite this and because it is the most comprehensive database available, it forms the primary data source for this study.

Each data source that was used to compile the database will be described below. For each of the countries a justification of effort taken to gather the data will be made in the cases where the dataset is not fully complete.

2.2.1 International Commission of Large Dams (ICOLD), World Register of Dams

The International Commission on Large Dams (ICOLD) is a non-governmental international organisation which provides a forum for the exchange of knowledge and experience in dam engineering. The Organisation leads the profession in ensuring that dams are built safely, efficiently, economically, and without detrimental effects on the environment. Its original aim was to encourage advances in the planning, design, construction, operation, and maintenance of large dams and their associated civil works, by collecting and disseminating relevant information and by studying related technical questions. Since the late sixties, focus was put on subjects of current concern such as dam safety, monitoring of performance, reanalysis of older dams and spillways, effects of ageing and environmental impact. More recently, new subjects include cost studies at the planning and construction stages, harnessing international rivers, information for the public at large, and financing. (Background description from ICOLD [22])

ICOLD produce the world register of dams. This database is compiled by ICOLD by accessing data through the ICOLD representatives of the member countries, is a comprehensive database of hydropower and no-hydropower reservoirs and provides detailed information on each reservoir listed.

The ICOLD database has some drawbacks for this project mainly because of the coverage and accuracy of the data provided. The primary of these drawbacks is that it does not provide geo-referencing or elevation information. There are also issues with the accuracy of the storage capacity and area of some of the reservoirs. The GRanD project team have also highlighted this as an issue.

Being the most complete source of data on dams globally the world register of dams forms the primary source of data for this database. Where data are incomplete secondary sources in each country are also utilised to fill these data gaps.

2.2.1 The Global Reservoir and Dam (GRanD) database [23]

To address gaps and shortcomings in global dam databases, the Global Water System Project (GWSP) [24], a joint project of the Earth System Science Partnership (ESSP), initiated an international effort to collate the existing dam and reservoir data sets with the aim of providing a single, geographically explicit and reliable database for the scientific community: the Global Reservoir and Dam (GRanD) database. The development of GRanD primarily aimed at compiling the available reservoir and dam information; correcting it through extensive cross-validation, error checking, and identification of duplicate records, attribute conflicts, or mismatches; and completing missing information from new sources or statistical approaches. The dams were geospatially referenced and assigned to polygons depicting reservoir outlines at high spatial resolution. While the main focus was to include all reservoirs with a storage capacity of more than 0.1 km^3*, many smaller reservoirs were added if data were available. The current version 1.1 of GRanD contains 6,862 records of reservoirs and their associated dams, with a cumulative storage capacity of 6,197* km^3*. (Source: GRanD technical documentation)*

Table 6 presents the number of ICOLD dams that GRanD have geo-referenced, and which contributed a total of 21% of the geo-references in the dams in our database. The elevation above mean sea level (AMSL) of these geo-referenced dams is also available and was added to the database.

Country	Number ICOLD dams	Number of GRanD dams	Percentage Geo-referenced
Albania	308	5	2 %
Austria	168	22	13 %
Belgium	17	5	29 %
Bosnia-Herzegovina	31	9	29 %
Bulgaria	181	46	25 %
Croatia	40	8	20 %
Cyprus	52	4	8 %
Czech Republic	126	35	28 %
Denmark	10	0	0 %
Estonia	2	0	0 %
Finland	56	19	34 %
FYRO Macedonia	18	0	0 %
France	597	114	19 %
Germany	307	60	20 %
Greece	61	19	31 %
Hungary	16	4	25 %
Iceland	25	6	24 %
Ireland	18	4	22 %
Italy	549	87	16 %
Kosovo	2	0	0 %
Latvia	5	3	60 %
Liechtenstein	2	0	0 %
Lithuania	20	2	10 %
Luxemburg	7	1	14 %
Malta	0	0	0 %
Montenegro	10	3	30 %
Netherlands	12	8	67 %
Norway	335	125	37 %
Poland	69	29	42 %
Portugal	151	53	35 %
Romania	246	80	33 %
Serbia	68	19	28 %
Slovakia	50	16	32 %
Slovenia	37	2	5 %
Spain	1267	252	20 %
Sweden	194	49	25 %
Switzerland	159	38	24 %
Turkey	671	101	15 %
Ukraine	22	9	41 %
United Kingdom	515	89	17 %
Total	6424	1326	21 %

Table 6: percentage of ICOLD dams that have been geo-referenced by GRanD

2.2.2 Google Earth manual geo-referencing of Croatia and Turkey

A complete set of geo-referenced dams was required for the potential transformation countries, Croatia and Turkey, this was a total of 40 dams in Croatia and 671 dams in Turkey. As presented in Table 6 GRanD only provides geo-referencing for 20 % and 15 % of dams in Croatia and Turkey respectively and thus the remaining dams were geo-referenced manually using Google Earth by visually searching there using the nearest town name in the ICOLD database, then when a dam was located close to "nearest town" it was verified visually in Google Earth where possible by comparing it with the picture of the dam if available. This task was extremely time consuming[6] and although all possible care was taken there may be errors present due to lack of information available when visually recognising the dams.

This methodology was the same one used by the GRanD project for geo-referencing dams in their database. When sites are geo-referenced, the elevation AMSL in metres can then be calculated through ArcGIS using SRTM elevation data. This option was preferred to obtaining elevation directly from Google Earth for consistency reasons, as the next modelling steps will be based on SRTM elevation data.

2.2.3 Shuttle Radar Topography Mission (SRTM) elevation data

Remotely sensed elevation data were obtained from the Shuttle Radar Topography dataset: "*The CGIAR-CSI GeoPortal is able to provide SRTM 90m digital elevation models (DEM) for the entire world. The SRTM digital elevation data provided on this site has been processed to fill data voids, and to facilitate its ease of use by a wide group of potential users. The SRTM 90 m DEM's have a (*horizontal*) resolution of 90m at the equator, and are provided in mosaicked 5 deg x 5 deg tiles for easy download and use. All are produced from a seamless dataset to allow easy mosaicking. These are available in both ArcInfo ASCII and GeoTiff format to facilitate their ease of use in a variety of image processing and GIS applications." [25]*

SRTM's vertical resolution is approximately 10 m depending on location, and SRTM data are used to calculate the elevation AMSL by importing the shapefile geo-referenced in Google Earth into ArcGIS. Then, by running the 'extract tool' in ArcGIS the geo-referenced dams combine with the SRTM elevation to calculate the elevation of each dam. SRTM elevation was validated with Google Earth data resulting in very consistent figures

2.2.4 Regulators and transmission system operators

An area where there was a lack of data in the primary data source was the mean annual energy (GWh/year) generated from hydropower plants. The electricity regulators and transmission system operators of each of the countries where data were absent were contacted to request this data, if publicly available. From the replies we received some new data which was previously absent, but many of the responses confirmed our initial feeling that this data are considered commercially sensitive and are not publicly available. The electricity regulators and transmission system operators of the countries in the database are listed in Table 7.

Country	Electricity Regulator	Transmission System Operator
Albania	Albanian Electricity Regulatory Authority	OST sh.a
Austria	Energie-Control GmbH (E-Control)	APG-Austrian Power Grid AG VKW-Netz AG
Belgium	Commission pour la Régulation de l'Electricité et du Gaz (CREG)	Elia System Operator SA
Bosnia-Herzegovina	State Electricity Regulatory Commission (SERC)	Nezavisni operator sustava u Bosni i Hercegovini
Bulgaria	State Energy & Water Regulatory Commission (SEWRC)	Electroenergien Sistemen Operator EAD
Croatia	Croatian energy regulatory agency	HEP-Operator prijenosnog sustava d.o.o.
Cyprus	Cyprus Energy Regulatory Authority (CERA)	Cyprus Transmission System Operator
Czech Republic	Energetický Regulační Úřad (ERÚ)	CEPS a.s.
Denmark	Energitilsynet - Danish Energy Regulatory Authority (DERA)	Energinet.dk
Estonia	Estonian Competition Authority - Energy Regulatory Dept (ECA)	Elering OÜ
Finland	The Energy Market Authority (EMV)	Fingrid OyJ
Former Yug. Rep. Of Macedonia	Energy Regulatory Commission of the Republic of Macedonia	Macedonian Transmission System Operator AD

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[6] We estimated at 30 – 40 sites being geo-referenced per day for one person not knowing the native language.

Country	Electricity Regulator	Transmission System Operator
France	Commission de Régulation de l'Energie (CRE)	Réseau de Transport d'Electricité
Germany	Federal Network Agency for Electricity	EnBW Transportnetze AG TenneT TSO GmbH Amprion GmbH 50Hertz Transmission GmbH
Greece	Regulatory Authority for Energy (PAE / RAE)	Hellenic Transmission System Operator S.A.
Hungary	Hungarian Energy Office (MEH / HEO)	MAVIR Magyar Villamosenergia-ipari Átviteli Rendszerirányító Zártköruen Muködo Részvénytársaság
Iceland	National Energy Authority	Landsnet hf
Ireland	Commission for Energy Regulation (CER)	EirGrid plc
Italy	Autorità per l'Energia Elettrica e il Gas (AEEG)	Terna - Rete Elettrica Nazionale SpA
Kosovo (under UNSCR 1244)	Energy Regulatory Office	KOSTT
Latvia	Public Utilities Commission (PUC)	AS Augstsprieguma tÏkls
Liechtenstein		
Lithuania	National Control Commission for Prices and Energy (NCC)	LITGRID AB
Luxemburg	Institut Luxembourgeois de Régulation (ILR)	Creos Luxembourg S.A.
Malta	Malta Resources Authority (MRA)	
Montenegro	Energy Regulatory Agency Of Montenegro	Crnogorski elektroprenosni sistem AD
Netherlands	Dutch Office of Energy Regulation	TenneT TSO B.V.
Norway	Norwegian Water Resources and Energy Directorate (NVE)	Statnett SF
Poland	The Energy Regulatory Office of Poland (ERO)	PSE Operator S.A.
Portugal	Energy Services Regulatory Authority (ERSE)	Rede Eléctrica Nacional, S.A.
Romania	Romanian Energy Regulatory Authority (ANRE)	C.N. Transelectrica S.A.
Serbia	Energy Agency of the Republic of Serbia	JP Elektromreža Srbije
Slovakia	Regulatory Office for Network Industries (RONI)	Slovenska elektrizacna prenosova sustava, a.s.
Slovenia	Energy Agency of the Republic of Slovenia	Elektro Slovenija d.o.o.
Spain	National Energy Commission (CNE)	Red Eléctrica de España: S.A.
Sweden	Energy Markets Inspectorate(EI)	Affärsverket Svenska Kraftnät
Switzerland	Swiss Federal Electricity Commission ElCom	Swissgrid ag
Turkey	Turkish Electricity	TEIAS
Ukraine	National Electricty Regulatory Comission of Ukraine	National Energy Company Ukrenergo
United Kingdom	Office of Gas and Electricity Markets (Ofgem)	National Grid Electricity Transmission plc System Operation Northern Ireland Ltd Scottish and Southern Energy plc Scottish Power Transmission plc

Table 7: electricity regulators and transmission system operators of countries in database (hyperlinked)

2.2.5 Sources of country specific dam information

Where information was not available from the primary data sources or from the regulators and the TSO's on dams, attempts where then made to access data from other sources. Table 8 provides a list of some of the other sources that were utilised.

Country	Secondary data sources	
Albania	National Agency of Natural Resources	
Austria	Europe Environment Agency	Hydro-Austria
Bosnia-Herzegovina	http://www.hydroworld.com/	
Bulgaria	Bulgaria Energy Holding	
Croatia	HEP Proizvodnja d.o.o.	
Czech Republic	CEZ	
Denmark	Energy Map	
Estonia	INFORSE - Europe	
Finland	Pamilo	Hydropower in Finland
Former Yug. Rep. Of Macedonia	Elem	
France	COMPAGNIE NATIONALE DU RHÔNE	
Germany	RWE	http://www.industcards.com/ppworld.htm
Iceland	Landsvirkjun	Mannvit
Ireland	Lee Catchment Flood Risk Assessment and Management Study	
Kosovo (under UNSCR 1244)	Kosovo Energy Corporation J.S.C.	
Latvia	Latvenergo	
Liechtenstein	Klimastiftung	
Lithuania	http://saule.lms.lt/main/hidro_e.html	http://www.kruoniohae.lt/en
Luxemburg	http://www.lahmeyer.de/en/projects/details/project/86/	
Montenegro	Elektroprivreda Crne Gore-EPCG	Hydropower in Montenegro
Serbia	Electric power industry of Serbia	Serbia Energy
Turkey	General Directorate of State Hydraulic Works	Artvin - Deriner Barajı ve HES

Table 8: list of secondary sources

2.3 Database fields

This section will describe each field in the database and explain any abbreviations used, if applicable.

Dam name. The dam name field contains the primary name of the dam. Names are given in forms with Latinised character sets.

Alternative dam name. If a dam is known by two names or has an alternative name then it will be listed in this field. Examples include the following dams in Austria

Dam name	Other dam name
Shkopet	Shkopeti
Tervolit	Tervol
Ulza	Ulez
Zadeje	Vau Dejes

River. The river field contains the name of the river that the dam is constructed on.

Nearest town. The nearest town field contains the name of the town nearest to the dam site. This data were of particular importance when manually geo-referencing the dams using Google Earth.

State/province/county. The state/province/county field is the secondary location, i.e. second administrative entity below country level. Whichever format is applicable to the country in question will be entered in this field.

Elevation (m). The elevation of the dam crest above mean sea level (AMSL) in metres, from the GRanD database and SRTM data as detailed in section 2.2.

Latitude and longitude (degrees and decimals). The latitude and longitude fields contain the latitude/longitude, in degrees and decimal, of approximately the centre of dam.

Dam height and length (m). The dam height and length fields contain the height/length of the dam structure in meters.

Dam volume. The dam volume is included in two fields with different units, one in thousands of cubic metres, (1000 m^3) -a unit consistent with ICOLD-, and the other in m^3 in order to avoid any confusion caused by the ICOLD unit 1000 m^3. This field is not

Reservoir capacity. The reservoir capacity is as well included in two fields with different units, one in thousands of cubic meters, (1000 m^3) -a unit consistent with ICOLD-, and the other in m^3 in order to avoid any confusion caused by the ICOLD unit 1000 m^3.

Reservoir area. The reservoir area is as well included in two fields with different units, one in thousands of square metres (1000 m^2) -a unit consistent with ICOLD-, and the other in m^2 in order to avoid any confusion caused by the ICOLD unit 1000 m^2.

Electric installed capacity (MW). This field is populated when the dam in question is operated as a hydropower plant.

Mean annual energy (GWh/year). The mean annual energy (GWh/year) field is populated when the dam in question is operated as a hydropower plant. It was found that this data are difficult to acquire for individual hydropower plants due to confidentiality requirements within many of the markets. Where publicly available the data were added.

Dam status. The dam status field defines if the dam structure has been changed over its lifetime. The abbreviations used are: A abandoned; H heightened; L lowered; U unchanged; R rebuilt; C under construction.

Year of completion. Year that the dam came into operation whether it is a hydro or no-hydro dam. If the dam was changed or repowered in its lifetime the re-powering date will appear as follows for example, 19xx/xx. The 19xx is the original completion date, /xx is the date of change or repowering.

Reservoir purpose. Field defining how the reservoir is being used. The abbreviations are: H= HPP; S= water supply; C= flood control; I= irrigation; N= navigation; R= recreation; F= fish breeding; X= others. If a reservoir has more than one purpose the letters will be listed on after another without space or comma. The priority of use for reservoirs with more than one purpose is defined by the order in which they appear. For example if a reservoir has it purpose listed as "HCI" this means that its main use is hydropower; its second main use is flood control; then irrigation. These codes follow the ICOLD convention.

Owner. Name of the company or organisation who is the owner of the dam, when known.

Consultant/contractor. Name of the company or organisation that designed/built the dam.

A field for observations (Note) was also included.

2.4 Disclaimer of warranty and citations of data utilised in database

ICOLD (International Commission on Large Dams). 1998–2009. World Register of Dams. Version updates 1998-2009. Paris: ICOLD. Available online at www.icold-cigb.net. ICOLD (International Commission on Large Dams). 1998–2009. World Register of Dams. Version updates 1998-2009. Paris: ICOLD. Available online at www.icold-cigb.net.

This database incorporates data from the GRanD database which is copyright of the Global Water System Project (2011). GRanD is described in further detail by Lehner et al. [26]

3 Potential for transformation to PHS

This section applies the methodology detailed in section 1 to the data described in section 2 for Croatia and Turkey, by means of a geographical information system (GIS), ArcGIS, to describe and quantify two potentials after topology A (TA) and topology B (TB). The section details the data and data files required to carry out the analysis, the design of the GIS model, the design of the different scenarios and the results of the scenarios.

A transformation site is the original dam under examination with a potential reservoir site which will create a new PHS plant.

3.1 Data required and data processing

To build up a GIS map the data must be first gathered and then converted into a usable format. In order to describe and quantify the potential for transformation to PHS a number of types of data are required as detailed below:

3.1.1 Coordinate system

A geographic coordinate system is a reference system that uses latitude and longitude to define the locations of points on the surface of a sphere or spheroid. A geographic coordinate system definition includes a datum, prime meridian, and angular unit[7].

Unlike a geographic coordinate system, a projected coordinate system is defined on a flat, two-dimensional surface with constant lengths, angles, and areas across the two dimensions – it is always based on a geographic coordinate system that is based on a sphere or spheroid.

The modelling process of describing and quantifying the potential for transformation to PHS requires the GIS data to be in projected coordinate system format. This is because the analysis is based around the ArcGIS slope tool, which in order to calculate the slope, requires all inputs to be in the same format. In this case the slope tool requires all data to be in metres and thus a projected coordinate system is required. All data are downloaded in GCS_WGS_1984 coordinate system. These data are then converted to projected coordinate system using ArcGIS' "project" tool (Data management tools/Projections and transformations).

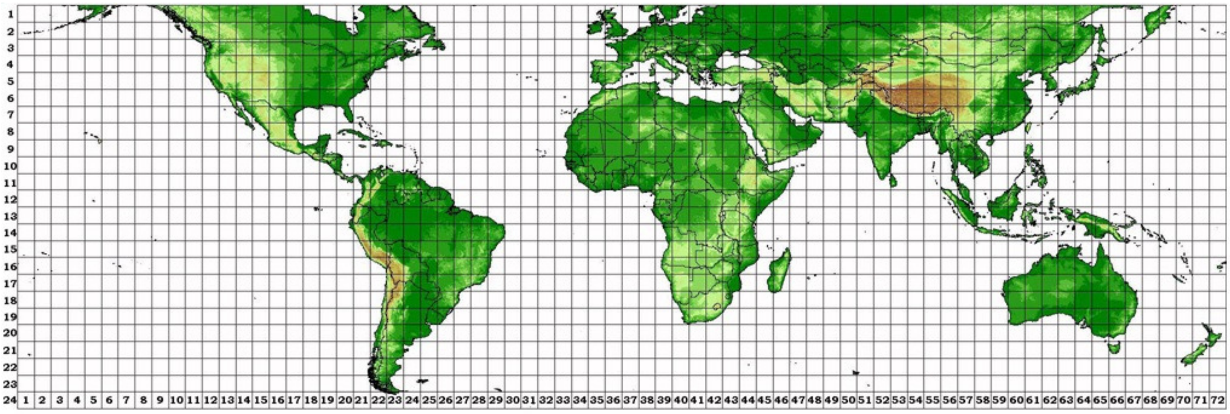

Figure 4: SRTM elevation data download map

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[7] See Wikipedia and ESRI (www.esri.com) for further definitions

Each country may cross many UTM zones so when projecting one UTM zone must be selected. The projected coordinate system selected for Croatia is WGS_1984_UTM_Zone_34N, and for Turkey is WGS_1984_UTM_Zone_36N

3.1.2 Shuttle Radar Topography Mission (SRTM) elevation data

The elevation data used for the analysis is processed SRTM 90m digital elevation data. These data were obtained from the European Commission's Joint Research Centre website, http://srtm.jrc.ec.europa.eu/ and can be downloaded directly from http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp.

The SRTM data are available for the whole world, which is broken down into 1728 blocks. Due to the data being available in blocks, the country of interest may cover more than one of these blocks. Each block is downloaded and then merged into one raster layer using ArcGIS' Mosaic tool (Raster Dataset/Mosaic to New Raster), to form one elevation file for each country.

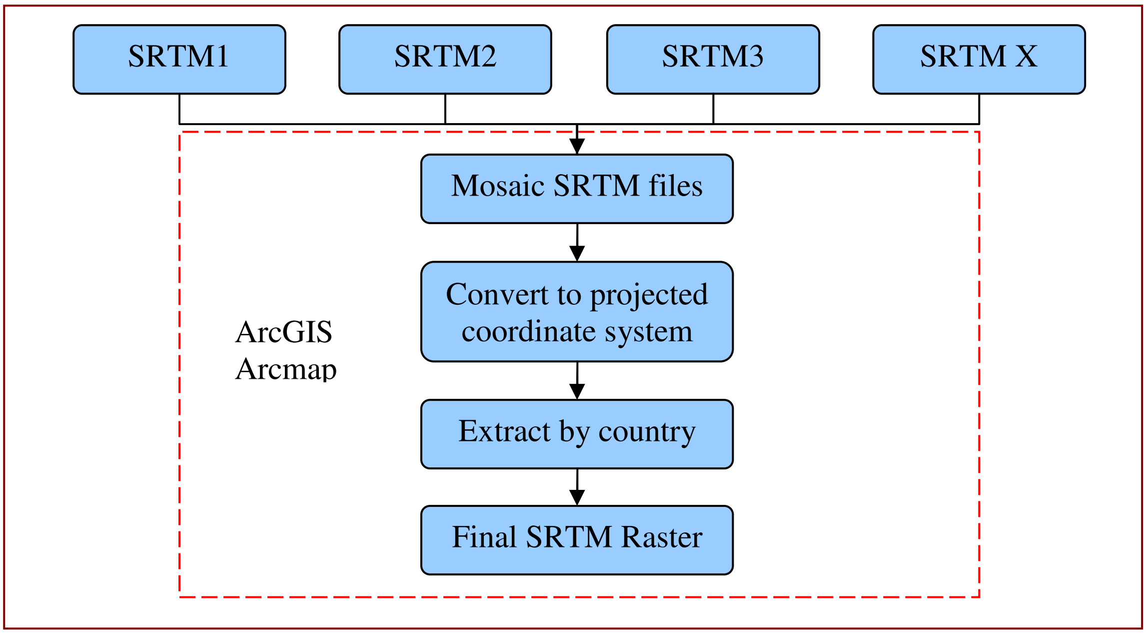

Figure 5: methodology for creating a single SRTM raster elevation file

Then the mosaicked geographic coordinate system raster file must be converted to projected coordinate system using the "project raster tool" which is in the ArcGIS toolbox "Data Management/Projections and Transformations/Raster/Project Raster".

This new mosaicked layer will not detail the political boundaries of the country of interest. This step uses a layer with the political borders of the country as a "cookie cutter" to select only the SRTM data that in within the political borders. This process is executed using the ArcGIS extract tool (Spatial Analysis Tools/Extraction/Extract by Mask).

3.1.3 Political borders

The political borders layer illustrates the shape of the border of the country in question. The layer file was obtained from DIVA-GIS [27] in geographic coordinate system format. The layer was converted to projected coordinate system using the "project tool" which is in the ArcGIS toolbox "Data Management/Projections and Transformations/Feature/Project".

3.1.4 Dam locations

As explained above, the methodology for geo-referencing dam locations was based on creating a database of all dams with a capacity above one million m^3 or 1 MW of installed hydropower capacity. The database was composed of ICOLD data which were then added geographical references (latitude, longitude) from the GRanD database for 15 – 20 % of the Croatian and Turkish dams. The rest of the latitude and longitude data were obtained manually by locating the dams in Google Earth based on the ICOLD name of the dam – the same methodology used to populate the GRanD database with geo-references. To put into context the extent of the manual work around 32 dams in Croatia and 570 dams in Turkey were geo-referenced manually. This task was extremely time consuming[6] and although all possible care was taken to reference each dam correctly there may be errors present, due to lack of information available when visually recognising the dams. The methodology for locating these dams in Google Earth was as follows.

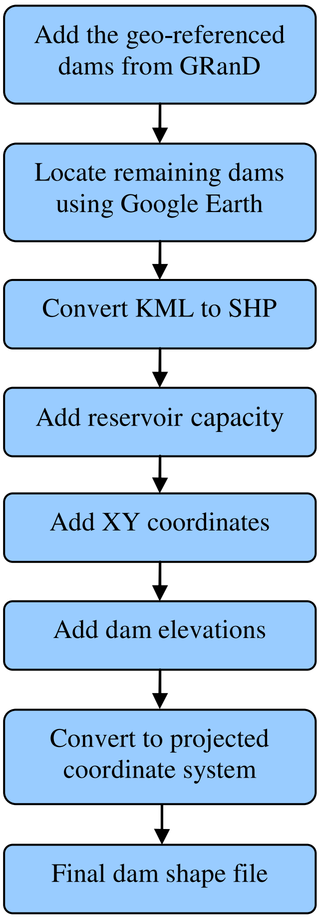

Figure 6: geo-referencing dam locations

- Each dam was searched for based on the “nearest town” field in the database using Google Earth.
- When a dam was located close to “nearest town”, it was verified visually in Google Earth where possible, by comparing it with the picture of the dam if available on the Turkish DSI website [12].

All the dam locations were recorded in a Google Earth KML file. In order to use the dam locations in ArcGIS the Google Earth KML file was converted to an ArcGIS shapefile. For this, a script that converts Google Earth KML files to shape files was obtained from ESRI [28]. This script is added to the ArcGIS toolbox and the file is converted to a shapefile

Reservoir capacity data were imported from the database through the import features of ArcGIS. Latitude and longitude coordinates were added to ArcGIS shapefile attributes table using the “add XY coordinates” tool, which is in the ArcGIS toolbox “Data Management/ Feature/Add XY Coordinates”.

The elevation from the SRTM raster was extracted and added to the dam location attributes table using the “Extract Values to Points” tool, which is in the ArcGIS toolbox “Spatial Analysis Tools/Extraction/Extract Values to Points”.

The dam locations geographic coordinate system shapefile file was then converted to projected coordinate system using the “project raster tool” which is in the ArcGIS toolbox “Data Management/Projections and Transformations/Raster/Project Raster”.

3.1.5 CORINE land cover (CLC) 2006 100m version 13 (02/2010) [29]

CLC is a map of the European environmental landscape based on interpretation of satellite images. It provides comparable digital maps of land cover for each country for much of Europe. This is useful for environmental analysis and for policy makers. CORINE stands for *Coordination of Information on the Environment*. The EU established CORINE in 1985 to create pan-European databases on land cover, biotopes (habitats), soil maps and acid rain.

The European Environment Agency, in conjunction with the European Space Agency, the European Commission and Member States produced an update of the European CLC database as part of a Fast Track Service on Land as part of the *Global Monitoring for Environment and Security* (GMES) initiative. This update involved:

- The creation of a change dataset for the period 2000-2006 with local interpretation of satellite imagery; and
- The application of this change dataset to the CLC2000 dataset to produce an update of the full inventory for 2006 (the snapshot database).

The CLC data for Croatia and Turkey were extracted from the European data site and are used for the inhabited areas and road/rail constraint. Table 9 provides the CORINE grid codes which identify the categories the data are divided into.

No.	Label 1	Label 2	Label 3
1	Artificial surfaces	Urban fabric	Continuous urban fabric
2	Artificial surfaces	Urban fabric	Discontinuous urban fabric
3	Artificial surfaces	Industrial, commercial and transport units	Industrial or commercial units
4	Artificial surfaces	Industrial, commercial and transport units	Road and rail networks and associated land
5	Artificial surfaces	Industrial, commercial and transport units	Port areas
6	Artificial surfaces	Industrial, commercial and transport units	Airports
7	Artificial surfaces	Mine, dump and construction sites	Mineral extraction sites
8	Artificial surfaces	Mine, dump and construction sites	Dump sites
9	Artificial surfaces	Mine, dump and construction sites	Construction sites
10	Artificial surfaces	Artificial, non-agricultural vegetated areas	Green urban areas
11	Artificial surfaces	Artificial, non-agricultural vegetated areas	Sport and leisure facilities
12	Agricultural areas	Arable land	Non-irrigated arable land
13	Agricultural areas	Arable land	Permanently irrigated land
14	Agricultural areas	Arable land	Rice fields
15	Agricultural areas	Permanent crops	Vineyards
16	Agricultural areas	Permanent crops	Fruit trees and berry plantations
17	Agricultural areas	Permanent crops	Olive groves
18	Agricultural areas	Pastures	Pastures
19	Agricultural areas	Heterogeneous agricultural areas	Annual crops associated with permanent crops
20	Agricultural areas	Heterogeneous agricultural areas	Complex cultivation patterns
21	Agricultural areas	Heterogeneous agricultural areas	Land principally occupied by agriculture, with significant areas of natural vegetation
22	Agricultural areas	Heterogeneous agricultural areas	Agro-forestry areas
23	Forest and semi natural areas	Forests	Broad-leaved forest
24	Forest and semi natural areas	Forests	Coniferous forest
25	Forest and semi natural areas	Forests	Mixed forest
26	Forest and semi natural areas	Scrub and/or herbaceous vegetation	Natural grasslands
27	Forest and semi natural areas	Scrub and/or herbaceous vegetation	Moors and heathland
28	Forest and semi natural areas	Scrub and/or herbaceous vegetation	Sclerophyllous vegetation
29	Forest and semi natural areas	Scrub and/or herbaceous vegetation	Transitional woodland-shrub
30	Forest and semi natural areas	Open spaces with little or no vegetation	Beaches, dunes, sands
31	Forest and semi natural areas	Open spaces with little or no vegetation	Bare rocks
32	Forest and semi natural areas	Open spaces with little or no vegetation	Sparsely vegetated areas
33	Forest and semi natural areas	Open spaces with little or no vegetation	Burnt areas
34	Forest and semi natural areas	Open spaces with little or no vegetation	Glaciers and perpetual snow
35	Wetlands	Inland wetlands	Inland marshes
36	Wetlands	Inland wetlands	Peat bogs
37	Wetlands	Maritime wetlands	Salt marshes
38	Wetlands	Maritime wetlands	Salines
39	Wetlands	Maritime wetlands	Intertidal flats
40	Water bodies	Inland waters	Water courses
41	Water bodies	Inland waters	Water bodies
42	Water bodies	Marine waters	Coastal lagoons
43	Water bodies	Marine waters	Estuaries
44	Water bodies	Marine waters	Sea and ocean
48	NODATA	NODATA	NODATA
49	Unclassified	Unclassified land surface	Unclassified land surface
50	Unclassified	Unclassified water bodies	Unclassified water bodies
255	Unclassified	Unclassified	Unclassified

Table 9: CORINE grid codes

Water courses (grid code 40) and water bodies (grid code 41) form the rivers and lakes layer and it was added for mapping and aesthetics and do not have any input to the model.

Inhabited areas and industrial and commercial units are included from: continuous urban fabric (grid code 1), discontinuous urban fabric (grid code 2), and industrial and commercial units (grid code 3).

3.1.6 UNESCO Sites

The United Nations Educational, Scientific and Cultural Organization (UNESCO) seek to encourage the identification, protection and preservation of cultural and natural heritage around the world considered to be of outstanding value to humanity. This is embodied in an international treaty called the Convention concerning the Protection of the World Cultural and Natural Heritage, adopted by UNESCO in 1972 [17].

Croatian cultural sites included in this analysis are: Episcopal Complex of the Euphrasian Basilica in the Historic Centre of Porec (1997); Historic City of Trogir (1997); Historical Complex of Split with the Palace of Diocletian (1979); Old City of Dubrovnik (1979); Stari Grad Plain (2008); and the Cathedral of St James in Sibenik (2000). The only natural reserve site included is the Plitvice Lakes National Park (1979).

Turkish cultural sites included the Archaeological Site of Troy (1998); City of Safranbolu (1994); Great Mosque and Hospital of Divriği (1985); Hattusha: the Hittite Capital (1986); Hierapolis-Pamukkale (1988); Historic Areas of Istanbul (1985); Nemrut Dağ (1987); and Xanthos-Letoon (1988). Two world heritage mixed nature/cultural sites were also included, the Göreme National Park and the Rock Sites of Cappadocia (1985), and the Hierapolis-Pamukkale (1988).

Shapefiles of UNESCO sites were not available for Croatia or Turkey. However, coordinates of the sites were available on the UNESCO website [17]. These coordinates were added to Google Earth and then converted from KML to an ArcGIS shapefile.

In order to use these data as a constraint in the model a buffer of 5 km is applied to each point. No transformation site is permitted within this 5 km area.

3.1.7 Environmental sensitivity

The environmental aspects were based around Natura 2000, an EU wide network of nature protection areas. It is comprised of Special Areas of Conservation (SAC), and of Special Protection Areas (SPAs). [31]. Even when Croatia and Turkey are not yet in the EU-27, and thus are not required to have Natura 2000 designated conservation areas, as EU candidate countries they are required to being establishing Natura 2000 areas. Croatian Natura 2000 data were obtained from http://Natura2000.dzzp.hr/Natura2000/; however, the authors were unsuccessful in finding Natura 2000 data for Turkey.

The prospective sites should not be in a Nature 2000 area.

3.1.8 Transport infrastructure

The rail and road GIS shapefiles were obtained from DIVA-GIS [27] in geographic coordinate system format. The shapefiles were converted to projected coordinate system using the "project tool" which is in the ArcGIS toolbox "Data Management/Projections and Transformations/Feature/ Project".

3.1.9 Electricity grid infrastructure

We were unable to obtain GIS shapefiles of the electricity grid infrastructure of Croatia or Turkey from the public domain. Maps of the Croatian and Turkish electricity grid infrastructure were obtained from the Global Energy Network Institute (GENI) [30]. There is limited accuracy with these maps but they are the best source of data available.

In order to use the information in these maps they had to be digitised using ArcMap. This is a manual process were the map is first laid over an existing GIS map using the geo-referencing toolbar of ArcMap. Once the maps are aligned as accurately as possible the electricity transmission lines are manually digitised by tracing them using the sketch tool. This digitised data are then saved in shapefile format for use in the model.

3.2 Design of ArcGIS model

Transformation topography & physical characteristics	
Distance between dams	5 km -> 1km
Minimum head	150 m
Topology A, assumed minimum new reservoir size	70 000 m^2
Minimum distance from new reservoir to inhabited sites	500 m
Minimum distance from new reservoir to existing transportation infrastructure	200 m
Minimum distance from new reservoir to UNESCO site	5 km
Maximum distance from new reservoir to electricity transmission network	50 km
New reservoir should not be within a Natura 2000 conservation area	

Table 10: overview table of the model parameters for TA and TB

3.2.1 Topology A design

The model parameters are used to form various scenarios with which to analyse how different transformation characteristics will affect the final results.

The buffer distance parameter is used to define the search distance from the existing dam to potential reservoir sites. A value of 5 km is chosen for the base scenario, but further scenarios were modelled reducing the distance of the buffer in 1-km steps down to a minimum buffer of 1 km. This will result in the following parameters for the model scenarios:

Scenario 5 => 5 km
Scenario 4 => 4 km
Scenario 3 => 3 km
Scenario 2 => 2 km
Scenario 1 => 1 km

Then the ArcGIS slope function was used to analyse the topography to ascertain the flatness of the potential transformation site.

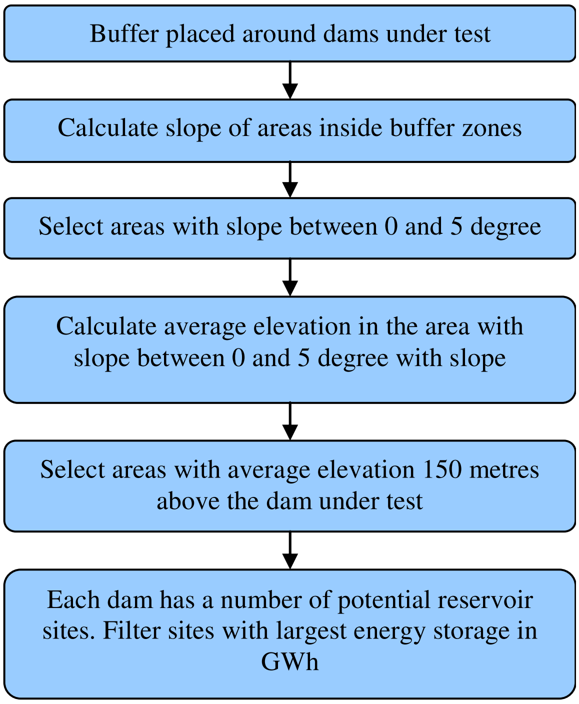

Figure 7: TA algorithm flow diagram

Overview of ArcGIS Slope function from its user manual [32]**:**

For each cell, Slope calculates the maximum rate of change in value from that cell to its neighbours. Basically, the maximum change in elevation over the distance between the cell and its eight neighbours identifies the steepest downhill descent from the cell.

Conceptually, the Slope function fits a plane to the z-values of a 3 x 3 cell neighbourhood around the processing or centre cell. The slope value of this plane is calculated using the average maximum technique (see references). The direction the plane faces is the aspect for the processing cell. The lower the slope value, the flatter the terrain;

the higher the slope value, the steeper the terrain. If there is a cell location in the neighbourhood with a NoData z-value, the z-value of the centre cell will be assigned to the location. At the edge of the raster, at least three cells (outside the raster's extent) will contain NoData as their z-values. These cells will be assigned the centre cell's z-value. The result is a flattening of the 3 x 3 plane fitted to these edge cells, which usually leads to a reduction in the slope. The output slope raster can be calculated in two types of units, degrees or percent (called 'percent rise'). The percent rise can be better understood if you consider it as the rise divided by the run, multiplied by 100. Consider triangle B below. When the angle is 45 degrees, the rise is equal to the run, and the percent rise is 100 percent. As the slope angle approaches vertical (90 degrees), as in triangle C, the percent rise begins to approach infinity.

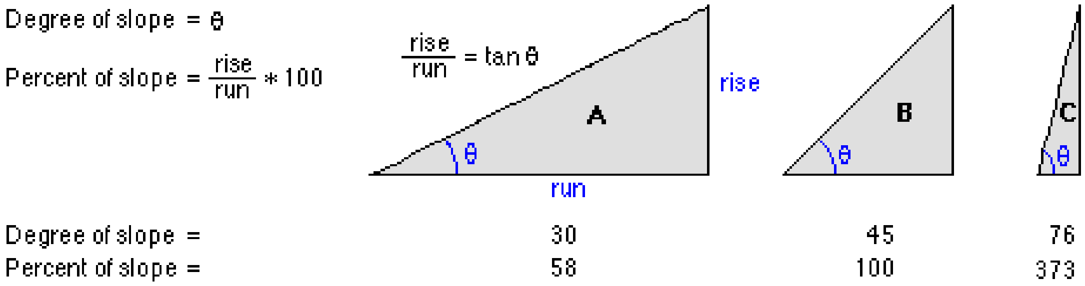

Figure 8: example of how slope is calculated

The Slope algorithm:

The rate of change (delta) of the surface in the horizontal (dz/dx) and vertical (dz/dy) directions from the centre cell determines the slope. The basic algorithm used to calculate the slope is:

$$slope\_radians = ATAN\ (\surd\ ([dz/dx]2 + [dz/dy]2))$$

Slope is commonly measured in degrees, which uses the algorithm:

$$slope\_degrees = ATAN\ (\surd\ ([dz/dx]2 + [dz/dy]2)) * 57.29578$$

The slope algorithm can also be interpreted as:

$$slope\_degrees = ATAN\ (rise\_run) * 57.29578$$

where:

$$rise\_run = \surd\ ([dz/dx]2 + [dz/dy]2]$$

a	b	c
d	e	f
g	h	i

Figure 9: determine the horizontal and vertical deltas

The values of the centre cell and its eight neighbours determine the horizontal and vertical deltas. The neighbours are identified as letters from 'a' to 'i', with 'e' representing the cell for which the aspect is being calculated.

The rate of change in the x direction for cell 'e' is calculated with the algorithm:

$$[dz/dx] = ((c + 2f + i) - (a + 2d + g) / (8 * x\_cell\_size)$$

The rate of change in the y direction for cell 'e' is calculated with the following algorithm:

$$[dz/dy] = ((g + 2h + i) - (a + 2b + c)) / (8 * y\_cell\_size)$$

(Slope algorithm description taken from ArcGIS desktop help, http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=How%20Slope%20works)

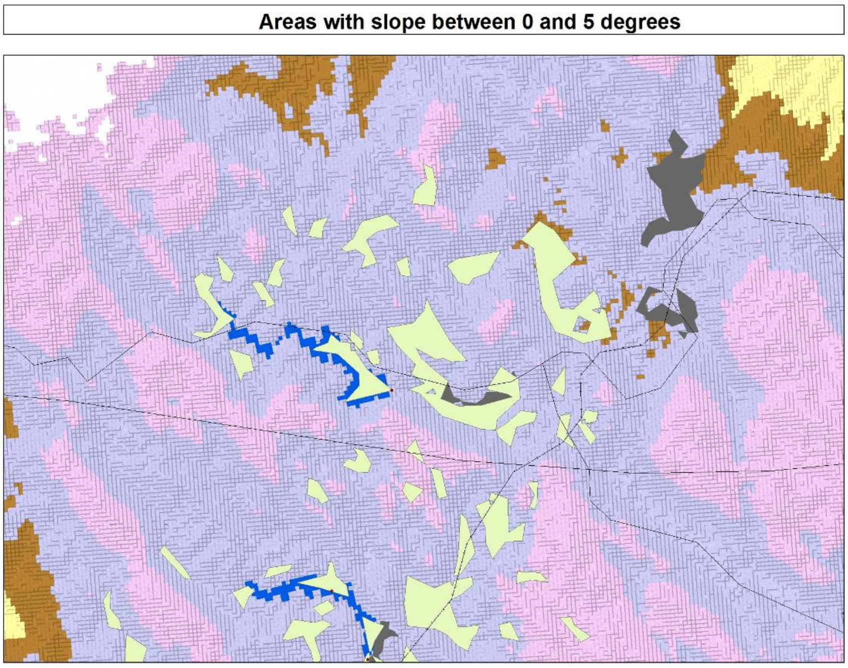

Figure 10: ArcGIS areas with slope between 0 and 5 degrees (in green)

A slope value of **5 degrees** was chosen as an acceptable flatness of the topography of a potential transformation site. Areas that have a slope between 0 and 5 degrees are filtered out using the "reclassify" tool and then transformed into polygon areas. These polygon areas are now the potential reservoir sites:

The average elevation within each polygon is now tested to see if it is greater than 150 metres above the Dam ID elevation, thus constituting the head of the scheme. If this is the case, the site passes the criterion and becomes a potential transformation site. The average elevation of the area for potential site is used and compared with the elevation of the existing dam. This will account for the volumes of material to be excavated and filled to make a sloping site flat before construction.

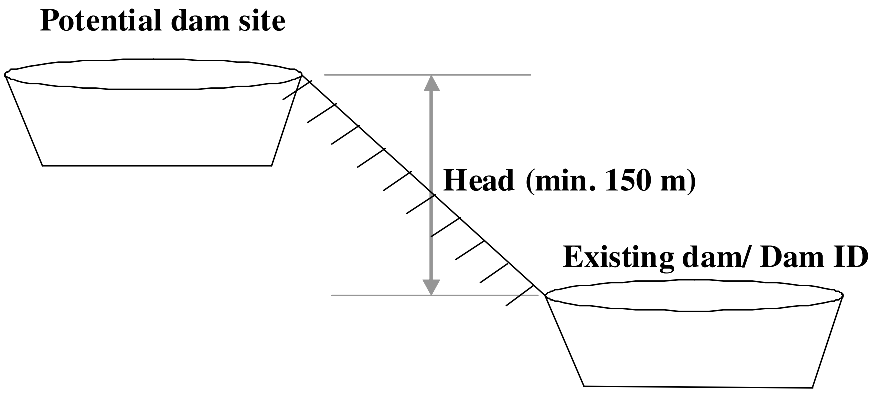

Figure 11: Head calculation

A minimum area where the slope parameter is satisfied also needs to be defined, and the figure of 70 000 m^2 has been chosen, see "***Volume and surface of a new reservoir.***" in section 1.3.1.

Some of the resulting areas have a potential volume greater than the existing reservoir, but it is assumed that the new reservoir – the one under search-, cannot be larger than the existing (lower) reservoir. In these cases the potential reservoir volume is made equal to the volume of the existing reservoir.

3.2.2 Energy storage potential

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

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

where:

E = *energy available (Joules)*
ϱ = *density* (kg/m^3) *(1019* kg/m^3 *for water)*
g = *acceleration of gravity (9.81* m/s^2*)*
h = *falling height, head (m)*
V = *volume* (m^3)
μ = *generation efficiency of (90%)*

Example:

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

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

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

3.2.3 Topology B design

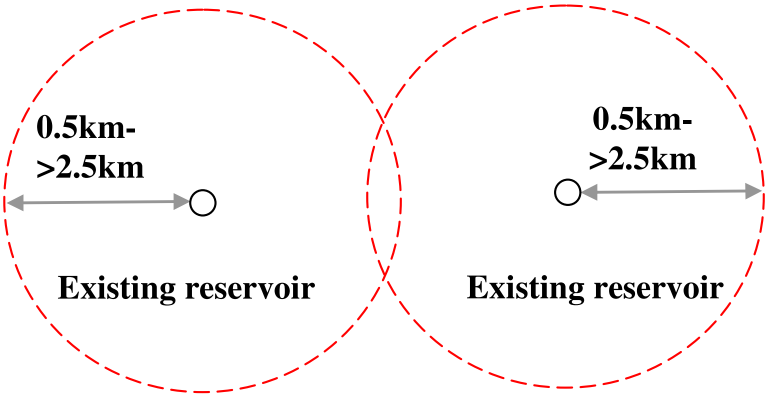

Figure 12: Buffer distance from existing dam to potential dam site or existing second dam

In a similar way to TA one model parameter, buffer distance, is used to form various scenarios with which to analyse how different transformation characteristics will affect the final results.

This parameter is used to define the search distance between existing dams. For the base scenario two existing dams must be within 5 km (scenario 5) of each other. To implement this each dam location has a 2.5 km buffer around it and wherever buffers intersect, this represents a potential transformation site.

Scenario 5 => 5 km (2.5 km +2.5 km)
Scenario 4 => 4 km (2.0 km +2.0 km)
Scenario 3 => 3 km (1.5 km +1.5 km)
Scenario 2 => 2 km (1.0 km +1.0 km)
Scenario 1 => 1 km (0.5 km +0.5 km)

3.3 Scenario design TA & TB

The buffer distance from the existing reservoir site will be the parameter used to create the TA and TB scenarios. There will be a total of five scenarios. The results for each scenario will return the number of suitable transformation sites of each scenario. A sensitivity analysis will be prepared to evaluate the results.

3.3.1 Scenarios

The buffer scenarios will vary the value of the buffer distance from 5 to 1 km in 1-km steps.

Scenarios	TA buffer distance (km)	TB buffer distance (km)
Scenario 5	5	2.5 + 2.5
Scenario 4	4	2.0 + 2.0
Scenario 3	3	1.5 + 1.5
Scenario 2	2	1.0 + 1.0
Scenario 1	1	0.5 + 0.5

Table 11: buffer scenarios for TA and TB

In all cases the minimum area of the reservoirs (potential and existing) is set at 70 000 m^2, and the minimum head at 150 m.

3.3.2 Constraint analysis

The constraint analysis will be applied to both unfiltered (TA only) and the filtered results. The parameters for each constraint are detailed below in Table 12.

Transformation physical constraints	
Minimum distance from centre of new reservoir to inhabited sites	500 m
Minimum distance from centre of new reservoir to existing transportation infrastructure	200 m
Minimum distance from centre of new reservoir to UNESCO site	5 km
New reservoir should not be within a Natura 2000 conservation area	
Maximum distance from centre of new reservoir to electricity transmission network	50 km

Table 12: physical constraints model parameters

The results section will present the following:

1. Physical potential (no constraints, filtered) (TA & TB)
2. Infrastructural potential (constraints, filtered) (TA &TB)

In the result charts for both unfiltered and filtered results, for both Croatia and Turkey the head refers to the height difference between the existing dam and the potential transformation site. Mean head refers to the mean head of the total number of sites for each scenario result.

3.3.3 Filtering potential transformation sites - example

All potential transformation sites in the model are recorded at first, and are referred to as the unfiltered transformation sites. There will be more than one potential transformation site for each existing dam as illustrated in Figure 13. The best potential transformation site will be selected by its energy storage potential (calculated from the methodology in section 3.2.2) and will be referred to as the filtered result.

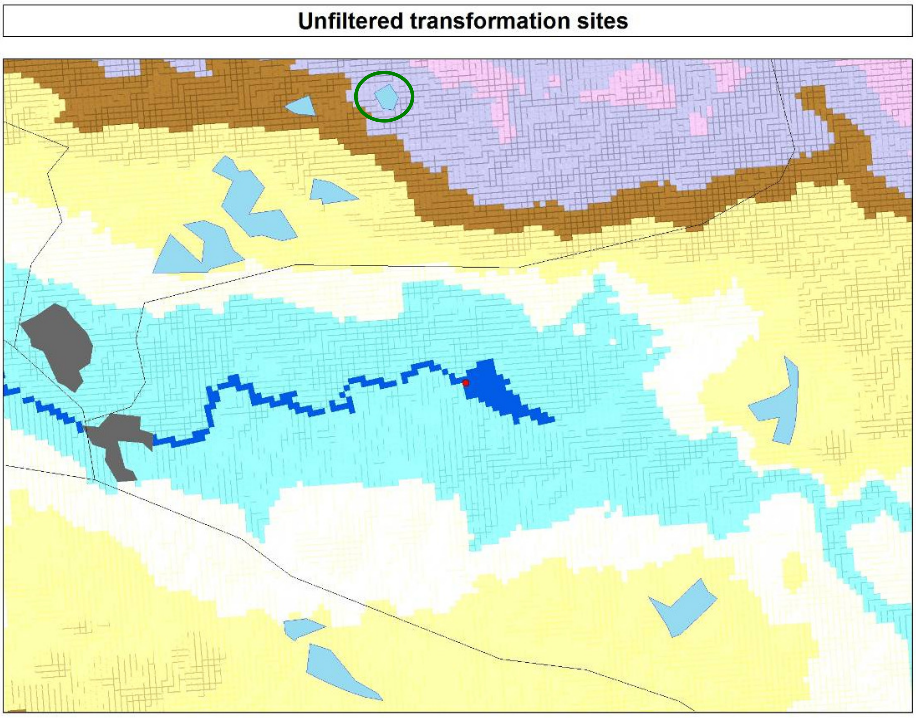

Figure 13: example of unfiltered results for a transformation site - light blue polygons

Following the filtering process one transformation site is selected, which is shown graphically when all blue polygons but one disappear – the one remaining is encircled in green in Figure 13

3.4 Result of the analysis

3.4.1 Croatia

Figure 14 presents a map view of the data for Croatia in ArcMap, a component of ArcGIS.

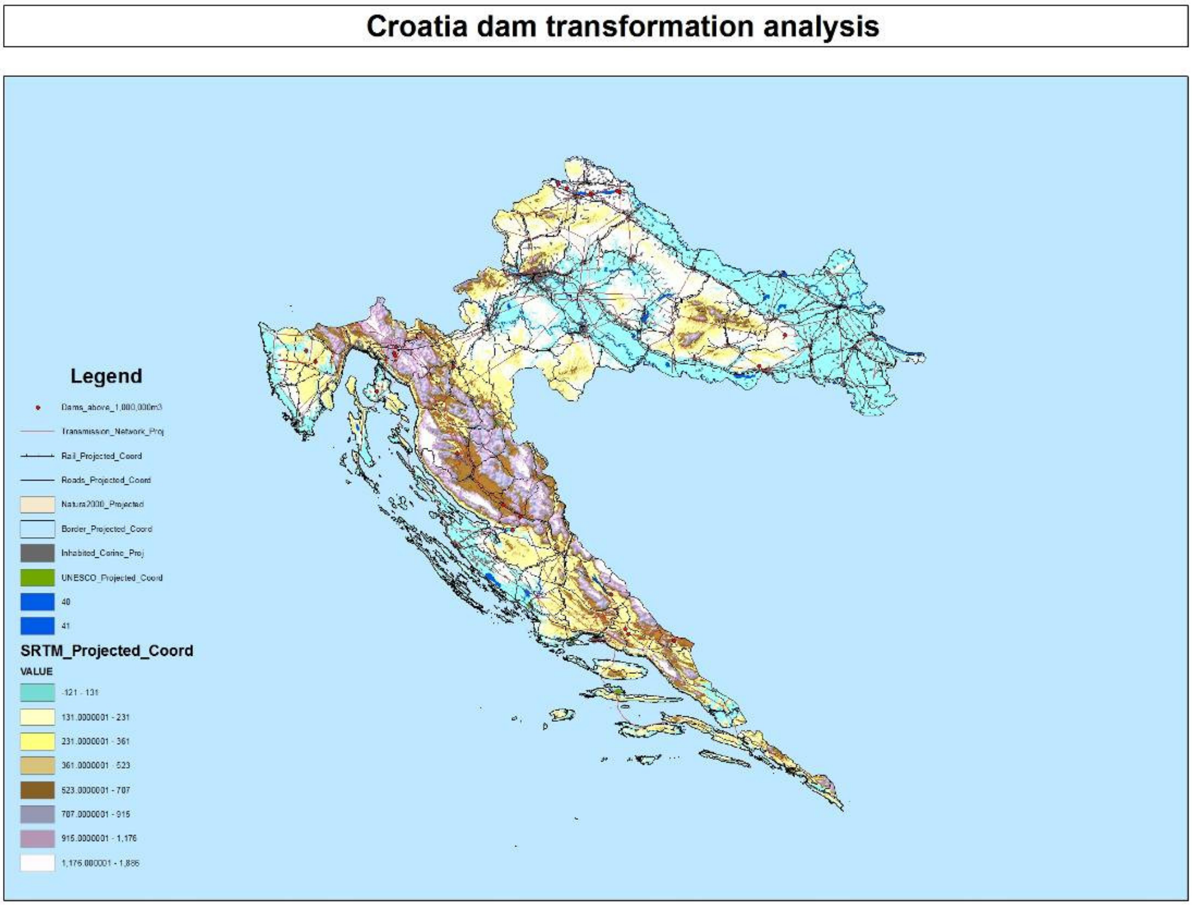

Figure 14: ArcGIS Croatian map and layers used.

The original data shows that a total of 23 dams have a reservoir capacity of greater than 1 000 000 m^3 in Croatia, and all those dams were analysed in the GIS model. The histogram in Figure 15 shows that in Croatia more dams are at an elevation of between 101 and 200 metres than at any other range.

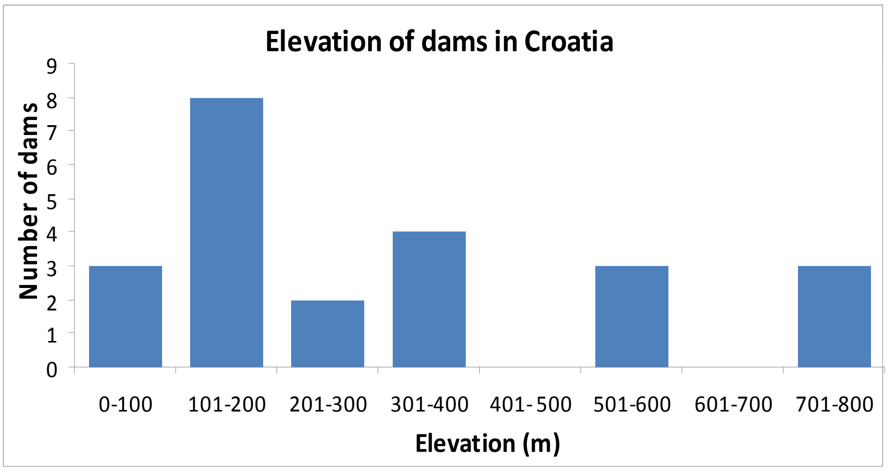

Figure 15: elevation histogram of the dams in Croatia, above 1 000 000 m^3 that are analysed in GIS

3.4.1.1 TOPOLOGY A TRANSFORMATION POTENTIAL

The existing Razovac dam will (1.84 million m^3) serve as an example to illustrate the process of filtering the sites with higher potential. This dam forms part of the Velebit PHS which uses the waters from the catchment area of the river Zrmanja, near Zadar. Water resources are the rivers Obsenica, Rieica and Otuæa with the storage basins Obsenica of 2.7 million m^3 and Stikada of 13.65 million m^3 [33], although only the latter is used as upper reservoir of the PHS system [34].

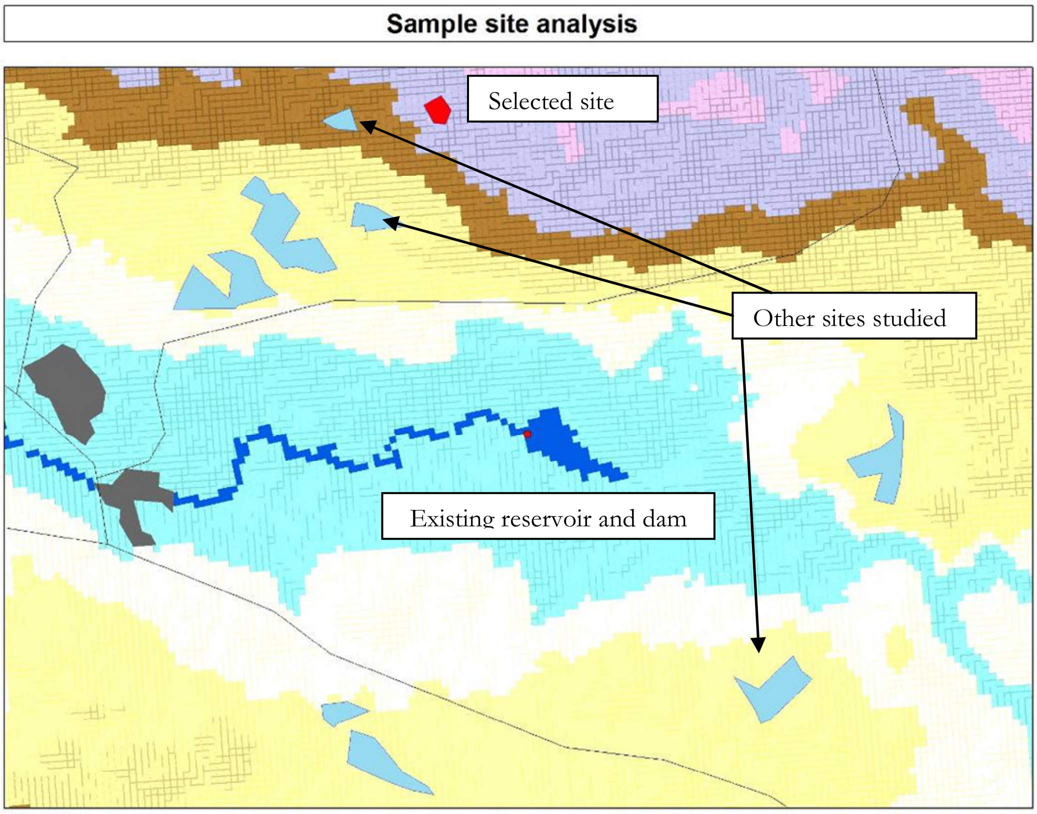

Figure 16: Croatian sample transformation site analysis - Razovac dam

The fact that Razovac is already a PHS system should allow an extra validation of the model.

By applying the algorithm shown in Figure 7 the GIS-based initial analysis, including the 5-km range, slope analysis, potential reservoir area above 70 000 m^2, and head above 150 m, results in 9 sites suitable for a prospective transformation to PHS, under TA theoretical potential scenario 5, as shown in Table 13.

Figure 16 shows as blue areas the potential transformation sites that meet the specified parameters. The red area shows the site that has been selected as the most suitable transformation site, as it offers the largest energy storage: it is site 1 in the table below.

Site no.	Reservoir volume (m^3)	Potential reservoir area (m^2)	Potential reservoir volume (m^3)	Head (m)	Energy storage (GWh)
1	1 840 000	85 808	1 716 161	778	3.34
2	1 840 000	82 085	1 641 702	610	2.50
3	1 840 000	156 909	1 840 000	338	1.55
4	1 840 000	396 075	1 840 000	335	1.54
5	1 840 000	651 523	1 840 000	300	1.38
6	1 840 000	368 152	1 840 000	299	1.37
7	1 840 000	352 798	1 840 000	282	1.30
8	1 840 000	577 357	1 840 000	241	1.11
9	1 840 000	119 716	1 840 000	237	1.09

Table 13: Croatian sample transformation site analysis – Razovac dam

The potential reservoir selected does not have the largest area in the column potential reservoir area. This is because the methodology limits the maximum volume of the potential reservoir to that one of the existing reservoir if the potential reservoir has a volume greater than the existing reservoir. The single factor that had higher influence on site 1 being chosen is that it has a higher head which results in this site having the highest potential energy storage of 3.34 GWh.

The Stikada reservoir has, under the same assumptions as the analysis above, a storage capacity of 18.42 GWh.

Box - Validation of model with the reality.

The current upper reservoir of the Velebit PHS system, Stikada, has a reservoir capacity of 13.65 million m^3 and elevation of 548 m AMSL. Google Earth shows that the closest distance between the Stikada and the Razovac reservoirs is 20 km. Because of the 5-km limit set up in the model the Stikada reservoir was not captured as a possible site for a second reservoir, thus incurring in the apparent contradiction that the actual upper reservoir was not captured by the model.

Therefore the Velebit PHS case shows that the analysis assumptions are on the conservative side.

We put the discussion of this point off to the conclusions and continue the analysis of country potential based on the initial assumptions.

The theoretical potential results, before any natural-spaces related constraint has been applied, are shown for the different scenarios in Figure 17. This figure shows, against the left axis, the number of dams which have at least one potential site for creating a new PHS, and against the right axis the total transformation potential (topology A) of Croatia. Under scenario 5, the least restrictive, the total physical theoretical potential shows 14 sites with a total energy storage capacity of 67.56 GWh.

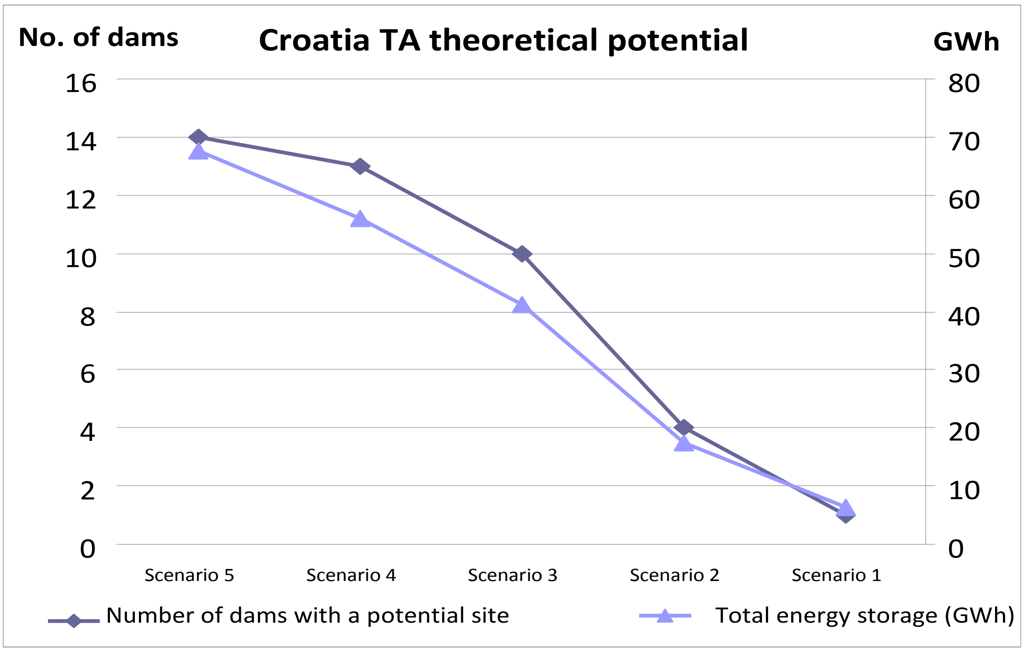

Figure 17: Croatia TA theoretical potential: number of potential sites and total potential storage

The application of other filters was subject to certain limitations of the model and for this reason filters were not exactly applied in the order prescribed by the methodology. Thus, next the transport infrastructure (> 200 m away); inhabited areas (> 500 m away), UNESCO sites (> 5 km away) and distance to the electricity grid (< 50 km away) constraints were applied, and the exclusion of environmentally sensitive areas (natural spaces filter) was applied later on. Whereas the application of the former three filters results in a limited reduction of storage capacity as shown in Figure 18, the natural spaces filter has a much higher impact.

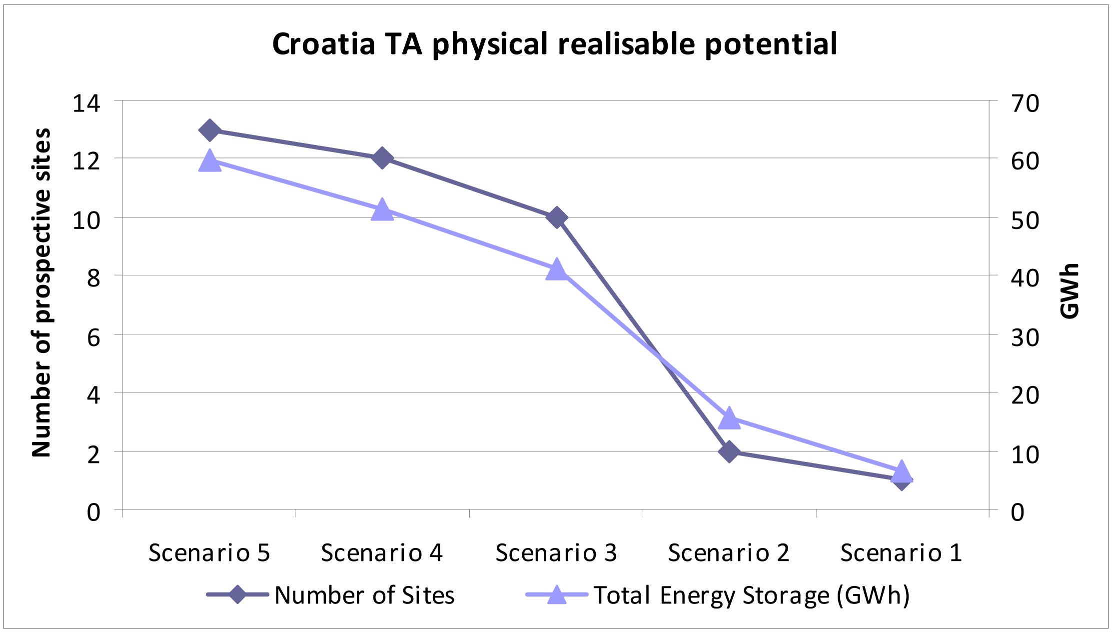

Figure 18: Croatia TA physical "realisable" potential after applying three filters

In effect, the total number of scenario 5 physical "realisable" potential (term is used in order to reflect this particular order of application of filters) sites is 13 with total energy storage of 59.75 GWh. This represents the loss of only one transformation site due to constraints, with the loss of 7.81 GWh of energy storage.

The introduction of natural spaces as a constraint is run independently to the other constraints. The large coverage of Natura 2000 areas in Croatia disqualifies over half (13 down to 6) of the suitable sites when this constraint is applied.

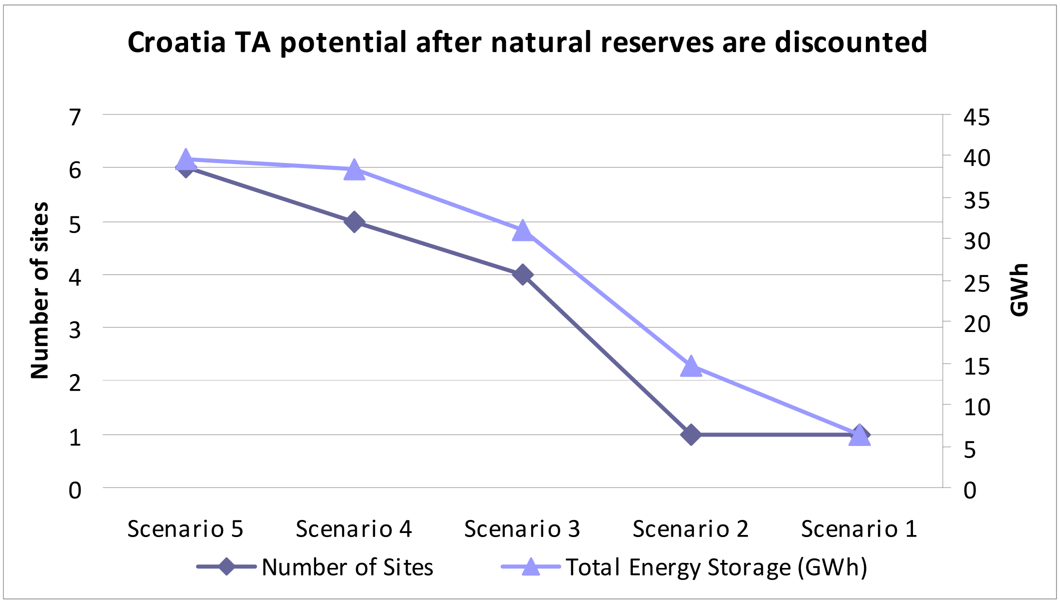

Figure 19: Croatian TA physical potential

However, lower-capacity options that were discarded at an earlier stage, might not have the same natural spaces restrictions as the filtered sites. The model could be run in an iterative way for those existing dams whose TA option was discarded at the natural spaces constraints in order to search whether any other of the possible sites would pass the natural spaces check.

3.4.1.2 TOPOLOGY B ANALYSIS

There are no solutions for TB in Croatia. Any dams that are within 5km of each other do not have an elevation difference of 150 m or greater to provide the sufficient head required by the methodology.

In order to find a TB transformation site we need to exceed the methodology parameters by extending the buffer distance to 11 km before we find a solution to TB. The decision taken at the modelling stage was that this distance between two existing dams would not be a viable transformation. However, the experience of the Velebit and other PHS shows that this assumption can be conservative in particular when a high head difference is possible.

3.4.1.3 CONCLUSIONS: COUNTRY POTENTIAL

The country potential is assumed to be without including the natural spaces constraint. As a result of not being any TB potential site, in the case of Croatia the country potential is the scenario 5 TA physical "realisable" potential filtered for other constraints. This yields 13 sites with 60 GWh of energy storage. This figure can only roughly be compared to the storage of the current PHS (20 GWh) because the latter corresponds to a major mixed-PHS where natural inflow plays an important role. For reference, peak Croatian demand is approximately 3.2 GW and annual electricity consumption above 18 000 GWh [63].

The different features and uses of PHS systems, e.g. whether a daily or weekly cycle, whether pure PHS of mixed with natural hydropower resources, make it difficult to define whether this potential for transformation is significant. The analysis did not define the assumptions that could result in an estimated installed power (whether pumping or generating) and thus a comparison cannot be made with the installed PHS capacity of the country. A future improvement of the model could approach this issue. In the case of Croatia the current PHS capacity is 282 MW generating and 245 MW pumping, most of it (276/240 MW respectively) at a single PHS, Velebit. Indeed a comparison with Croatian installed PHS can be misleading because Velebit is a mixed PHS-conventional scheme which in 2009 consumed 117 GWh pumping [34] from which is estimated to have generated 82 GWh[8] of the total 468 GWh generated.

A different approach consists of comparing the country potential for storage with the storage of the upper reservoirs in existing PHS in the country. For Croatia, section 3.4.1.1 unveiled that under the same assumptions used to calculate site potential the upper reservoir of the Velebit PHS has a storage capacity of 18.42 GWh, and contributed to the generation of 110 and 82 GWh from 158 and 117 GWh pumped in 2008 and 2009 respectively. The extrapolation of this pattern to the 60 GWh of country potential yields 3.25 times the current Croatian installed capacity, i.e. between 266 and 357 GWh generated. However, again this approach can lead to the wrong figures because the 18.42 GWh of storage in the upper reservoir of the Velebit PHS did not only contribute to the PHS system but generates an average 377 GWh of pure hydropower annually [34].

Given that it cannot be ruled out any new PHS to be a mixed system, possibly the best way to put the potential into context is to compare the 60 GWh of potential with the approximately 20 GWh of currently existing PHS to conclude that under the limitations in this study ***the country potential for transformation to PHS in Croatia is at least three times the capacity of existing PHS plants***.

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[8] According to EIA [21] in 2008 the Croatian PHS plants pumped 158 GWh and generated 110 GWh. Given that Velebit is 98% of the PHS generation, it can be assumed that the cycle efficiency of the Velebit PHS plant is 70 %.

3.4.2 Turkey

Figure 20 presents a map view of the data for Turkey in ArcGIS.

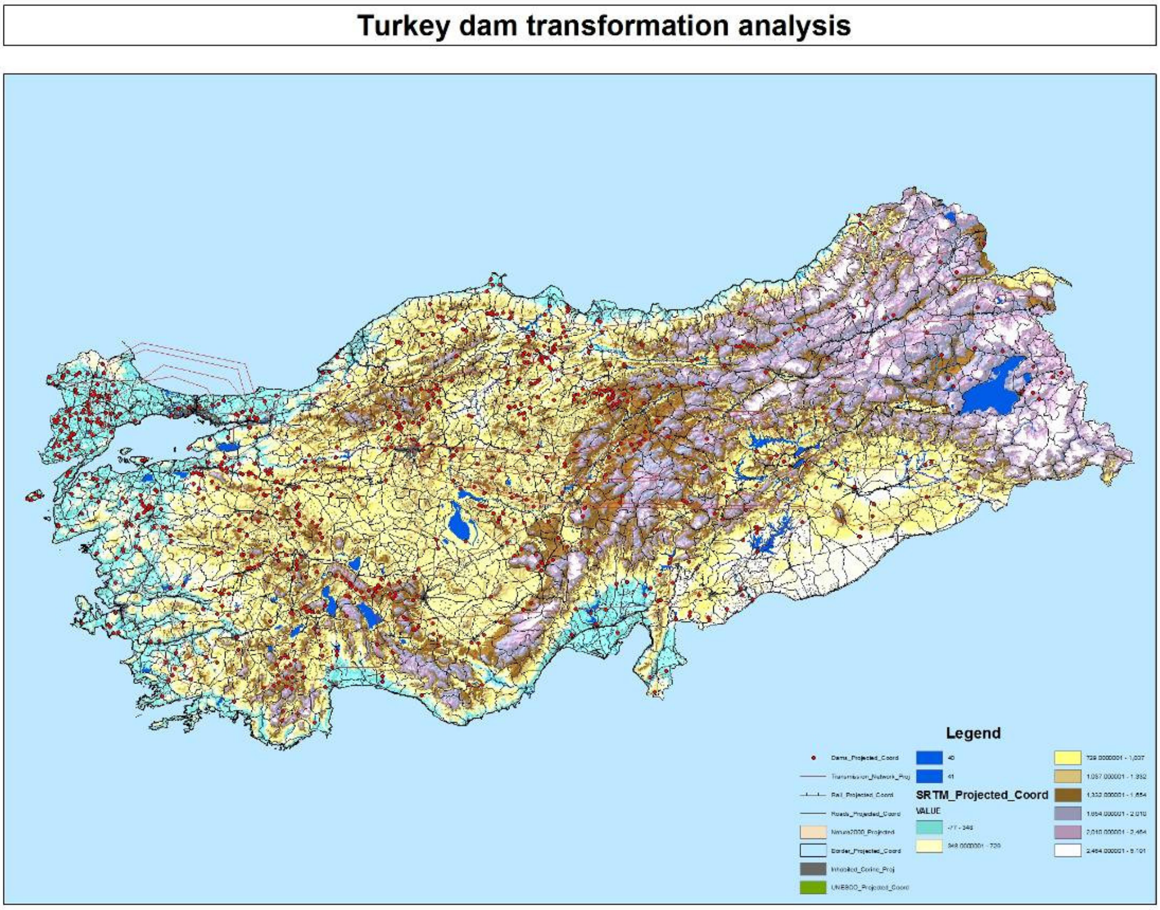

Figure 20: map of Turkey with the layers included in the analysis

The authors were unable to acquire accurate transmission network data for Turkey. For this reason the transmission network constraint have been disabled for the analysis of Turkey.

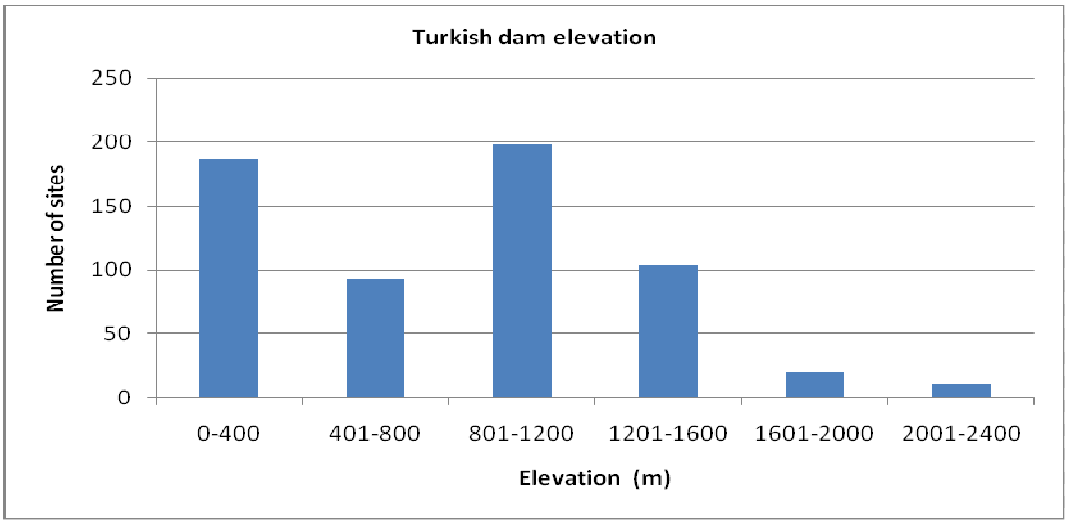

Figure 21: elevation histogram of the dams in Turkey, with a reservoir capacity of 1 000 000 m^3 or above

A total of 612 reservoirs larger than 1 000 000 m^3 in Turkey were analysed in the GIS model. The histogram, Figure 21, shows that there are a large proportion of dams at elevations between 0 and 400 metres and between 801 and 1 200.

3.4.2.1 TOPOLOGY A ANALYSIS

The physical "realisable" potential[9], before the natural spaces constraints has been applied, shows for scenario 5 a total of 448 potential sites for a total energy storage of 4 372 GWh.

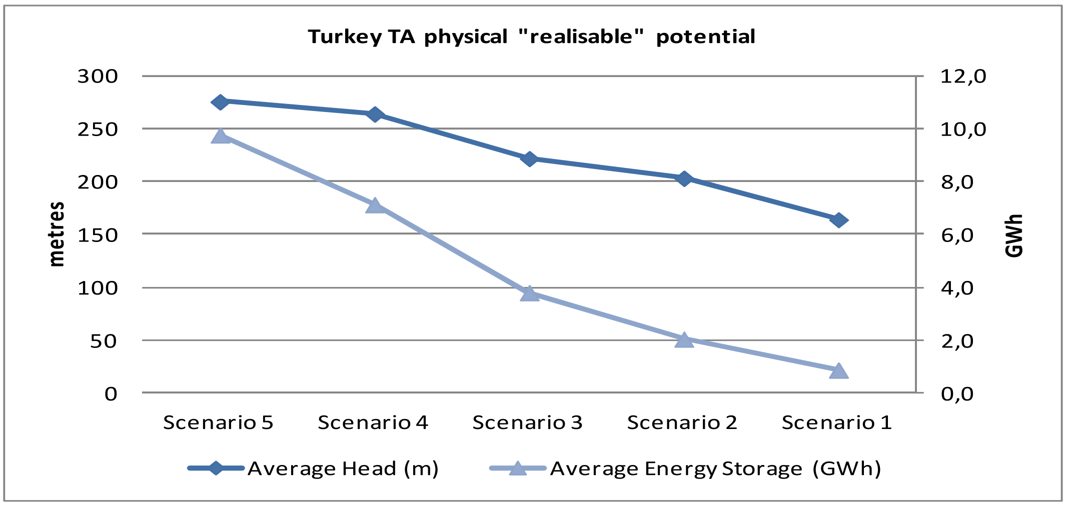

Figure 22: Turkey TA physical "realisable" potential**Error! Bookmark not defined.**, number of potential sites and total storage

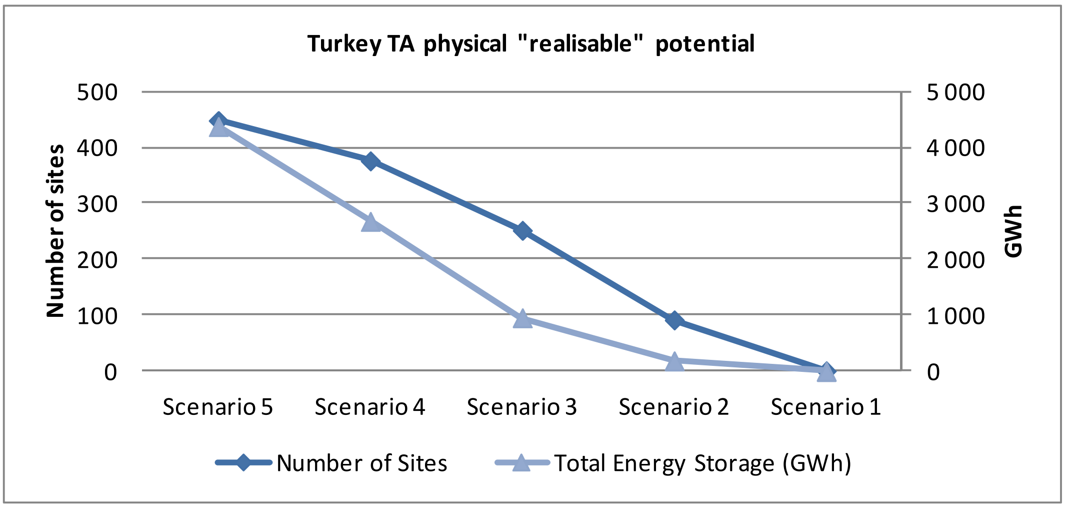

Figure 23: Turkey TA physical "realisable" potential, average head and average storage

These potential sites can also be seen in terms of average head and energy storage per site, as shown in Figure 23. In the case of scenario 5 the 448 sites have an average head of 275 m and an average energy storage of 9.76 GWh.

The physical potential after environmental constraints have been applied shows a total number of 444 potential sites with total energy storage of 3 817 GWh. This represents the loss of 4 potential transformation sites due to constraints, with a more significant loss of 555 GWh of

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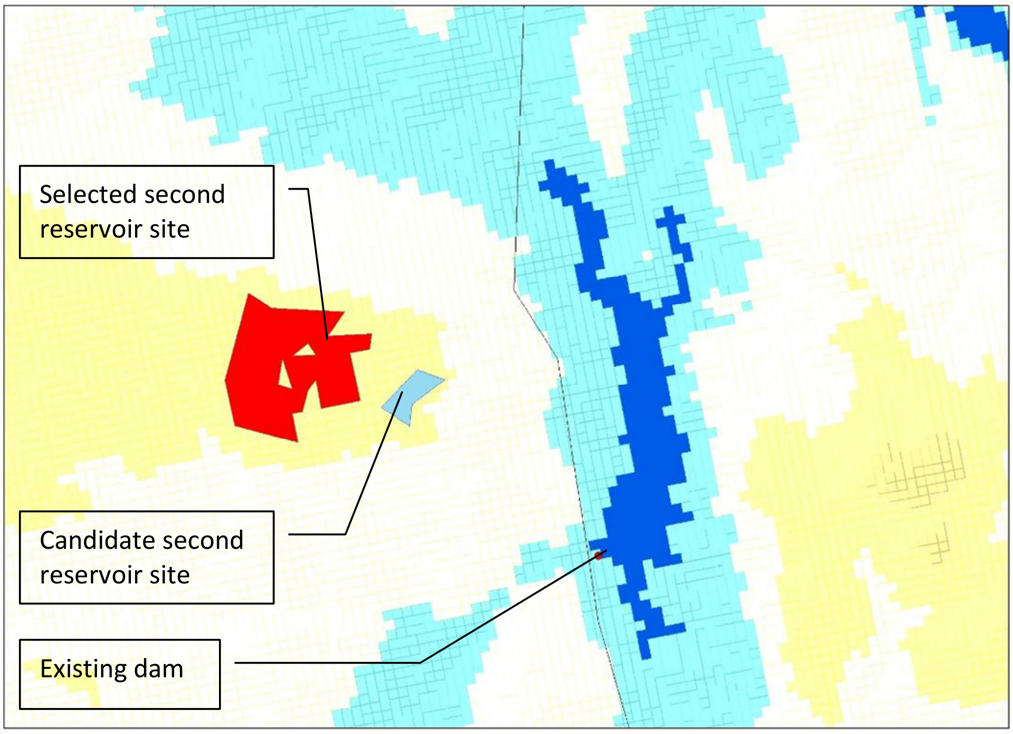
[9] As explained above we introduce the term "realisable" between quotes to reflect that this potential was not in the methodology but the result of constrains during its application which can and should be adapted

energy storage. However, it has to be noted that the filters applied at this stage did not include the distance to the electricity grid as we could not find a suitable dataset.

The sample site for analysis will be from the TA physical realisable potential scenario 5 results. The sample transformation site analysis is carried out on Karacaoren II Dam.



The blue area shows a potential transformation site that meets the specified parameters, the red area shows the site that has been selected as the most suitable transformation site, as it has the largest energy storage and the red point is the existing dam. The details of this site are highlighted in blue in Table 14.

Site no.	Reservoir volume (m³)	Potential reservoir area (m²)	Potential reservoir volume (m³)	Head (m)	Stored energy (GWh)
1	48 000 000	1 106 519	22 130 381	613	34
2	48 000 000	116 761	2 335 216	549	3

Table 14: Turkish sample transformation site analysis

The transformation site selected has a potential energy storage of 34 GWh.

3.4.2.2 TOPOLOGY B ANALYSIS

The theoretical potential under the five scenarios is very small for TB. Scenario 5 yields 3 theoretical potential sites from a total of 612 dams under analysis; their average head is 294 m and total energy storage of 3.36 GWh.

The physical “realisable” potential after the application of the natural spaces filter results in only 2 physical “realisable” potential sites, in both cases the dams at a distance of between 4 and 5 km from each other. They have an average head of 361 m and a total energy storage of 3.04 GWh as illustrated in Figure 25. This represents the loss of one transformation site due to constraints with the loss of 0.32 GWh of energy storage.

Turkey has not adopted Natura 2000 yet so the natural spaces filter did not include them. However, the model will analyse Natura 2000 as a constraint if the data becomes available in the future. Therefore the physical "realisable" potential becomes the physical potential.

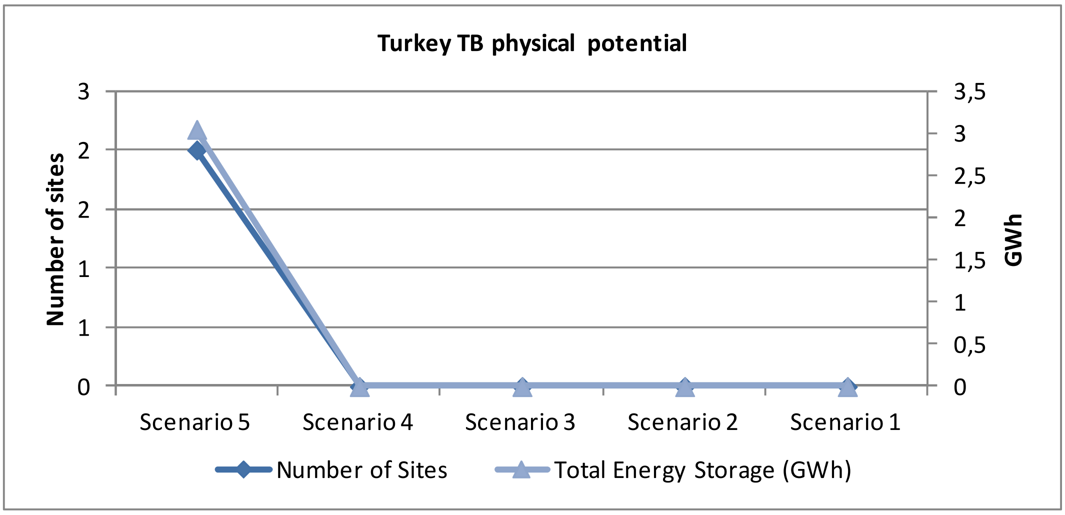


Figure 25: Turkish TB physical potential, number of potential sites and total storage

3.4.2.3 COUNTRY POTENTIAL

The country potential is presented based on the TA and TB physical potential filtered results under scenario 5, and it is presented in Table 15. As TB takes priority over TA any dam that is included in a TB transformation will be excluded from the TA transformation sites. In this case four sites are excluded from TA with the loss of 17 GWh of potential storage which are replaced by 2 TB sites adding 3 GWh of potential storage.

	Number of Sites	Total Energy Storage (GWh)
TA Scenario 5	440	3 800
TB Scenario 5	2	3
Country Potential	443	3 803

Table 15: Turkish country potential

4 Barriers to the realisation of this potential

4.1 Topographical barriers

The model developed in the previous section has identified potential transformation sites based on head difference, distance between existing and potential sites, flatness of the surrounding topography and reservoir volume. It also implemented constraints relating to the construction of new reservoirs in relation to inhabited sites etc. However the model is unable to analyse potential sites based on their geology and hydrology.

4.1.1 Geology

The geological formation of the potential site could be a barrier to the realisation of a potential transformation site. A detailed geological analysis of each potential transformation site would need to be performed to assess its feasibility for transformation to PHS. Porous bedrock is one potential barrier, for example, as water losses due to seepage may be larger in porous karst (limestone) areas [63]. The construction of underground penstocks may also be hindered by local geology.

In temperate zones many upland sites suitable for constructing new upper reservoirs are on peat-covered slopes. Peat soils may pose a barrier due to their unstable nature when disturbed. The disturbance could arise either from construction of the reservoir itself, or from the construction of access roads for equipment. Large-scale peat movements have occurred in areas adjacent to wind farm construction in Ireland [35]. Large cut-and-fill operations on peat are problematic as safe storage of excavated peat is difficult.

Finally, the earthquake risk of the potential site also needs to be assessed.

4.1.2 Hydrology

A lack of surface water at or near to the potential transformation site could be a potential barrier to the realisation of the potential. If the potential reservoir site has an inflow this would make the site more suitable for the construction of a new reservoir and the creation of a mixed PHS plant. An analysis of the hydrology of the existing reservoir is needed to identify if there are seasonal variations in the supply and level of water. The incoming sediment loads to any existing or new reservoir also must be assessed, as silting may pose a further barrier to transformation by reducing the usable reservoir volumes over time.

Evaporation is not expected to be a significant problem with PHS [59].

4.1.3 Infrastructure

The analysis of transport and grid infrastructure should go one step further than was possible with the model. In effect, a complete analysis of the road infrastructure in the region of the potential transformation site would be needed to evaluate if it can support high volumes of and/or heavy construction machinery. A detailed analysis of the local electricity grid infrastructure would also be required. In the case of existing conventional hydropower sites, grid infrastructure will be in place. However, it may need to be upgraded to provide two-way power flows to facilitate pumping as well as generation. Whether the grid has to be extended or reinforced this improvement might add value to the stability of the grid and this could help overcome this barrier.

For non-hydro dams the local grid infrastructure has to be examined in detail. Issues to consider include the proximity to the distribution and/or transmission network, proximity to the nearest substation, the availability of spare capacity at the substation, the feasibility of upgrading existing substations where they are inadequate. For sites to be connected to the distribution network the presence of other large, variable loads and generators (such as wind farms or energy-intensive industries) on the local network may be a potential barrier as well as an opportunity: for example, a PHS plant and a wind farm can be associated so that the latter provides pumping power with minimum transmission losses.

4.2 Economic barriers

4.2.1 Electricity market analysis

This section performs a preliminary analysis of the electricity markets of Croatia and Turkey. This includes the identification of market signals that would justify investment in new electricity storage facilities within each market (investment in renewable technology).

4.2.2 Croatia [36]

The electricity market in Croatia is based on electricity trading through bilateral contracts concluded between the supplier, the trader and/or the generator. In addition, a contract for using the network must be signed with the transmission or distribution system operators -*HEP-Operator prijenosnog sustava* (HEP-TSO) and *HEP-Operator distribucijskog sustava* (HEP-DSO) respectively- depending on the voltage level the customer is connected to. During the realisation of contracts deviations in supply and demand occur and therefore the need for system balancing. Real time system balancing is the responsibility of the TSO. In order to cover power system deviations in each hour, HEP-TSO offers balancing energy for sale or purchase to market participants.

In 2007, Croatia adopted a feed-in tariff legislation based on the tariff system for the production of electricity from renewable energy sources and cogeneration [37] and the regulation on incentive fees for promoting electricity production from renewable energy sources and cogeneration [38]. Tariffs for wind power plants reach 90 €/MWh.

Croatia is directly interconnected to Slovenia, Bosnia and Herzegovina, Serbia and Hungary, and this creates the potential (if the amount of PHS is increased) to store surplus wind generation from these neighbouring countries. It has been estimated that Slovenia has a potential to install 600 MW of wind generation [39], Serbia has a potential to install 1 300 MW of wind generation [40]. Hungary must meet the 13 % renewable target as part of the EU 2020 targets and wind generation will be the main contributor to this target [41].

Providing more storage in this region could add value to increasing renewable penetration not only in Croatia, but in all interconnected countries.

4.2.3 Turkey

The Electricity Market Regulatory Agency was introduced in 2001 to liberalise the electricity market in an attempt to enhance competition. Since then, liberalisation of the market is still undergoing as the reforms are not yet completed [42]. The Turkish renewable energy act considers renewable all non-fossil based energy sources. Wind power, run of river hydropower plants and reservoir hydropower plants with reservoir areas smaller than 15 km^2 are all identified as renewable energy sources [43].

Turkey has vast untapped hydropower and wind potential. According to UNESCO Turkey technically feasible hydropower potential is 213 000 GWh [44]. After its General Directorate of State Hydraulic Works currently Turkey has 172 hydroelectric power plants in operation with total installed capacity of 13 700 MW generating an average of 48 000 GWh/year, which is 35 % of the economically viable hydroelectric potential [12]. The large quantity of untapped hydropower potential in Turkey could make the development of PHS unattractive, unless the penetration of wind power becomes very large indeed.

In December 2006, the Ministry of Energy published the wind map of Turkey, which has stimulated wind power investments from 172 MW at the end of 2007 to 1 329 MW at the end of 2010. Alone this last year, 528 MW of new wind energy capacity was added in Turkey, on a year-on-year growth rate of 66 %. Turkey hopes to install up to 20 GW of wind by 2023, helping the country to obtain 30 % of its electricity generation from renewable sources [45].

Turkey has adopted a hybrid system within which renewable power plants built before 2012 are eligible for the 50 – 55 €/MWh REFiT for first 10 years of operation, providing a hedge against foreign exchange risk. Furthermore retail licence owners are required to allocate a portion of the electricity purchases to renewable power.

4.2.4 Capital cost

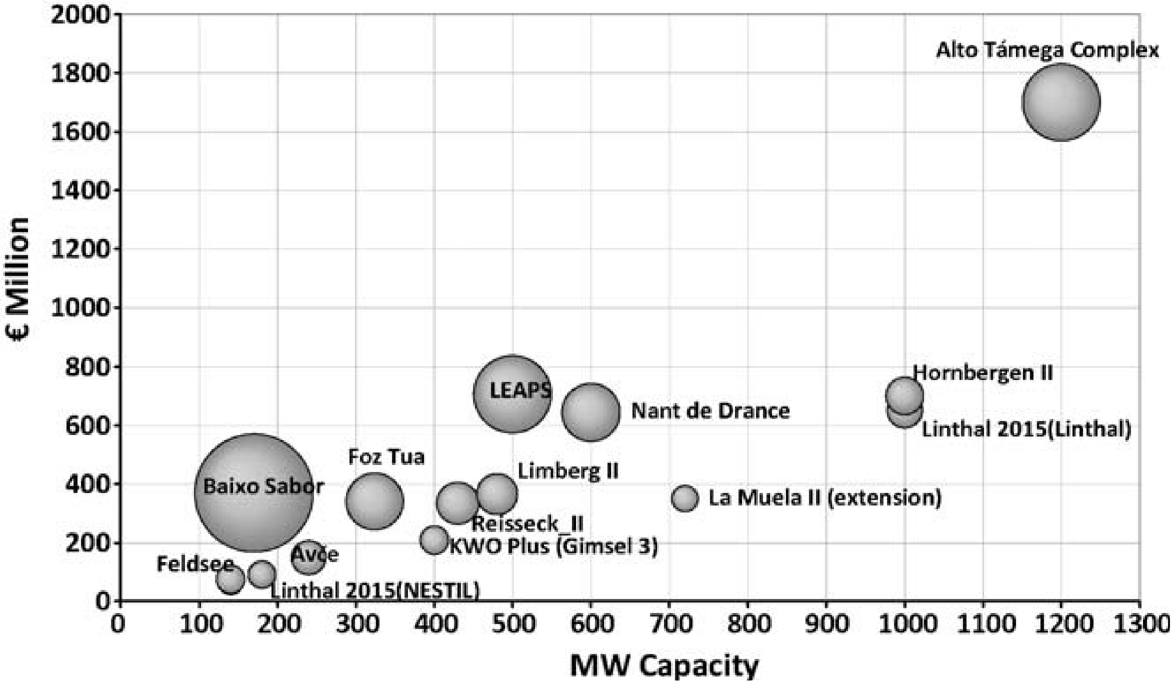


Figure 26 capacity vs. project and specific capital cost (ex transmission line) for proposed PHS in Europe/US. Y-axis is full CapEx cost. The size of bubble is indicative of relative cost per MW. Plants in Switzerland and US were converted to Euro using the following exchange rates. (1 CHF = 0.6515€, 1 USD = 0.70715€). Source: Deane et al. [50]

Project costs for PHS are very site specific with some quoted costs varying from of 600–3 000 €/kW [46]. In the lower end of the price range a figure of 500 EUR/kW for power generation-related costs and 0-16 EUR/MWh for storage capacity-related costs has been quoted based on pre-2004 estimates [47]. The use of reversible pump-turbines involves that a single penstock can be constructed, which can reduce construction costs by up to 30 % with a small increase in the plant cost [48].

Figure 26 shows the large variation in capital cost for two similarly-sized projects, LEAPS and Limberg II (500 MW). LEAPS [49] is an example of a TA transformation, it uses an existing lower lake and the project will build an upper reservoir and penstock and powerhouse. Limberg II [5], an example of a TB transformation, uses two existing reservoirs and builds penstock and generation equipment. These cases highlight the potential capital cost savings of developing TB transformation sites over TA sites.

The breakdown of costs into their various constituents (dam construction, penstock construction, plant etc.) is also highly site-specific and detailed information on individual projects is difficult to obtain. A sample of these data provided by Krajačić et al. [64] for a PHS project in the island of Krk (Croatia) is presented in Figure 27. The total cost for a 10 MW, 2 pumps and turbines system is 16.78M€.

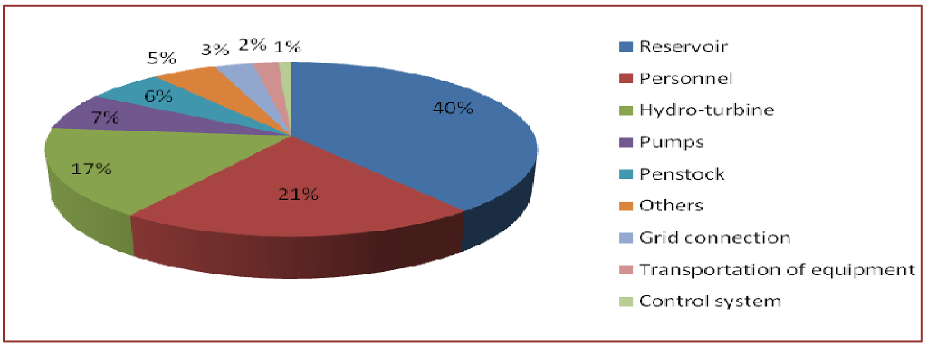


Figure 27: Split of cost for a specific PHS project

Variability in capital costs is inherent in PHS projects. The construction cost is site and country specific due to the high labour and material intensity of this type of construction projects. Thus the uncertainty of capital costs can be a barrier to transformation.

4.3 Social barriers

Due to the nature of hydropower projects there are many social barriers that arise. They are discussed in more detail below.

4.3.1 Inhabited sites

The building of large dams to create reservoirs often leads to the resettlement of local residents as farmland and dwellings are submerged, for which large hydropower projects normally receive adverse publicity. In some cases when an existing site, like an abandoned quarry, is utilised as a reservoir for a PHS transformation the public acceptance may be greater for such a development. The construction of new power line infrastructure to transport electricity to and from PHS plant can affect dwellings and settlements in its close proximity.

It is difficult to gauge social acceptance before a site has gone through the planning process. Social acceptance is a barrier that has a lot of uncertainty associated with it for hydro and PHS developments. In the long term, well-managed, suitably landscaped sites may become appreciated by their local communities as visually attractive leisure areas.

4.3.2 Navigation

When damming an existing waterway to create a reservoir, reduction in water levels may affect navigation or recreational users (e.g. canoeists). These could be potential barriers to the development of PHS but due to the close-system nature of a PHS and the fact that the reservoir that is the basis for transformation was already built, it is unlikely to affect PHS transformation projects.

4.3.3 Trans-boundary issues

If regions up and down the river are not in the same country, placing a dam in one region may affect flood risks or water supply issues in another country. This could be a potential barrier to the development of PHS due to political sensitivity.

4.4 Environmental and planning barriers

4.4.1 Conservation issues

If the potential transformation site is within or in close proximity to a Natura 2000 designated site, a EUROPARC Federation designated site [15], a UNESCO designated site [16, 17], a site of special scientific interest (SSSI), a special area of conservation (SAC), a special protected area (SPA), a national park or affect the catchment home to protected species, then development of this transformation may be difficult. In the case that a development is allowed to proceed in one of the listed protected areas the developer may be asked to replace any habitat that has been removed or damaged due to the development, resulting in an additional cost.

4.4.2 Fisheries

If the potential transformation site is on or affects a river that supports migratory fish or other animals, spawning grounds or if the river is used for angling, development of this transformation may be difficult. This could be a potential barrier to the development.

4.4.3 Environmental benefits

In some cases, a properly designed PHS system can even be used to improve water quality through aeration, preventing algal growth and fish kills [4] [5].

4.5 Water supply barriers

4.5.1 Water resources

If the potential transformation site is on a watercourse that supplies drinking water or water for irrigation, this could be a barrier to development, as the operational requirements for multiple uses will have to be managed together. However a reservoir that is constructed for a PHS development could also have a secondary function as a storage reservoir for irrigation or drinking water supply, which may make a proposed project more economically attractive.

4.5.2 Chemical and physical water quality [51]

An analysis would need to be performed to assess if the development of the PHS has the potential to affect the quality of water of the watercourse or if pollutants could be discharged during construction. Also the potential that the development could cause significant algal growth would need to be assessed. These studies would be carried out as part of a planning process and if the results were negative it may become a barrier to the development.

4.5.3 Biological water quality

An analysis must be completed to assess if changes in river flow are likely to cause a significant change in the invertebrate community.

4.6 Flood protection

An analysis must be completed to assess if changes to the river result in reduced flow capacity of the river or if any alterations are needed that they do not increase the potential to cause flooding in the surrounding area. The development of the site must not affect any available floodplain area or block potential overland flood flow that would result in increased events of flooding.

PHS has the potential to curtail flooding by scheduling pumping during flood risk periods. This could be used to offset any other negative effects of the development of the site.

4.7 Conclusions of the barriers analysis

It is possible to broadly classify the barriers identified in this section as hard and soft barriers. Hard barriers are those imposed by site conditions or by the absence of suitable infrastructure. In general, they may be addressed by technological solutions, but the costs may be prohibitive. Often such barriers are highly site-specific. In the case of geological and hydrological barriers, further work would need to be carried out on sites that are identified in order to identify possible solutions and the associated costs. For example, seepage losses can be reduced by lining reservoirs with impervious materials such as clay or synthetic membranes.

A clear operational strategy for a proposed transformation scheme should be identified in order to fully assess site feasibility. It should incorporate the wider operating environment: flood protection, other reservoir uses, renewable penetration, and proposed renewable development to 2020 and beyond.

The capital costs for developing PHS can be prohibitive, depending on the topography of the site. However, by utilising existing reservoirs capital cost can be reduced dramatically. New technological developments may allow some other hard barriers to be overcome. Variable speed, reversible pump-turbines will increase the operational flexibility of planned PHS facilities, and will better equip them to support the integration of variable renewable generation. New concepts such as coastal seawater PHS, where the sea acts as a lower reservoir, may open up a greater number of potential sites. However, there is only one such plant in operation in the world, a 30 MW demonstration facility located in Okinawa, Japan [52] and it is unclear why no further such developments took place. PHS using an underground cavern as the lower reservoir has also been proposed and if successful, would eliminate many of the environmental problems associated with constructing reservoirs on the surface [53].

Soft barriers relate to societal acceptance and the regulatory and market environments for PHS and general energy infrastructure development. These can often be addressed by non-technical measures but may prove to be difficult to resolve. Societal acceptance of projects can be improved through campaigns of public information, by consultation and communication with local communities, and by referencing successfully completed (and attractive) projects. If the regulatory environment poses barriers (e.g. through long delays in obtaining planning permission), this can be addressed through legal measures, but these will often require a concerted effort in order to be effected. This usually takes the form of lobbying the responsible agencies at a national or EU level. Similarly, if barriers are imposed through the existing rules of electricity markets, it may be possible to make changes through submissions to national regulators. However, this may meet with resistance as regulators prefer not to make frequent changes to market rules, as the resulting uncertainty may deter future investments.

Several international research projects focus or recently focused on barriers to electricity storage. Those include STORIES ("*Addressing barriers to STORage technologies for increasing the penetration of Intermittent Energy Sources*", 2007-10) and stoRE ("*Facilitating energy storage to allow high penetration of intermittent renewable energy*", starting May 2011) with funding from the EU programme Intelligent Energy Europe [54], [65]. The former addressed island systems and promotion measures whereas the latter aims to identify the best practices in Europe for overcoming non-technical barriers to the development of energy storage facilities.

5 Topics for future research

The topics for further research can be broken down into 3 distinct areas: post modelling site analysis; future model development; and further related research.

5.1 Post modelling site analysis

Post modelling site analysis would entail further more detailed analysis of the global country potential, based on detailed knowledge of specific sites, from either measurements or non-GIS sources such as operator reports or environmental assessments.

Geological assessment. The model developed here assesses sites based on their slope. In order to fully assess the suitability for transformation to PHS further analysis on the geological makeup of the site and surrounding area would be required. This could be used e.g. to more accurately identify costs –depending on the type of rock a new reservoir might need an waterproofing layer, or is costlier to dig [63].

Hydrological assessment. A hydrological assessment of the global country potential would be needed to evaluate the inflow into existing reservoirs or the inflow into the potential reservoir sites. It might be that existing GIS water models could provide the input for this assessment.

Flood risk assessment. The analysis of barriers details and discusses, in general, a list of potential cases which could cause flood risks. Future research would require an analysis of each flood risk, using the points mentioned in section 4.6 for the country potential.

Additionally, PHS may be used for flood protection; the model could present the capacity of water storage in the proposed PHS schemes and relate it to other parameters that identify the role of PHS in flood protection. Those parameters could be hydraulic, population, infrastructure, etc.

5.2 Future model development

5.2.1 Investigate the availability of additional data layers

The incorporation of geology and hydrology (e.g. precipitation and evaporation) data would improve the functionality of the model developed in this work. A layer of geological data would allow some unsuitable sites to be either flagged or eliminated, for example sites located on peat soils or sites with porous bedrock such as limestone (see the discussion in section 4.1.1). A layer containing evaporation or potential evapotranspiration would be useful in order to infer the likely evaporative losses from storage reservoirs. However, evaporation is highly spatially variable, especially in upland regions where orography and local winds may have large effects, and large-scale model datasets may not be capable of fully representing this variability. Precipitation data would help to quantify inflows to reservoirs.

5.2.2 Other model improvements

Alternative, higher-resolution, terrain datasets may be available, on a commercial basis. These datasets, if suitable, may improve the accuracy of the site selection process. We recommend that the model be tested in a small region with a subset of any new terrain dataset before proceeding to recalculating transformation potentials on a country-wide basis. In this way, the effects of the resolution and quality of the terrain information on the results can be assessed.

A potential extension to the model would be to estimate cut and fill volumes for reservoir construction. This exercise is likely to be computationally intensive for large areas [55].

With a substantial investment of time[6], ICOLD reservoir sites in countries other than Croatia and Turkey could be geo-referenced by using the manual cross-referencing technique with Google Earth used to update the Turkish and Croatian databases. Alternatively, other sources of data could be found even in GIS format which could reduce the effort for data preparation.

The individual resulting schemes could be analysed to distinguish between daily- or weekly-cycle PHS, a way to do this by combining the capacity of the proposed PHS in GWh with reasonable assumptions on pumping capacity, some work was already done e.g. by EWI and energinautics [56]. The country potential could be appropriately split between both types of PHS.

We assumed that when both TA and TB transformations are possible for the same site the choice is TB owning to lower transformation costs. This disregards the possibility of TA yielding much more potential. The model could introduce the evaluation of cost advantage vs. higher energy storage potential. Likewise, there are a number of areas where a combination of parameters can be sensible:

- Criteria for distance between reservoirs and head may be considered in combination. For example a second reservoir site 5 km away with 150 m head does not seem like a suitable site [59], [63].

- Topology B is always preferred over Topology A, but this can be challenged. For example, two existing reservoirs 5 km away with a head of 150m may not be a desirable development for a PHS (TB). However if suitable sites with 600m head exists within 1-2 km of one of the two reservoirs, it may be favoured compared to utilizing the second reservoir. The cost of constructing the secondary reservoir is relatively small compared to the overall cost of the project [59].

Some of the reservoirs can be as long as 20 km (Peruca, in Croatia), therefore the 5-km limit for the second reservoir , currently at the centre of the dam, could be based not any point in the lake, thus multiplying the explored area and thus the possibilities of finding a suitable site [63].

The head parameter could be adapted to be net head by taking into account losses, average head, or a combination of both elements.

Maximum head could be an additional technical constraint. Existing PHS technology limits the head between the two reservoirs to 700-800 m. In the example for Croatia, the selected site is at the (feasible) edge of existing technology [59].

5.2.3 Extension of scope: site pre-selection.

It has been highlighted that for the purposes of identifying maximum feasible PHS country potential, maximum energy storage seems the proper criterion. However, for the pre-selection of a PHS site this may not be the most suitable criterion. Other criteria, such as maximum head or minimum distance between the reservoirs (both of these reduce the CapEx) may also be used. Therefore the methodology could extend the scope for site pre-selection. "Two possible approaches to this could be (a) to combine two or more criteria with different weights for finding the "optimum" site or (b) to select "optimum " sites based on more than one criteria separately (separate runs which could possibly identify different sites)." [59]

5.2.4 Reaching the final user

This model could provide an increasing valuable service to the final users if their needs were incorporated in the form of layers. Possible layers include:

- Full data on grid capacity is needed to estimate the cost of grid connection.

- More detailed calculation of the size and shape of the new (second) dam proposed in TA.

- Cost data for the different items, e.g. cost per cubic metre of concrete for the dam, per km of grid extension.

- Building time data for the different items, data on permitting delays and other project-management aspects.

- Electricity interconnection capacity would help determine the possibilities for increased PHS to support the electricity system of neighbour countries.

Possible users include the spatial planning bodies of regional or national governments; utilities; and developer of pumped hydropower schemes. They should first and foremost be consulted on which kind of output from the model, in terms of specifications and format, would be needed to let them reduce costs or improve their work.

5.3 Further related research

Further related research relates to areas that would benefit the future of PHS, considering different types of plants, detailed costs, operation within electricity systems and markets.

5.3.1 Analysis of the types of existing PHS

PHS has different configurations depending on the topography it is sited in.

- 2 existing reservoirs with natural inflow (transformation studied as TB)

- 1 existing reservoir and 1 artificial, newly-built one, usually the upper one (studied as TA)
- 2 artificial reservoirs (closed loop)

There are also variations on these 3 configurations. Research into existing PHS plant configuration would allow for the categorisation of each PHS plant under the above headings. This knowledge would be useful for planned PHS, especially in the area of capital costs. Novel technologies such as coastal seawater PHS could also be included in this categorisation.

5.3.2 Analysis of capital cost

As highlighted in section 4.2.4, the uncertainty of capital costs for PHS is a major barrier to the future development. Research into breaking down the capital costs into its constituent parts (penstock, generation equipment, reservoir construction, or even a more detailed split) would provide more certainty for developers. Following on from the categorisation of existing PHS, a capital cost for each configuration could make capital cost estimation more accurate in the future.

5.3.3 Evaluate the role of PHS within the electricity markets in Europe

A barrier for developers of PHS is the uncertainty of income streams from energy markets. Energy payments from trading in the wholesale market are normally the main source of income for PHS operators. However, some market structures also pay capacity payments for the availability of generation and/or pay for the availability of generators for ancillary services (reserve, black start etc.). Research into how existing PHS operate within existing European markets would provide some level of income certainty, and an indication of whether projects can be financially viable. Furthermore, stakeholders have highlighted the need to identify as part of the evaluation of the potential the economic aspects including the potential income of a PHS plant from energy[10], capacity, and ancillary services, or whether there are any other financial incentives. "*Even though market analysis is not your focus, a more detailed overview of market issues would add value to your report*" [59].

5.3.4 Connection with the National Renewable Energy Action Plans (NREAP).

Under the renewable energy Directive (2009/28/EC) EU Member States have to prepare plans to meet their respective 2020 goals of renewable energy contribution. Given that large-scale energy storage is nowadays only possible with reservoir-based hydropower or PHS, there is a clear connection between the implementation path shown in NREAPs and the need for energy storage. This connection is shown in the NREAP which include projections of PHS as well as other hydropower installation.

Further research could look at how PHS (and the transformation to PHS) could enable grids to accommodate a higher variable-RE component.

5.4 Potential co-operation with GRanD

This project has benefitted from the data provided by the GRanD project. If further work is to be carried out in this area, then formal co-operation with GRanD may be mutually beneficial.

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[10] As [60] suggested "what is important is the difference between off-peak and peak electricity prices, multiplied by efficiency"

6 Methodological remarks and conclusions

In this analysis of potential for transformation the authors were obliged to take decisions based on empirical analysis as well as on their own experience, with the limitations imposed by the model and with availability of data being a key influencing factor. Because of the latter those decisions at times had to be arbitrary and not necessarily matched the reality. A good example to illustrate this point is the TA case for Croatia which was contrasted with the reality. This one, the Razovac dam, is part of the Velebit PHS system where the Štikada reservoir is the upper one. Here the reality challenged two key assumptions of the design of the model, namely that the size of the potential new upper reservoir should not be bigger than the lower (existing) reservoir, and that the economic distance between the two reservoirs should be lower than 5 km. Indeed the validity of the latter assumption was further challenged by other example, the PHS project "Atdorf" (1.4 GW, 13 GWh) in Baden-Württemberg (South Germany) with a distance between the two (new) reservoirs of 8.5 km [62].

Every scenario for high penetration of renewable energy in electricity systems highlights the need for electricity storage ([56], [57]) and puts storage as a key factor for reducing the cost of energy if the renewable electricity is of a variable nature. This modelling exercise is, to the knowledge of the authors, the first approach to identifying and quantifying the potential for transformation to pumped hydropower storage in European countries based on one or two existing dams. However, this exercise belongs to the field of research and, as the reality check has hinted, its results might be some stages away from the accuracy and definition required for an actual project feasibility study. This is important because (we believe) the ultimate goal of an exercise to quantify the potential for increasing PHS should be dual: to feed the decision-making process with sound science and to reduce the costs of transformation for all actors involved: governmental spatial planning agencies, engineering companies and PHS developers.

Reviewers have highlighted that the parameters used to restrict the search for suitable sites were too restrictive regarding reality. There are inhabited areas less than 200 m from a reservoir, penstock can be buried so they can cross transport infrastructure and thus the 100-m distance to the latter might be a unnecessary restriction [63]. The restriction of 5 km to UNESCO sites may be excessive when, e.g. this is an isolated chapel in the middle of the mountains

“Throughout this report the primary focus was on the storage capacity, which is necessary since we are investigating the availability of potential reservoirs. However, power capacity is somewhat independent of the storage capacity i.e. to increase the power capacity more penstocks can be constructed at existing PHS sites. Some research has indicated that increasing the power capacity could enable higher wind penetrations without any increase in the storage capacity” [58] [65]

Hydrology is a critical criterion especially for areas/countries in dry climates, such as those in Southern Europe. The assumption that the existing reservoir volume can be potentially used for PHS is not necessarily valid in dry areas. For example in Cyprus dams are rarely full or even near full, they are oversized in order to maximize the water collection in rainy years and use it for storage in dry years. In these cases the addition of a second reservoir would increase the volume of water stored at the peak rainy season but during those period the reservoir could not be used as PHS but as permanent water storage. Furthermore, a PHS plant cannot use all the existing volume of the reservoir, otherwise debris and silt would be drawn up the pump-turbine. Large level differences are not technically favourable for the mechanical equipment; depending on the shapes/areas of the reservoirs large head differences may develop from the start of the pumping cycle to the end. As a first step, the model could limit the volume of the reservoir by a certain percentage (say, 80%) to account for all these factors [59].

The next steps could include the opening of a dialogue with these stakeholders that would result in a more flexible model able to provide more accurate results that are closer to reality and therefore start to be useful for at least some of those actors. Eventually, the process started with this work could (some would say "should") be expanded to the whole of Europe.

7 Conclusions

The country potential for transformation to PHS in Croatia is of 60 GWh, which compares with the current installed PHS storage of 20 GWh. However, the latter is mostly (98%) in one single, mix-PHS installation which generates 80% of its electricity from pure hydropower resources. If a volume factor[11] is applied as proposed by [56], 60 GWh would correspond to turbine capacity of 2.3 GW

The realisable potential for transformation in Turkey shown by this analysis is 3 800 GWh. This figure corresponds to 146 GW of turbine capacity at a volume factor of 26, and can be compared with the estimated 35 GW of peak demand and 230 000 GWh of generation in 2010. Unfortunately there is not an option to compare this transformation potential with the existing PHS capacity because currently there are no PHS plants in Turkey.

We need some insight on how the prospective new PHS could be used to help stabilise the grid and increase the uptake of renewable energy. In effect, some of the potential PHS could be used for intra-day balancing, i.e. pumping at night when there is excess electricity from baseload (coal or nuclear) plant, and generating during the day. Some other PHS with higher storage capacity could be used for weekly or monthly storage if economically feasible. A PHS transformation based on the Karacaoren II Dam in Turkey, with 34 GWh of storage capacity, could be used to store electricity from excess wind rather than curtailing wind production.

In effect, wind energy cycles may last hours but most frequently last 3-4 days depending on the local climatology. In electricity systems with high wind penetration and low export capacity, islands or electrical "peninsulas" such as Ireland or Inner Mongolia in China, wind would need to be curtailed whereas a PHS plant with large storage capacity can absorb and then release these wind energy during peak demand and thus having the additional environmental effect of avoiding the use of the peaking plant fuelled by fossil fuels whether natural-gas or coal (e.g. in China), and benefiting from a subsequent reduction in greenhouse gas reductions.

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[11] According to [56] "The volume factor represents the ratio of storage size and the turbine capacity (e.g. 1 GW pump storage turbine has a 26 GWh storage basin)"

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Further reading

The following documents can contribute to enhance the issues analysed in this scientific and technical report:

- J. Deane, B. Ó Gallachóir, and E. McKeogh, "Techno-economic review of existing and new pumped hydro energy storage plant," Renewable and Sustainable Energy Reviews, vol. 14, no. 4, pp. 1293-1302, May 2010.
- Bogenrieder W. "Pumped storage power plant-renewable energy". Volume 3 'Energy technologies' of Landolt-Börnstein Group VIII 'advanced materials and technologies, 2006. "The cycle of pumping and generating can be repeated on a daily, weekly or even seasonal basis. In the daily cycle the reservoirs can be filled and emptied within a 24 hour period while in the weekly cycle the upper reservoir is partially drawn down and partially refilled during weekdays and completely refilled during weekends when the system load is normally low. Seasonal pumping is applied in hydropower systems with a large annual variation in inflow of water to the reservoirs."
- Limberg II PHS, Verbund, http://reports.verbund.at/2006/csr/selectedprojects/pumped-storagepowerplantlimbergii.html "Abstract: The new pumped-storage power plant, Limberg II, which is being constructed by Verbund-Austrian Hydro Power AG (AHP) to supplement the existing Kaprun power plant group, is located at the rear of the Kaprun Valley. The balancing and backup power plant, Limberg II, will more than double the output of the Kaprun power plant group from 353 MW to 833 MW by making optimal use of the difference in height between the existing Alpine storage lakes, Mooserboden (2 036 m above sea level) and Wasserfallboden (1,672 m above sea level)." 17 years construction to 1995, 166 Mm3 between these first two reservoirs. Very interesting environmental aspects
- EPRI (Electric Power Research Institute), 1990. "Pumped Storage Planning and Evaluation Guide". Prepared by Harza Engineering Company, Chicago. "A comprehensive and stand-alone guide is offered for the preliminary evaluation of pumped-

storage sites, to help (a) evaluate performance and benefits of pumped storage in a utility system, including dynamic benefits, (b) identify the physical characteristics of a site suitable for pumped-storage development, (c) establish the site's energy storage potential and installed capacity, (d) estimate capital cost, and annual operation and maintenance expense, and (e) conduct an economic analysis. ***A PC-based computer program*** has been written and is included in the Guide Book to assist in benefit analysis. The concept of dynamic benefits is explained, and how pumped storage contributes to them is described. Six of the major power system generation planning models are evaluated to help utility planners select the model best suited for their application. A methodology is provided to help planners screen and select sites encompassing cost, benefit, environmental, and regulatory factors. Step-by-step procedures are described, one simplified and the other more detailed, to facilitate the use of the guide. Background descriptions are provided to assist those unfamiliar with pumped-storage practice. A series of cost curves are provided to permit the development of a preliminary capital cost estimate for a site, based on a few key parameters which define the physical characteristics of the site."

- USA Army Corps of Engineers. Engineering and design–hydropower (evaluating pumped-storage hydropower). Publication number: EM 1110-2-1701; December 1985. Available at http://140.194.76.129/publications/eng-manuals/em1110-2-1701/c-7.pdf "Abstract: Pumped storage operation can be best understood by examining an off-stream pumped-storage project which operates on a daily/weekly cycle (the most common type of pumped storage development in the United States). The early sections of this chapter discuss the analysis of this type of project. Later sections are devoted to pump back, seasonal pumped storage, and other aspects of pumped storage development."
- Allen A.E, 1977: "Potential for conventional and underground pumped-storage, IEEE Transactions on Power Apparatus and Systems 96(3), May 1977. "The purpose of this paper is to present a very brief review of the current state of pumped-storage, with a cataloguing of its benefits and problems, and a brief summary of future potentialities. The potential for pumped storage is directly related to the public's viewpoint."

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European Commission

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Cover picture: Dam of Cortes II, part of the pumped-hydropower scheme Cortes – La Muela, in Spain. Courtesy of Iberdrola

Abstract

Electricity storage is one of the main ways to enable a higher share of variable renewable electricity such as wind and solar, the other being improved interconnections, flexible conventional generation plant, and demand-side management.

Pumped hydropower storage (PHS) is currently the only electricity storage technology able to offer large-scale storage as that needed for accommodating renewable electricity under the 2020 EU energy targets.

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.

The authors developed a geographical information systems (GIS) -based methodology and 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 and then exposes the results of its application to two countries as case studies. 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 2 potential TB sites providing three additional GWh of storage potential.

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