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Identification and application of indicators for the assessment of pumped hydro storage projects with renewable energy generation

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Abstract. Pumped hydro storage is crucial in Europe's energy strategy to achieve a 100% renewable energy-based electricity system by 2050. As a consequence of the large number of factors involved and the variety of criteria included in a proper assessment of renewable generation projects with pumped hydro storage, this paper aims to identify and calculate technical, economic, environmental and social indicators in order to provide a tool to improve the decision-making process in this type of large-scale projects.

Key words. Pumped hydro energy storage, renewable generation, site selection, indicators selection, assessment.

1. Introduction

The energy sector is undergoing a profound transformation driven by climate change reduction and the efficient use of natural resources. By 2050, Spain must achieve climate neutrality and the electricity system must be based exclusively on renewable sources [1]. Today, these objectives can be difficult to reach for several reasons. First, large amount of the energy generated by renewable sources is rejected as a result of grid constraints and technical reasons associated with the security of electricity systems. Secondly, most renewable energy sources depend on weather conditions, i.e., they are uncertain and uncontrollable, producing imbalances in the grid. Therefore, to overcome these drawbacks, the combination of wind and photovoltaic generation together with reversible pumped storage is growing. Pumped hydro energy storage (PHES) facilities consist of two large reservoirs, one located at a low level and one located at a higher elevation (there must be a minimum elevation difference of at least 250 meters). During off-peak hours, water is pumped from the lower reservoir to the upper reservoir, where it is stored until it is needed. When needed, i.e. during peak hours of electricity production, water from the upper reservoir is released through turbines, which are connected to generators that produce electricity [2]. It should be noted that this type of storage is the most mature and viable technology on a large scale. PHES has a fast response time, which is ideal for load leveling applications, and the use of variable speed machines allows for frequency regulation in both pumping and generating modes. Thus, PHES systems improve their efficiency by approximately 3% and extend the lifespan of the system [3]. However, despite the many advantages presented, pumped hydro storage plants have some drawbacks, such as their dependence on specific geological formations due to the construction of two large reservoirs with sufficient height between them, difficult access for electrical connection, high investment costs and the construction of dams could cause an environmental impact high [2].

From the literature reviewed, previous works [4], [5], [6] identify criteria for the selection of suitable sites to implement reversible pumped storage plants, but, nevertheless, a classification with new indicators is needed to obtain a complete and coherent planning of pumped hydro storage projects with renewable generation facilities. It is essential to include the distinction of technical, economic, environmental and social criteria, as well as sub-criteria linked to each of these criteria to enhance the decision-making process. Addressing this gap in the literature, this article aims to identify and calculate criteria and sub-criteria that can provide the most complete view possible of the real impact of pumped hydro storage projects with integration of renewable energy, by incorporating the most relevant aspects in the assessment of these large-scale storage projects.

The remainder of this article is structured as follows: Section 2 identifies the indicators considered for analyzing PHES projects. Section 3 explains in detail the selected criteria and sub-criteria and applies them to a real case study. Finally, Section 4 summarizes the main conclusions of this work.

2. Indicators selection

Projects assessment is a complex process due to the large number of factors involved, and the wide variety of criteria, objectives and participants included in each of them. Pumped hydro energy storage projects with integration of renewable energy must be economically viable, technically feasible (efficient and reliable), environmentally sustainable (minimization of environmental impact) and socially beneficial to the community (maximum benefits). As a consequence, coherent and appropriate planning of these projects requires the implementation of four criteria such as technical, economic, environmental and social, and, in this way, a global vision of the problem can be obtained. Similarly, these criteria require the linkage of a set of numerical sub-criteria for decision making. In this research, 24 sub-criteria have been identified, among which the following stand out: working hours generated, income for the community, distance to protected natural areas, economic profitability, geotechnical ratios, average power, L/H ratio and power at the discharge point in the grid, among others. Figure 1 presents the indicators identified in this article to achieve an adequate assessment of projects for the integration of renewable energy production sources with PHES in Spain.
In short, the identification of these indicators improves the understanding of such large and complex projects in which a large part of society is affected by them. The proposal of these criteria allows to provide a tool that can contribute to the improvement of the quality of the decisions related to this type of projects with a simple, economic, transparent and reliable method. In addition, these indicators can be applied to any region and analyze the real impact and benefits of pumped hydro storage projects.
In the following section, the indicators mentioned above are explained in detail and applied to an actual project study.

3. Application

3.1. Case study definition

The selected indicators have been calculated for the case of a real project of renewable energy production facilities that also incorporates a reversible pumped storage facility, as shown in Figure 2. The project consists of 1209 MW of photovoltaic power, 702 MW of wind power and 396 MW of pumping.
When developing a pumped hydro storage project, there are several aspects to take into account, such as the availability of the water resource, access to the grid connection, the difference in level between the reservoirs, among others. Therefore, there must be a balance between all these factors.
The project analyzed with the indicators proposed in this paper should minimize environmental impact and avoid special protection zones for birds. The project presents good conditions for the hybridization of storage with photovoltaic and wind generation plants.
Regarding the water resource, the catchment point for this project has a high water flow rate and, therefore, the time required to fill the reservoirs would be reduced. The difference in elevation between the lower and upper reservoir of the facility is more than 320 meters. Figure 2 shows the polygonal areas of the generation plants and pumping.
Subsequently, the following subsections explain the calculation of social, economic, environmental and technical indicators for decision-making process. In addition, the application of these criteria to the study project is included.

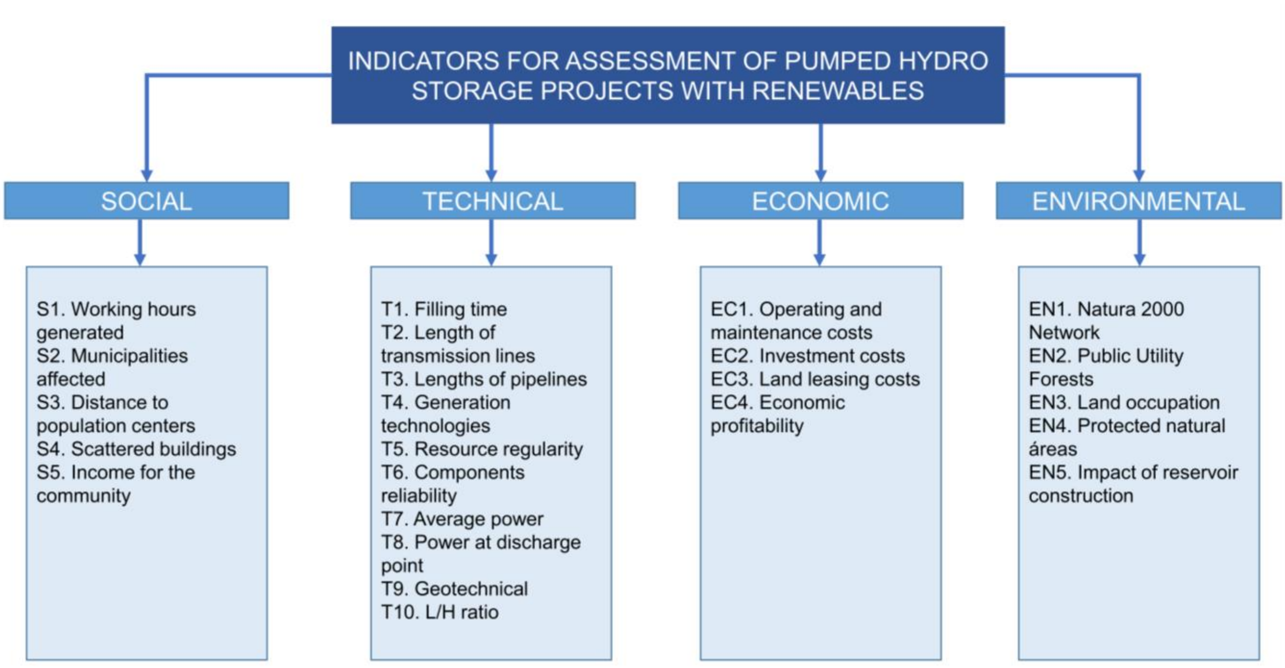

Figure 1. Ranking of indicators identified for the assessment of pumped hydro storage projects

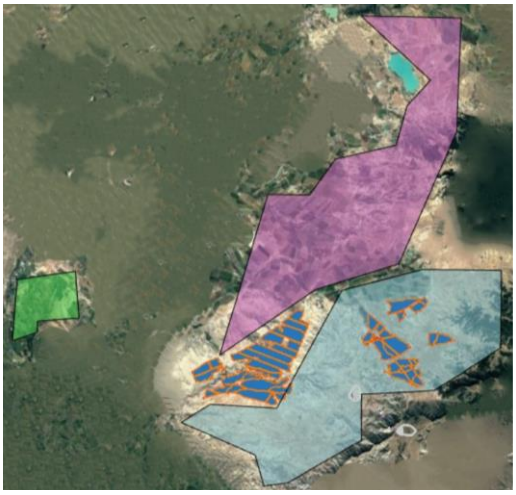

Figure 2. Polygonal areas of generation plants and pumping

3.2. Calculation of social indicators

S1. Working hours generated

This indicator calculates the working hours that could be generated by the construction phase and the subsequent operation and maintenance phase of the facility.
To obtain this indicator, the facilities are broken down into three blocks (wind, photovoltaic and pumping) and, using employment/MW ratios and installed power, the employments that would be generated by each of the facilities are obtained. Subsequently, the corresponding hours that these jobs would represent during the lifespan of the facility (25 years are considered) are obtained.
Table I indicates the employment/MW ratios in each of the phases of the study project, based on the International Renewable Energy Agency, and Table II shows the calculation of working hours generated from these data.

Table I. Employment/MW ratios in project phases [7], [8]

	Employment/MW ratio in construction phase	Employment/MW ratio in operation and maintenance phase
Photovoltaic	5.5	0.7
Wind	5	0.22
Pumping	6	0.1

Table II. Total hours generated

	Photovoltaic	Wind	Pumping
Power (MW)	1209	702	396
Employment in construction phase	6650	3510	2376
Employment in operation phase	895	154	40
Total employment (25 years)	29025	7360	3376
Total hours generated	49,342,500	12,512,000	5,729,200

S2. Municipalities affected

Total number of municipalities that will be affected by both pumping and renewable facilities.
In this case study, 4.

S3. Distance to population centers

It is important that the facilities (especially wind power and pumping technology) are located as far away as possible from urban centers to ensure the safety of the population and avoid rejection of these facilities by the inhabitants. In this case, the minimum distance of the polygonal areas of the facilities is 1.51 km from the nearest population center.

S4. Scattered buildings

Square meters of built-up area located within the polygonal areas of the facilities. In this case, this indicator is 83.34 ha. This is a high value, which may cause greater rejection of the project by the local population.

S5. Income for the community

For the calculation of this indicator, the sum of tax on constructions, installations and works, real estate taxes and tax on economic activities is considered, based on data from the Spanish legislation, [9], [10].

Table III shows the values for the case study.

Table III. Results of income for the community

	Value
Real estate taxes	2000€/MW/year
Tax on economic activities	2000€/MW/year
Power (MW)	396
Tax on constructions, installations and works (million euros)	10.34
Real estate taxes + tax on economic activities (million euros)	4.61
Total (million euros)	15.45

3.3. Calculation of economic indicators

EC1. Operating and maintenance costs

Operating costs include both direct and indirect labor. For the calculation of this indicator, the following variable costs are considered for each technology (see Table IV).

Table IV. Operating and maintenance costs

	Photovoltaic	Wind	Pumping
Power (MW)	1209	702	396
OPEX (€/kW/year)	13.3	37	15.33
Total (€/year)	16,091,790	25,974,000	8,363,520

EC2. Investment costs

Costs that are necessary to implement the project. Table V shows the costs of this project analyzed:

Table V. Investment costs

	Photovoltaic	Wind	Pumping
Power (MW)	1209	702	396
CAPEX (€/kW/year)	551.9	892	-
Total (€/year)	667,210,830	626,184,000	-

EC3. Land leasing costs

These costs will depend very much on the technology, i.e., whether the land is leased for wind farms or for photovoltaic and pumping.
In the case of solar, the rental price of rural land for the placement of photovoltaic modules ranges from 1000 euros/hectare to 1500 euros/hectare [11].
In the case of pumping, since it is a relatively new technology and no current data on ground rental costs are available, it is assumed to be the same as in the case of photovoltaic since, like photovoltaic, it involves total land occupation.
In the case of wind farms, as the exact number of wind turbines is known, a price range is established from 1250 euros/MW to 7500 euros/MW, based on wind generation research [12]. For the calculation of this indicator, an intermediate value of 3000 euros/MW is selected. Table VI presents the results for the case study.

Table VI. Land leasing costs

	Photovoltaic	Wind	Pumping
Power (MW)	1209	702	396
Hectares	2765.70	-	88
Land leasing costs (€/year)	2,765,700	2,106,000	88,000

EC4. Economic profitability

The last economic indicator is the economic profitability, by calculating the NPV, IRR and Payback of the project. The calculation assumes taxes of 30%, an electricity sales price of 4.4 cents/kWh and an annual inflation rate of 2%, and the NPV calculation includes a discount rate of 5%. Table VII shows the results obtained for the case study.

Table VII. Results of economic profitability

NPV (€)	IRR (%)	Payback
89,366,455	5.63	12 years

According to these results, the analyzed project would have good profitability, since there is a high wind and photovoltaic production in the area together with the high pumped hydro storage capacity, thus obtaining a high income.

3.4. Calculation of environmental indicators

EN1. Natura 2000 Network

This network refers to a European ecological network of biodiversity conservation areas. Its purpose is to ensure the survival of species and habitat types in Europe over the years [13]. It consists of three zones: the so-called SACs (Special Areas of Conservation), the so-called SCIs (Proposed Sites of Community Importance) and, finally, the SPAs (Special Protection Areas for Birds). The installation of wind farms or photovoltaic plants is prohibited in these areas.
This indicator measures the minimum distance between the project's polygons to be analyzed and the nearest SCIs, SPAs or SACs. In this case, the area closest to the polygonal zones of the installation is an SPA that is 100 m from a wind turbine.

EN2. Public Utility Forests

These are those forests that are declared "of public utility" because they provide a service to society. Unlike the previous indicator, it will be possible to implement renewable technologies on public utility forests.
This indicator refers to the hectares of the polygonal areas that are located on these types of forests. In this case, a total of 3325.32 ha are located on public utility forests.

EN3. Land occupation

Square meters occupied by the polygonal areas of wind farms, photovoltaic plants and pumping.
In the case of both photovoltaic and pumping, the entire surface will always be occupied. However, in the case of wind energy, there must be minimum distances between wind turbines to avoid aerodynamic interference that could lead to increased turbulence and thus a loss of power. For this reason, minimum distances of 3 rotors perpendicular to the prevailing wind direction and 8 rotors in the direction of the prevailing wind have been maintained. Here, the V162-6.0MW wind turbine model is used, which has a hub height of 125 meters and a rotor diameter of 162 meters. A distance of 500 meters between wind turbines in alignments perpendicular to the dominant wind direction and a distance of 130 meters between alignments in the direction of the dominant wind must be complied with at all times. Table VIII shows the areas occupied by each technology in the project analyzed.

Table VIII. Area occupied by facilities

Wind surface (ha)	Photovoltaic surface (ha)	Pumping surface (ha)
21,430	2158.75	88

EN4. Protected natural areas

Areas that, due to their outstanding natural values, are specifically designated for nature conservation. The implementation of renewable technologies will not be possible in these areas.
This indicator measures the minimum distance from the polygonal points of the facility to be studied to the nearest protected natural areas. In this case, there are no protected natural areas near the facility.

EN5. Impact of reservoir construction

Land movement required for the construction of the ponds. For the calculation, it has been considered necessary to take into account, on the one hand, the total cubic meters of land that will need to be moved (see Table IX), since it will be of interest that this value be as low as possible. On the other hand, it has been considered necessary to consider the net balance (that is, the difference between the clearing and the embankment) that will indicate the amount of land that is necessary (see Table X).

Table IX. Volume of land to be moved

	Upper storage	Lower storage	Total (m^3)
Clearing	4,472,510	5,054,610	-
Embankment	822,700	621,170	-
Total	5,295,210	5,666,780	10,961,990

Table X. Net balance results

	Upper storage	Lower storage	Total (m^3)
Clearing	4,472,510	5,054,610	-
Embankment	822,700	621,170	-
Total	3,649,810	4,433,440	8,083,250

3.5. Calculation of technical indicators

T1. Filling time

A very important indicator is the one that refers to the hydrology or filling time of the project. A ratio defined as the maximum flow rate requested divided by the total volume of the installation is calculated. In this case, there is a supply from a river with a high flow rate, so the filling time is very short (see Table XI).

Table XI. Results of filling time

Maximum flow rate (m^3/s)	Total volume (hm^3)	Filling time
5	7.57	18 days

T2. Length of transmission lines from pumping station to discharge point

In this case study, the total length of the discharge line is 35.4 km. The longer the distance of this discharge line, the worse the project will be, since the higher the construction costs of the power line and the larger the affected area will be, which will increase the paperwork with the different municipalities that would be affected.

T3. Length of pipelines required from pumping to water collection point

This indicator determines the distance in km that the pipelines should have from the water intake point to the reservoir to fill it. In this case, the total length of the pipelines is 12.29 km.

T4. Generation technologies

This indicator refers to the equivalent hours of both wind and photovoltaic resources, since these hours are associated with the performance of the wind farms. In this project, there is a total of 3174 equivalent hours of the wind resource and 1863 equivalent hours of the solar resource.

T5. Resource regularity

Due to the high uncertainty of wind energy, an indicator has been included to report on the regularity of the resource for the project to be analyzed. Average wind speed and solar irradiation data from 1999 to 2020 are determined from the EMD software [14]. Once the average wind speed and average solar irradiation are obtained, the coefficient of variation is calculated (see Table XII).

Table XII. Results of photovoltaic and wind resource regularity

Average speed	Irradiation	Coefficient of wind variation	Coefficient of solar variation
6.81 m/s	220.35 W/m^2	3.11%	1.11%

T6. Components reliability

This indicator refers to the total annual failures or downtime hours for wind turbines and photovoltaic panels. In the case of wind turbines, a total of 0.52 failures per turbine per year and a total of 44.51 hours of inactivity per turbine per year are obtained from research [15]. Therefore, considering the equivalent hours, the hours of inactivity and the percentage of hours in which the wind turbines would not operate are obtained (see Table XIII).

Table XIII. Wind turbine reliability results

Wind turbine downtime hours	Total hours	%
5207.67	371,358	1.40

In the case of photovoltaic energy, a study shows that, only 0.05% of photovoltaic modules fail per year based on the International Renewable Energy Agency, [16].
According to the percentages obtained, it is shown that photovoltaic energy will be much more reliable than wind power.

T7. Average power

This indicator is associated with the average power of the installation. This power will be calculated from the useful volume of the reservoirs, the cycle time (estimated at 12 hours), the average slope, and a performance factor of 0.9 (see Table XIV).

Table XIV. Average power results of the installation

Flow rate (m^3/s)	Average power (MW)
132.87	383.86

T8. Power at discharge point

This indicator determines the total power that can be injected into the substations where the project will be connected, based on data from the electricity system operator [17]. The nearest substation in this case has a connection capacity of 396MW, which is a high value, so additional income can be obtained from the sale of surpluses generated.

T9. Geotechnical

Another technical indicator that is interesting to study is the seismic hazard at which the different selected facilities are located.
The seismic hazard map of Spain is used to calculate this indicator [18]. This map shows Spain divided by contour lines where a value below 0.04 indicates that there is no earthquake risk in that area and a value above 0.06 begins to be considered a risk area.
The case study is located in a zone between 0.03-0.04 of seismicity risk, so it is a low value, that there is no earthquake risk.

T10. L/H ratio

Another very important indicator within the technical criteria of the project is the ratio defined as L/H where L is the distance between storages and H is the difference in elevation between these storages. It is important that this ratio be less than or equal to 10, based on report [19]. This study project presents a slightly higher but still acceptable ratio (see Table XV).

Table XV. L/H ratio results of the analyzed project

L (m)	H (m)	L/H
321	3780	11.78

4. Conclusion

The combination of renewable generation plants with pumped hydro storage is one of the alternatives most widely used on a large scale in order to manage grid imbalances, due to the high uncertainty of renewable production, and to meet the energy targets set by Spanish and European regulations.
Renewable energy projects in rural areas focus on minimizing the environmental impacts caused by renewables facilities, without considering the other criteria: social, technical and economic. The identification and application of indicators of different categories in this article aims to provide an adequate tool to assess the real impact of pumped hydro storage projects, and in further research, these indicators can be used to prioritize different economic investment and energy generation alternatives over others and make a more robust defense of the best option to implement.

References

[1] D. Sanchez, “Ley 7/2021, de 20 de mayo, de cambio climático y transición energética,” *FORO: Revista de Ciencias Juridicas y Sociales Nueva Epoca*, vol. 24, no. 2, pp. 1-46, 2021.

[2] S. Rehman, L. M. Al-Hadhrami, and M. M. Alam, “Pumped hydro energy storage system: A technological review,” *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 586–598, 2015, doi: 10.1016/j.rser.2014.12.040.

[3] P. C. Nikolaos, F. Marios, and K. Dimitris, “A review of pumped hydro storage systems,” *Energies*, vol. 16, no. 11, 2023, doi: 10.3390/en16114516.

[4] X. Yong, W. Chen, Y. Wu, Y. Tao, J. Zhou, and J. He, “A two-stage framework for site selection of underground pumped storage power stations using abandoned coal mines based on multi-criteria decision-making method: An empirical study in China,” *Energy Conversion and Management*, vol. 260, no. 4, p. 115608, 2022, doi: 10.1016/j.enconman.2022.115608.

[5] S. Kucukali, “Finding the most suitable existing hydropower reservoirs for the development of pumped-storage schemes: An integrated approach,” *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 502-508, 2014, doi: 10.1016/j.rser.2014.05.052.

[6] B. Lu, M. Stocks, A. Blakers, and K. Anderson, “Geographic information system algorithms to locate prospective sites for pumped hydro energy storage,” *Applied Energy*, vol. 222, no. 1, pp. 300-312, 2018, doi: 10.1016/j.apenergy.2018.03.177.

[7] A. E. Eólica, *Estudio macroeconómico del impacto del sector eólico en España*. Deloitte, 2021.

[8] IRENA, “Renewable energy and jobs: Annual review 2023,” irena.org. https://www.irena.org/Publications/2023/Sep/Renewable-energy-and-jobs-Annual-review-2023 (accessed Jan. 29, 2024).

[9] “BOE.” boe.es. https://www.boe.es/buscar/act.php?id=BOE-A-2004-4214 (accessed: Jan. 29, 2024).

[10] “Estimaciones IBI y IAE.” elperiodicodearagon.com. https://www.elperiodicodearagon.com/lo-ultimo/2018/08/27/lluvia-millones-medio-rural-aragones-46747701.html (accessed: Jan. 29, 2024).

[11] “Precios alquiler suelo FV.” elpais.com. https://elpais.com/economia/2020-10-30/los-agricultores-se-frotan-las-manos-plantando-paneles-solares.html (accessed: Jan. 29, 2024).

[12] “PRECIOS – OEGA.” observatorio.eolico.uvigo.es. https://observatorio.eolico.uvigo.es/observatorio-de-precios/?lang=es (accessed: Jan. 29, 2024).

[13] “Red Natura 2000.” miteco.gob.es. https://www.miteco.gob.es/es/biodiversidad/temas/espacios-protegidos/red-natura-2000.html (accessed: Jan. 29, 2024).

[14] “EMD International.” emd-international.com. https://www.emd-international.com/energypro/ (accessed: Mar. 19, 2024).

[15] M. D. Reder, E. Gonzalez, and J. J. Melero, “Wind turbine failures - Tackling current problems in failure data analysis,” *Journal of Physics: Conference Series*, vol. 753, no. 7, pp. 1-11, 2016.

[16] D. Hawila, A. Khalid, and R. Ferroukhi, *Renewable Energy Benefits: Leveraging Local Capacity for Solar PV*. Masdar City, United Arab Emirates: IRENA, 2017.
[17] "Red Eléctrica." ree.es/es. https://www.ree.es/es (accessed: Jan. 30, 2024).
[18] "Mapas de sismicidad y peligrosidad - Instituto Geográfico Nacional." ign.es. https://www.ign.es/web/mapas-sismicidad (accessed: Jan. 29, 2024).
[19] M. S. Phillips, W. L. Peirson, and R. Cox, "Appraisal of the potential of pumped storage in New South Wales," 2013.