

# Integrating Renewables with Pumped Hydro Storage in Brazil: a Case Study

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May 30<sup>th</sup>, 2019

## Abstract

The share of Variable Renewable Electricity (VRE) is expected to increase in the Brazilian power grid in the years due to favorable conditions which include economic performance and resource availability. Wind and solar photovoltaic projects will likely lead new capacity investments. While existing hydropower can support this growth, in the long run, difficulties for the development of new hydro plants will make it harder for the power system to integrate VRE. The standard option is to build new open cycle gas turbine plants, which provide capacity to supply peak demand and reserves at the expense of increasing the emission of greenhouse gases. An alternative is to develop a flexible and resource: Pump Hydro Storage (PHS). We advocate the following process to examine this alternative: (1) the use of specialized geoprocessing algorithms that operate on a digital terrain model to screen for most promising sites for the construction of PHS; (2) the use of an engineering module to design PHS candidate projects in the selected sites and calculate their costs; (3) the use of an Integrated Resource Planning optimization model a study to evaluate the set of candidates that are selected by an. In a site-specific level, hybrid PHS + solar PV projects can be optimized and then integrated as a “system of systems” to improve grid stability, reliability, robustness and resiliency.

## 1. Introduction

It is an interesting time, globally, in the energy industry, as the world faces the dual challenge of increasing the availability of electrical energy while reaching toward a zero-carbon future – and to do so in a way that minimizes any negative impacts on people and environment. The importance of an adequate supply of reliable electricity in supporting economic development and growth is unquestioned, as is the need for that electricity to be clean and low carbon. The need to provide equitable access to electricity for underserved people is also unquestioned. Moreover, the demand for increased electrical supplies is further amplified by the trend toward electrification of economic sectors previously served primarily by fossil fuels, such as transportation or heating.

The conversation in the electrical power sector has taken a sharp turn in just the last couple of years. It is no longer about whether it is realistic, or even necessary, to *slow* the emission of greenhouse gases, and whether much of the world outside the developed countries could afford it. It is now very much about how fast carbon emissions can be reduced entirely, and how to do it. The conversation now is about the energy transition, the transition from a hydrocarbon economy to a no-carbon economy.

IEA, in its World Energy Outlook 2018, put it as “the share of electricity in global energy use is growing while the rise of low-carbon technologies is prompting a major transformation in the way electricity is generated. What might tomorrow’s power sector look like? How can it ensure reliable supply while reducing emissions?”

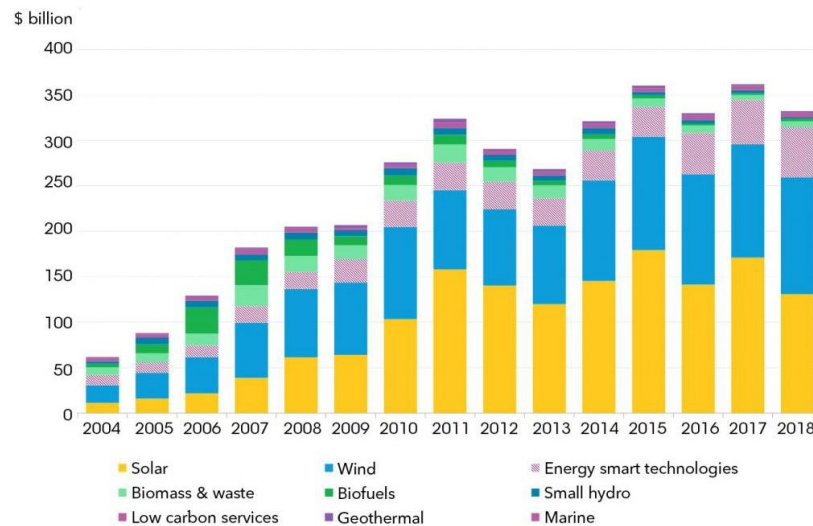
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The rapid expansion of VRE sources<sup>3</sup> such as wind power and solar photovoltaic is a global phenomenon. Initially promoted by governmental programs backed by subsidies, mostly in developed nations, VRE is now competitive in several countries in the world without any subsidies. The price of PV modules, for example, has decreased from \$1.00 per Watt to \$0.30 per Watt in only 8 years. In one-decade, solar photovoltaic capacity grew by an impressive factor of 50-fold. For wind power the growth in the last 10 years is equally impressive. According to IRENA Renewable Capacity Statistics 2018 [27] global installations increased from 115 GW in 2008 to 514 GW in 2017, a growth factor of 4.5 in 10 years.

Perhaps the largest demonstration of this trend is the fact that most of the investments of new electricity generation worldwide is already from VRE sources, having surpassed 300 billion USD for five straight years [28].



**Fig. 1 – Global investments in renewable energy. Source: Bloomberg NEF**

Solar PV installations, all alone, topped 100 GW in 2018. In one year, installations surpassed the cumulative market until 2012. It is now by far the largest source of global investments in terms of installed capacity, around double the amount of wind power, which has stabilized a little above 50 GW in the last three years. The power sector is experiencing a transition with some implications, such as:

- VRE growth tends to reduce electricity market prices, thus negatively impacting the economics of conventional sources of power such as hydropower, coal or natural gas fired power. Such impacts include lower revenues on one side and higher production costs on another, due to more frequent startup/shutdown decisions, increased maintenance and smaller lifespan.

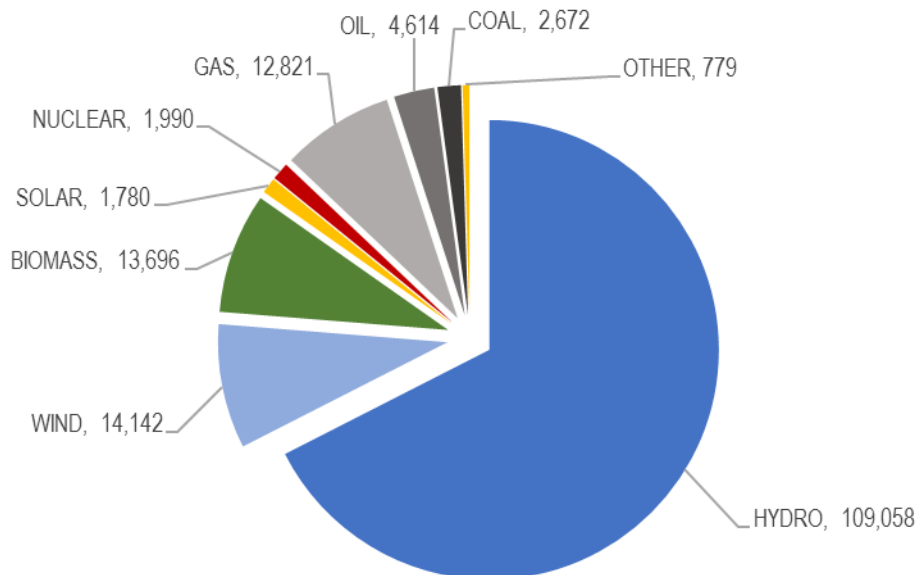
<sup>3</sup> Variable Renewable Electricity (VRE) will be used throughout this report as sources of electricity that – to a large extend – depend on “uncontrolled” primary renewable energy sources, such as wind speed or solar radiation

- Increased need for flexibility to cope with production variability in multiple scales of time to assure a reliable and continuous supply of electricity; and need for market mechanisms to value this flexibility, in addition to energy and capacity.
- Transmission networks reinforcements to integrate VRE sources; these need to be well planned as the grid is a relevant factor when deciding for the best siting of new VRE.

As the list shows, it is thus critical to adapt power system expansion and operation planning practices and to anticipate questions in search for clever solutions before they become problems.

## 2. The Brazil Case

On the back of decades of investment in large hydropower, Brazil has a unique opportunity to demonstrate an adaptation to the rapid transition to a massive expansion of VRE. Currently 67% of system capacity is based on hydropower and 18% on biomass, wind and solar power.

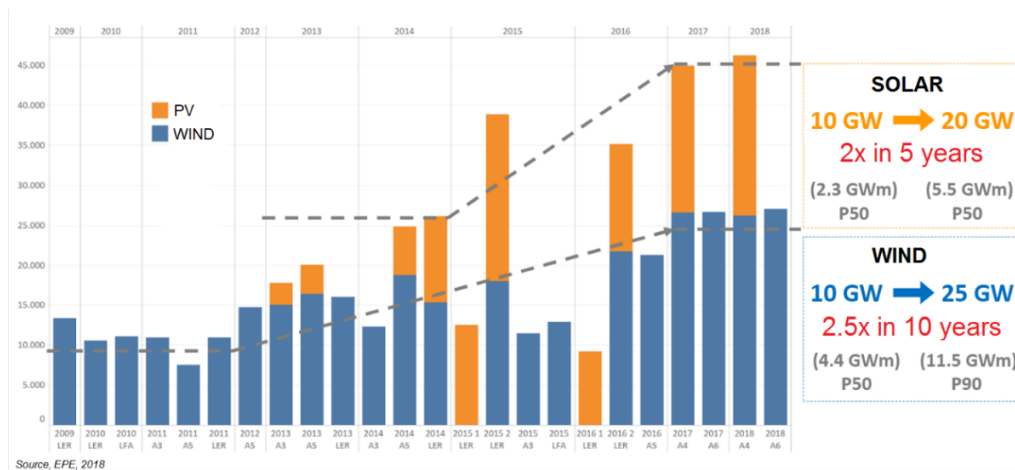


**Fig.2 – Capacity per source (MW) for the Brazilian electric matrix. Source: ONS, Jan. 2019**

This mix has provided a very good system – low carbon, renewable, and largely domestic with minimum imports – delivered to the major economic centers through a single national, interconnected grid. Dispatch is controlled by a central system operator (ONS) with the use of sophisticated models that optimize the operation of hydropower plants and their reservoirs in the various river cascades to provide a reliable and minimum cost supply.

There are significant questions, whether or how this general approach can be sustained into the future. Recent drought episodes have exposed limitations to a system so dependent on hydrological circumstances. As reservoir levels dropped, the system had to turn to thermoelectric sources with higher operating costs, to fill in the gaps. Finding new reservoir sites for large hydropower is not easy. Meanwhile costs of non-hydro renewables have continued to drop. Wind, biomass and, more recently, solar photovoltaic have emerged as major contributors to the system.

Brazil is also experiencing a large expansion of VREs. Wind has more than doubled in capacity in the last ten years, and solar has doubled in just the last five. And this is without any subsidies. While many countries adopted premium “feed-in” tariffs to incentivize VRE in which distribution companies were obliged to pay for this electricity, Brazil was an early adopter (since 2004) of electricity auctions for new capacity of all sources of electricity, including VRE, that award long term Power Purchase Agreements (PPA) to the winners. One of the reasons were that large projects with economies of scale, such as huge hydropower projects were favored by aggregating the demand requirements of several of the distribution companies of the country in a single auction. The awarded seller would sign bilateral contracts of firm energy with each of distribution company in proportion to its share of the load requirements. With few adaptations, the same basic auction mechanism in Brazil has been applied to VRE, as shown in Figure 3, which accounted for most of the wind and more recently solar power installations.



**Fig. 3 - VRE capacity procured per auction since 2009. Source: EPE, 2018**

In terms of VRE evolution in the country, it is worth observing generation data from the National Interconnected System (SIN). Hydropower is still the dominant supply source, though its relative participation in electricity production has decreased from 80% in 2010 to about 70% in the last few years. The remaining 30% of the production comes from a mix of thermal power and VRE, with the relative participation of these two sources rapidly changing. In 2015 VRE accounted for less than 4%, reaching 9% by 2018.

Historically hydropower plants were built in different river basins with diverse hydrological regimes that worked as a “weather portfolio”, with long transmission lines transporting electricity in space from “wet” areas to “dry” areas. Reservoirs, in turn, carried water (or electricity) from “wet” period to “dry” periods, sometimes years into the future, with multi-year regulation capacity. The energy benefit of reservoirs becomes apparent when we consider that in the entire Southeast region - where most reservoirs are located - the inflow energy in the wet period is three times larger than in the dry period. Variability is also strong from year to year.

In the last two decades, however, there has been a shift away from large storage projects. Power to flooded area ratio of new plants has been much higher due to environmental constraints; plants

were generally “run of river” and did not significantly modify the natural seasonal pattern of river flows. Therefore, the difference between the energy produced in the wet and dry periods is large. This is especially true for the new projects in the Madeira (Santo Antônio, 3680 MW and Jirau, 3750 MW) and Xingu (Belo Monte, 11,230 MW) rivers that amount to almost 20 GW of capacity. Inflows during the wet period are 7 times higher than in dry period for the Madeira and more than 20 times for the Xingu.

The era of large dams seems to be left behind. The main reason is that most of the untapped potential sites are in the tributaries of the Amazon river, with complex environmental licensing and strong opposition. In addition, most untapped sites do not seem to offer favorable topography for storage reservoirs. Thus, the historic dependence on hydropower, with thermal power only complementing the supply in drier periods, is being quickly modified. Particularly in the extended droughts during the last several years, the cost of energy to consumers has risen with the requirement for extended operation of thermal units.

Fortunately, energy sources such as sugar cane biomass and wind power, compensate for the relative loss of regulation capacity because their seasonal pattern tends to be complementary to hydropower. Similarly, with solar, when there is ample rainfall, there may less solar energy; in dry seasons there will tend to be more sun. A portfolio of hydropower, biomass, wind and solar power can combine to increase reliability and economic efficiency.

There are additional economic drivers. VRE sources are smaller projects, less capital intensive, require less construction time and attract a wider range of investors, including investment funds. The smaller construction time mitigates load growth uncertainty whereas a larger number of players, developing less-complex projects, reduces the risk of cost overruns and project delays. In addition, as socio-environmental impacts are much lower, particularly in solar and wind farms, licensing is faster and easier.

In the recently released draft of the *Plano Decenal de Expansão 2027* - PDE (Ten-Year Plan), the Brazilian Energy Planning Agency (EPE) has described a likely expansion path with less emphasis on hydropower, and more emphasis on biogas, wind and solar (VRE). In this indicative plan, it was expected there may be 17600 MW of VRE’s, and only 4400 MW new hydropower. Of note, there would also be over 5000 MW of combined cycle gas plants.

**Table 1 – Indicative cumulative reference expansion plan**

|                               | 2023 | 2024 | 2025 | 2026 | 2027  |
|-------------------------------|------|------|------|------|-------|
| Open cycle thermal plants     | 1509 | 3997 | 7762 | 7762 | 13142 |
| Combined cycle thermal plants |      | 3454 | 3972 | 3972 | 5124  |
| Biomass + Biogas              | 480  | 1010 | 1540 | 2070 | 2600  |
| Wind power                    | 2000 | 4000 | 6000 | 8000 | 10000 |
| Hydropower                    |      | 118  | 674  | 1034 | 1351  |
| Small hydro                   | 350  | 700  | 1150 | 1600 | 2050  |
| Solar PV                      | 1000 | 2000 | 3000 | 4000 | 5000  |

### 3. Dealing with Short Term Variability

In addition to seasonal and year to year variability, the power system must be ready to respond to short term variability (<1 hour) of the production of VRE.

Of interest in Table 1, above, is the call for OCGT (Open Cycle Gas Turbines) + Storage. This is about the need for flexible, dispatchable energy - available as necessary to meet peak demands and system stability requirements, such as when there is a demand surge or an outage. Thermoelectric open cycle (gas turbines) with rapid response rates, and “storage technologies” (batteries such as Lithium-ion) are seen to expand to 13GW by 2027. The plan also mentions PHS as one approach to providing this service. In fact, several studies investigate the possibility of PHS supporting a 100% renewable matrix [3],[4],[5] and policies towards a low carbon matrix [9].

VRE variability can be extreme on even a short time step as seen with data from actual Brazilian system operation. The next figure shows large fluctuations of wind power in the Northeast - an increase of 1385 MW in less than two hours, followed by a sharp decrease from 15:30h and lasting for about one hour. Even shorter-term variation is also apparent in the jagged, saw-tooth pattern throughout the day, as much as ten or more reversals in a 30-minute increment.

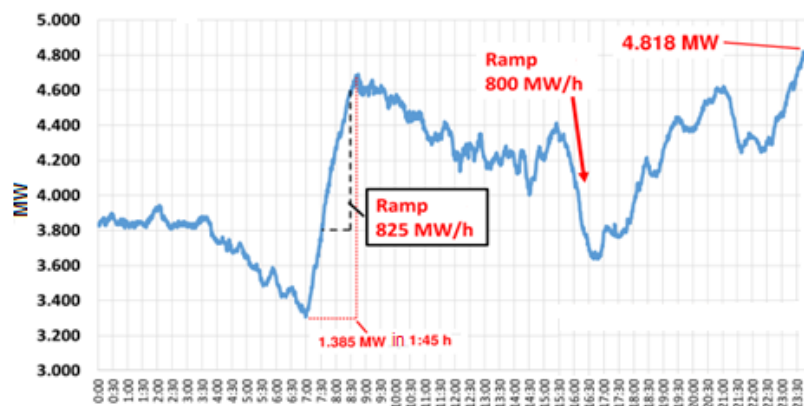


Fig. 4 – Wind power variability in the Northeast (June 26<sup>th</sup>, 2016). Source: ONS

Taking as given that there will be a large expansion of VRE, and that it can be achieved with available resources without subsidies, the question then shifts to a critical detail about how? What exactly is expected of the system of electrical services, and how are those expectations addressed?

We start by identifying performance attributes needed in electrical power systems.

- **Stability** – operating variations do not produce disruptive response in the larger system, in terms of voltage, frequency, or risk of rolling brownouts;
- **Reliability** – ability to consistently meet production targets; firmness of energy produced;
- **Flexibility** – ability to rapidly respond to changes in load/supply elsewhere in the system;
- **Robustness** – ability to provide energy under a range of external conditions (drought, flood, cloudiness) as well as to provide extra energy to other parts of the system;
- **Resiliency** – ability to respond to unexpected changes in external conditions.

And, of course, we expect this performance at a reasonable cost with minimum social-environmental impacts.

Simply providing gross gigawatt hours is not enough if these attributes are not present. With a small initial degree of VRE penetration into the power system, large grids tend to provide enough flexibility that the variations are simply absorbed. The large share of hydropower in the Brazilian electricity matrix, for example, can still largely support the current penetration of VRE. As the amount of VRE increases, the Brazilian power system will eventually need more flexible generation and operation reserves. Some possibilities for providing these services, that may be used concurrently, include:

- a) Installing new capacity in existing hydro plants, by initially exploring available space in the powerhouses where possible. A recent MSc dissertation [29] suggests that up to 5 GW of capacity could be added in 12 plants (see table). An example is São Simão HPP, that could add 4 units or 1 GW of new capacity with a slight forebay elevation. The thesis mentions the increase of capacity of old units (when retrofitting) is also possible, which could add up to 6 GW of new capacity if all units with more than 30 years of operation were retrofitted.

**Table 2 – Possible capacity additions in powerhouses in Brazil**

|    | Usina                    | Concessão   | Tipo de máquina | Rio           | Estado | nº poços  | Pot. disponível poços [MW] |
|----|--------------------------|-------------|-----------------|---------------|--------|-----------|----------------------------|
| 1  | Curuá-Una                | Eletrobrás  | Kaplan          | Curuá-Una     | PA     | 1         | 10                         |
| 2  | Foz do Areia             | COPEL       | Francis         | Iguaçu        | PR     | 2         | 838                        |
| 3  | Luiz Gonzaga (Itaparica) | CHESF       | Francis         | São Francisco | PE     | 4         | 1000                       |
| 4  | Jaguara                  | CEMIG       | Francis         | Grande        | SP-MG  | 2         | 213                        |
| 5  | Mimoso                   | EDP         | Kaplan          | Pardo         | MS     | 1         | 8                          |
| 6  | Porto Primavera          | CESP        | Francis         | Paraná        | SP     | 4         | 440                        |
| 7  | Rosana                   | Duke Energy | Kaplan          | Paranapanema  | SP-PR  | 1         | 89                         |
| 8  | Salto Santiago           | Tractebel   | Francis         | Iguaçu        | PR     | 2         | 710                        |
| 9  | São Simão                | CEMIG       | Francis         | Paranaíba     | MG-GO  | 4         | 1075                       |
| 10 | Taquaruçu                | Duke Energy | Kaplan          | Paranapanema  | SP-PR  | 1         | 105                        |
| 11 | Três Irmãos              | CESP        | Francis         | Tietê         | SP     | 3         | 485                        |
| 12 | Três Marias              | CEMIG       | Kaplan          | São Francisco | MG     | 2         | 123                        |
|    | <b>Total</b>             |             |                 |               |        | <b>27</b> | <b>5096</b>                |

- b) Installing new hydropower plants in the system, which has shown to be increasingly difficult as most of potential lies in tributaries of the Amazon or near indigenous lands, with projects that are socially and environmentally complex.
- c) Installing open cycle thermal plants, that are less capital intensive but expensive to operate due to smaller efficiencies and high natural gas price in Brazil. They also emit greenhouse gases. The PDE 2027 (Ten-Year-Plan) included this technology to assure capability of meeting peak demands and other variations.
- d) Installing Batteries in selected parts of the network, though this option would require further costs reduction to make economic sense at larger scales.
- e) Installing pump hydro storage (PHS) plants making use of existing facilities or in new locations, either running as open or closed loop systems.

The challenge forward is to find new approaches to the use of the existing hydropower base, together with new innovations, to open the way for a massive further expansion of VRE. But these projects often carry their own constraints in terms of large capital costs and socio environmental



concerns. Alternative approaches to providing the necessary and desirable “attributes” of performance is of growing concern.

IHA in a recent report asserts that “energy storage will be a key component in accelerating global efforts to meet the ambitious climate mitigation and sustainable development goals” [22]. IEA likewise says, “Flexibility is the new watchword for power systems.” [23]. PDE 2027 also emphasizes the need for flexible sources, whether gas turbine (open cycle), technical storage such as Li-ion batteries at large scale, or PHS.

#### **4. Pump Hydro Storage Projects**

As seen, there are numerous approaches to addressing variability and of providing the necessary attributes of performance. The choices among these will vary from one country situation to another, including many soft, smart system management options [24], and they will vary within a country in terms of time scales: inter-annual, seasonal, daily and micro variations. An appropriate mix of pumped storage options in support of the entire interconnected grid should be carefully examined and appropriately designed [2],[6],[7].

It seems that Brazil is a natural setting for a large development of PHS. Eletrobras, the Brazilian state-owned utility, examined possible PHS projects in several regions of the country in the end of the 1980s. Perhaps this may particularly fit with the option of adding new capacity to existing plants, and with planning for system level synergies – designing the portfolio of sources in the interconnected grid to provide the system attributes. Also, at the site level, existing hydropower reservoirs offer a couple of opportunities to take advantage of the existing environmental footprint, and unused transmission and substation capacity.

There is often vertical topography adjoining existing hydropower reservoirs. This, may provide an opportunity for PHS, taking advantage of the existing reservoir for one of the water bodies, and potentially taking advantage of existing electrical works - switchyards, substations and transmission lines. Particularly with run-of-river or low storage hydro projects, there tends to be a low capacity factor due to hydrological seasonality, potentially leaving transmission capacity not fully used. In many situations there are synergies across the grid that can be built upon to achieve VRE integration. First is the synergy between the rainy season and the dry season. When it rains there is ample water flow for hydro; when it does not, there is ample sun, biomass is harvested and – in the case of Brazil’s Northeast – wind speed increases. In some locations in Brazil with favorable conditions for both wind and solar power, wind speed increases at nighttime, suggesting that transmission reinforcements to integrate the portfolio could be optimized.

What remains, however, in order to take advantage of these synergies, particularly as VRE reaches very high penetration levels, are flexible, dispatchable energy sources to stitch together the components, to fill the gaps. Distributed PHS could do this by absorbing surplus power that would otherwise be lost and store it for later use. This would have the further clean energy result of reducing the dependence on hydrocarbons for gas turbines.

An interesting example is that of the Frades II project in Portugal, which uses a head of 420 meters between the upper and lower reservoirs, to drive two variable-speed pump turbines, each with 390



MW. It helps the Portuguese power system cope with a large share of wind power and to supply peak demand.

Some thirty years ago, a project from state owned utility Eletrobras, using a screening for the site selection of PHS projects in Brazil based on available cartographic information (1:100,000 or 1:50,000 scale) and basic filters as shown below:

- 1- Gross head of at least 250m and at most 800m
- 2- Maximum distance from load center of 300km
- 3- In case of tunnels the length should be at most 10 times the head

The process initial identification of 366 projects in 14 states totaling 1000 GW of capacity. Naturally, it is expected that such potential will be largely reduced when economic considerations and others (e.g. local geology, environmental or social constraints) are taken into consideration.

More recently (2019) the Brazilian Energy Planning Agency (EPE) a survey of possible PHS sites in the state of Rio de Janeiro, finding some 15 sites meeting their criteria. Unfortunately, they elected to exclude existing hydropower reservoirs from consideration, based on a concern over permission from existing owners [26].

The screening of prospective sites has been approached by several. A recent article of researchers from the Australian National University [1] utilizes specialized geoprocessing algorithms to “filter” the landscape in a systematic way to find and prepare candidate locations for reservoir sets. More generally, the use of GIS to filter hotspots for PHS projects has been largely utilized based on the availability of digital terrain models (with topographic data) and modern GIS software [1],[10],[11],[12],[13],[16],[17],[19].

As the numbers suggest from the Eletrobras PHS inventory study prepared in the end of the 1980s, finding prospective sites is a necessary but insufficient condition. It is necessary to examine if the candidate projects make economic sense, which demand two more actions. If the process is to be automated a model needs to estimate project costs based on a good approximation of the engineering solution applicable to that specific location. Then, it is necessary to evaluate the economic benefit of the project. This last step can be made in simplistic way by tagging economic values to the services provided by the project, such as peak/of peak price differentiation, value of capacity or reserves. Ideally, however, the economic benefit of the projects should be examined with an integrated resource planning model that evaluates each PHS candidate project by explicitly modeling its operation in the existing (or planned) power grid. Because this approach is based on the actual simulation of the operation of the power system, it has the advantage of allowing planners decide which projects make more sense in terms of location (i.e. grid connection), capacity (MW) and energy storage (MWh) depending on the local grid requirements.

Regarding cost estimation, engineering guidelines, such as the recent development of the open license tool HERA, developed by PSR and EDF as part as an R&D project in Brazil<sup>4</sup> are ideal. HERA starts from a digital terrain model, inflow measurements and geological data, which are used to simulate the construction of hydro projects, automatically determining reservoirs and quantifying socio-environmental impacts based on other layers of information and corresponding

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<sup>4</sup> <https://www.psr-inc.com/software/?current=p7065>

costs. Next, HERA's engineering module designs hydraulic structures, combines them and tests combinations of engineering layouts for each site from a list of nearly - sometimes more than 200 in a single location. Thousands of projects can be prepared by this process in the river basin in a reasonable time with the aid of cloud-based distributed processing. The best alternatives are selected by the solution of a large-scale optimization model that includes economic parameters and several socio-environmental attributes, for example constraints for conservation of aquatic ecosystems, including environmental flows, flooded areas, river connectivity (length not fragmented by dams) and others.

HERA has been successfully used by The Nature Conservancy (TNC) in three pilot projects: (i) Gabon, primarily to evaluate the impacts of environmental flows to the *Ngoulmendjim* project; (ii) Coatzacoalcas basin, Mexico, to address mostly social impacts; and (iii) Magdalena basin, Colombia, to demonstrate the benefits of basin planning and to how financial risks of large-scale projects - that tend to have cost overruns and delays - should be part of the planning process [25]. Finally, HERA it is being proposed in Brazil as decision tool to support hydro-inventory studies, by providing a more objective and transparent process to the stakeholders, including developers, governmental institutions and water & environmental agencies.

The envisaged process is the following:

- (1) Investigate promising sites with the aid of specialized geoprocessing algorithms that operate on digital terrain models, an approach used by many, thus not entirely novel *per se* [1],[10],[11],[12],[13],[16],[17],[19];
- (2) Extend HERA's engineering module to design PHS projects in the selected sites and estimate corresponding the project cost from its components, which includes civil works related to the construction of the dam, powerhouse and others; costs related to possible impacts of the construction of the upper / lower reservoirs to the surrounding areas; costs related to equipment acquisition such as penstocks, turbine-pump-generator sets, gates, and others;
- (3) Perform an expansion planning of the power sector with an Integrated Resource Planning model that minimizes investment and operation costs, including reserves. Demand growth forecasts are given and representative candidate projects of different technologies, such as solar PV, wind parks, biomass cogeneration prepared. In the case of PHS, candidates are based on steps (1) and (2) above. In a site-specific level, hybrid PHS + solar PV projects could be optimized and then integrated as a "system of systems" to improve grid stability, reliability, robustness and resiliency with the nationwide IRP model [21]. The Snowy 2.0 project of Australia, for instance, is expected to expand the original Hydroelectric Scheme with an additional 2000MW and 350GWh of energy storage to increase security and reliability of the system [20].

## 5. Hybrid Solar-PHS Projects

It is also suggested for the Brazil situation that hybrid<sup>5</sup> projects may a good fit. The idea around hybrid projects is that by integrating several sources at the *project* level, the attributes of

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<sup>5</sup> The term hybrid project has sometimes been used to refer to a project serving isolated systems – stand-alone projects. It could just as well refer to an entire grid which is operating to integrate numerous complementary sources, connected by a transmission network. Here we are referring to the concept of projects at one location or one

performance can be achieved at the *project* level, making it much easier for the national grid system operator to manage for those attributes at the level of the entire grid. If hybrid projects were deployed in Brazil, they could help provide stability, reliability, flexibility to the system. Such hybrid system could perhaps be deployed most easily as part of existing hydro facilities, that could also add new capacity when possible.

Of course, solar systems are inherently variable, generating only during the sunlight hours and more when it is not cloudy, generally requiring some storage function when deployed at large scale. By combining PV with pumped storage, the necessary flexibility can be provided [2],[5],[7]. This concept is being conceived in Australia in a project whose lower and upper reservoirs are discontinued gold mine pits with a water head of 300 meters. A 250MW capacity facility could be installed with a storage capacity worth six hours of continuous operation at rated capacity. The concept is thus to make the variable solar power “dispatchable”.



**Fig. 6 – Pits of abandoned mine for PHS in Queensland, Australia. Photo: Genex**

Another issue with VRE sources can be addressed, as part of hybrid projects. The space requirement for PV or wind plants is significant, and terrestrial environment footprint must be considered [30]. It is best if VRE facilities are located on already disturbed land. The water surface of existing reservoirs offers a potentially useful surface for *flotovoltaic* solar systems. *Flotovoltaic* systems potentially offer a couple of additional benefits. Floating on the reservoir surface, they will maintain cooler operating temperature, leading to higher efficiencies than land-based systems, as much as 10% more efficient. In addition, one operation and maintenance requirement for PV systems is to keep panels clean, something that is easier to do when water is readily at hand. This concept of *flotovoltaic*, of course, needs to be demonstrated by the market practice, with developers adopting it for economic reasons. So far in Brazil it has been only been deployed in R&D or small-scale demonstration projects. Perhaps because it requires reservoir surfaces that typically are owned by hydropower companies, it has not yet been the subject of development by private entrepreneurs.

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part of a river basin that are designed and operated in an integrated way to produce the desired attributes, and which then feed into the larger grid.

There are some practical constraints that can be foreseen on potential *flotovoltaic* installations. For reservoirs being used for recreational purposes - motor boats, water skiing, jets skis and fishing - there will be a tradeoff with solar panels. In addition, systems will have to be designed against wave action and the impact of storms. Protected bays may offer better sites than large open water bodies, again raising the potential tradeoff with areas valued for recreational fishing.

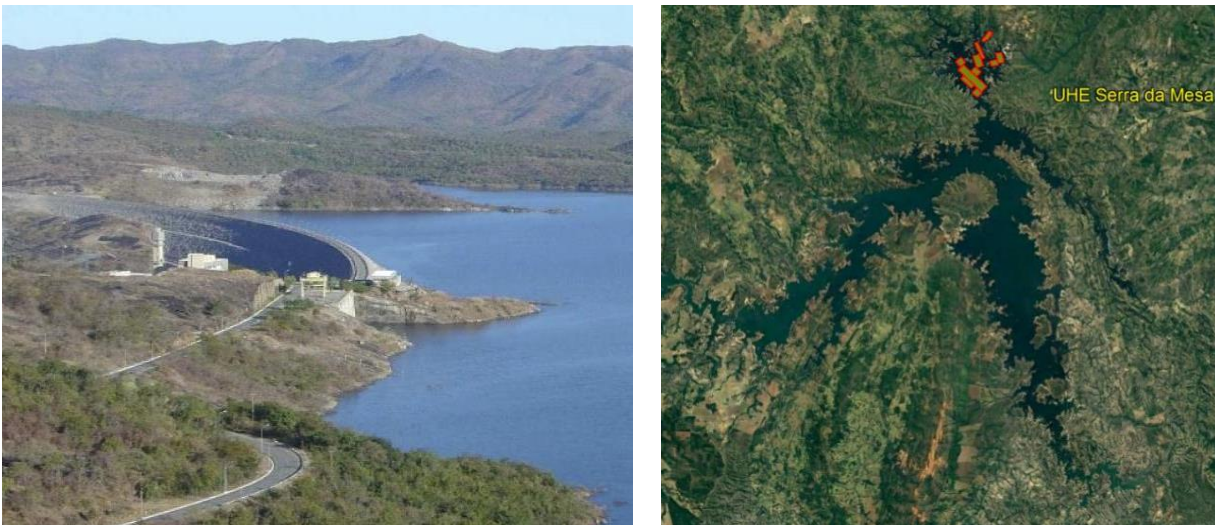
For purposes of illustrating the hybrid systems concept suggested for further research, *flotovoltaic* systems were selected. In each of these cases, however, land-based solar systems are also generally feasible on near-by, already disturbed land. One of the subjects of further study would be to examine options between land and water-based PV systems.

Thus, the idea of hydropower, solar, PHS hybrids can in theory at least, provide a possible additional tool to achieve system performance attributes [8]. Here we lay out two hypothetical hybrid projects, both based on existing hydropower facilities [14],[15],[17],[18]. The pumped storage component of each is designed to provide either a few hours or several days of solar backup storage.

These examples are suggested to stimulate further research and development. Their actual feasibility is not yet studied, particularly as to alternatives and costs. In addition, the willingness of current project owners and operators to be involved in such an analysis is not yet known.

### ***Serra da Mesa Dam and Reservoir***

Serra da Mesa is a very large reservoir and hydropower plant in the upper part of the Tocantins river basin that regulates flows for six run-of-the-river hydro plants in the entire cascade, including the mega 8370 MW Tucuruí HPP. It has a storage capacity of 54.4 bcm and a surface area of 1,784 km<sup>2</sup> and has been in operation for 20 years. The idea proposed, for further research, would be to construct solar PV and PHS at the project site, to take advantage of the facilities already there, and to extend the performance of the Serra da Mesa complex.

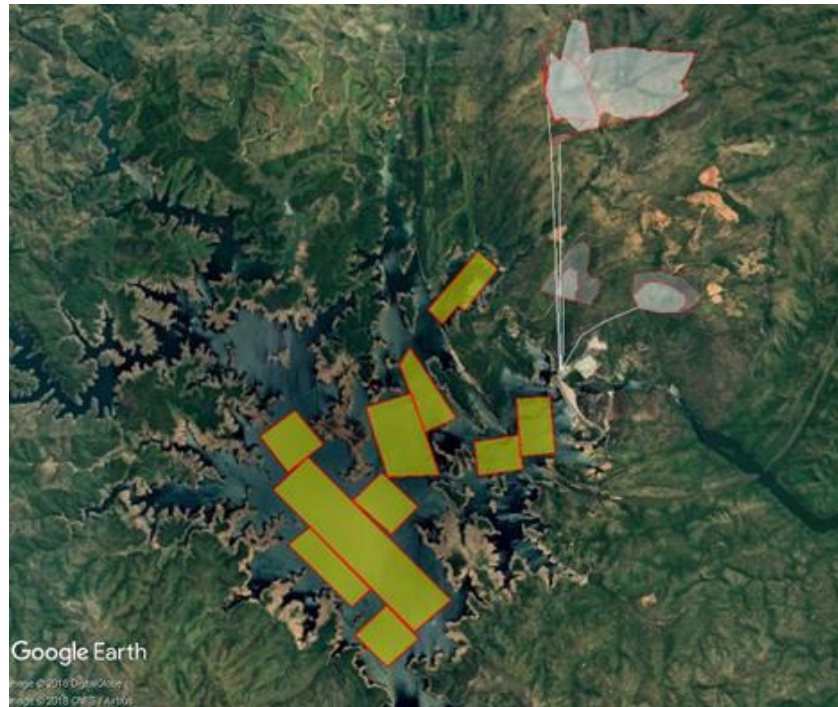


**Fig. 7 - Serra da Mesa Dam and Reservoir**



Two examples are shown. For illustrative purposes we have selected *flotovoltaic* solar parks.

The very large surface area of the reservoir could potentially support a huge *flotovoltaic* park, but there are undoubtedly practical constraints. Interestingly, the part of the reservoir near the dam is somewhat isolated from the large body of the rest of the reservoir; the example presented, limits *flotovoltaic* development to that portion. An ultimate area of 1500 ha is shown within this relatively protected area. Assuming an energy density of 1.5 ha per MW, this could provide 1000 MW of capacity.



**Fig. 8 – PHS in Serra da Mesa**

Also shown are several different possible pumped storage configurations. The largest of these would involve an upper reservoir of 500 ha surface area, about 100 mcm volume, an embankment of 100 meters in height. The 2-directional penstock would be 5.8 km in length. With an average head of approximately 450 m, it could provide energy storage of 110 GWh<sup>6</sup>. This could effectively provide solar back-up for 1000 MW, 6 hours each day for 18 days, thus firming the energy output for 1000 MW at Serra da Mesa over more than two weeks.

The smaller, near-term development selected for illustration would have 600 ha of solar, also fit within the near-dam area. This is assumed to provide a capacity of 400 MW. The pumped storage component would consist of an upper reservoir of 9.5 mcm, penstock of 2.5 km, and an average head of 240 m. At 400 MW, this could provide energy storage of 5.6 GWh; or solar backup of 6-7 hours each day, for 2 days.

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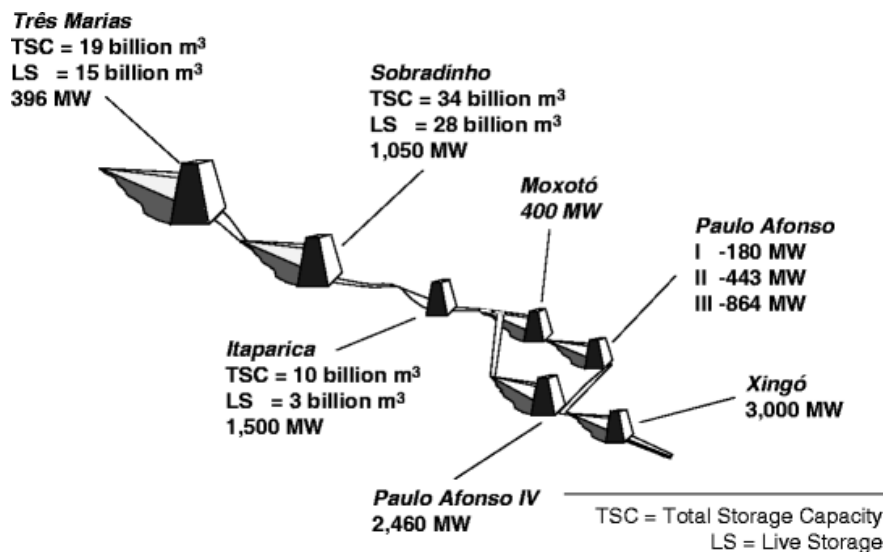
<sup>6</sup> Calculation based on Capacity = gravity coeff.  $\times$  turbine-generator efficiency  $\times$  net head  $\times$  turbined flow. Thus for 1000 MW = flow is given by  $10^6 \text{ kW} / (9.8 \times 0.9 \times 450\text{m}) = 252\text{m}^3/\text{s}$ . Thus, 100 mcm of storage capacity would be used in  $(100 \times 10^6 \text{ m}^3) / 252 \text{ m}^3/\text{s} / (3600 \text{ s/hour}) = 110 \text{ hours}$  and the stored energy is  $110\text{h} \times 1\text{GW} = 110 \text{ GWh}$ .



**Fig. 9 - Serra da Mesa Dam and Reservoir**

### ***Sobradinho Dam and Reservoir***

The Sobradinho project is a large reservoir in the state of Bahia. It was completed in 1982; has a total reservoir capacity of 34 bcm (useful storage 28 bcm), a surface area of 4200 km<sup>2</sup>, and installed generating capacity of 1050 MW. Along with Tres Marias reservoir, it provides storage to regulate flow in the cascade of hydropower units on the São Francisco River system.



**Fig. 10 – Sobradinho Dam in the São Francisco river cascade**

Recent hydrological conditions, with half as much inflow as average over the last five years, has left its reservoir water level very much reduced. Even with this depleted storage there is a call for an increase in the minimum release for downstream flow. Operations to help meet variable loads in the region cause even greater drawdowns, leaving a further reduced power pool. This region in inland Bahia has a large amount of VRE already developed, particularly wind, with large potential for increase.

The idea proposed for further research, as with the Serra da Mesa case above, would be to construct solar PV and PHS at the project site, to take advantage of the facilities already there, and to extend the performance of the Sobradinho complex. This could provide an increase in total energy production and provide flexible energy to help the variable load in the region. It would also allow for conservation of stored water now being used and allow for the maintenance of a higher average power pool.

The Sobradinho Reservoir offers a huge potential for *flotovoltaic* systems, although as discussed above, there are also numerous possible sites for land-based PV parks on nearby disturbed land. There is currently a pilot demonstration *flotovoltaic* installation on the reservoir.



**Fig. 11 - a *flotovoltaic* panel demonstration project**

Numerous pumped storage options exist along the margins of the reservoir, including both short- and long-term storage.



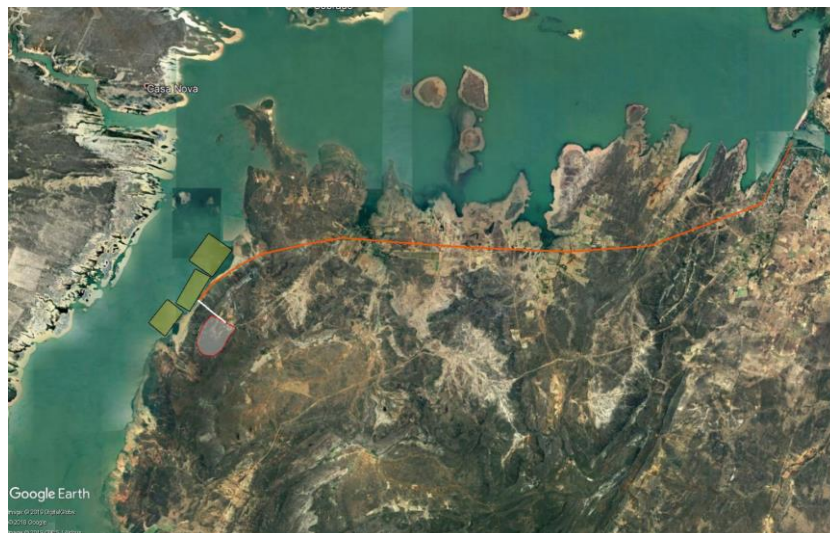


**Fig. 12 - Sobradinho hybrid pump storage solar options**

### ***Saco da Arara site, 580 mmsl***

One interesting site is along the eastern shore of the reservoir southwest of the existing dam. An upper reservoir of 16 mcm storage could be constructed, by excavation and embankment. Situated at 580 mmsl, it would provide an average head of 180 m. If this were apportioned over 2.5 days, 6 hrs/day, it would deliver a flow rate of about 300 m<sup>3</sup>/s; thus, producing a capacity of 460 MW. This would require a penstock and tunnel connecting the upper reservoir to Sobradinho reservoir of about 2km in length.

A flotovoltaiac installation is postulated, along the near shore of the reservoir to provide some protection from wave action over the long fetch lengths of the reservoir. 700 ha are shown, presumably providing 466 MW of variable capacity. The site would be connected to the existing Sobradinho hydropower complex by a transmission line of approximately 36 km.



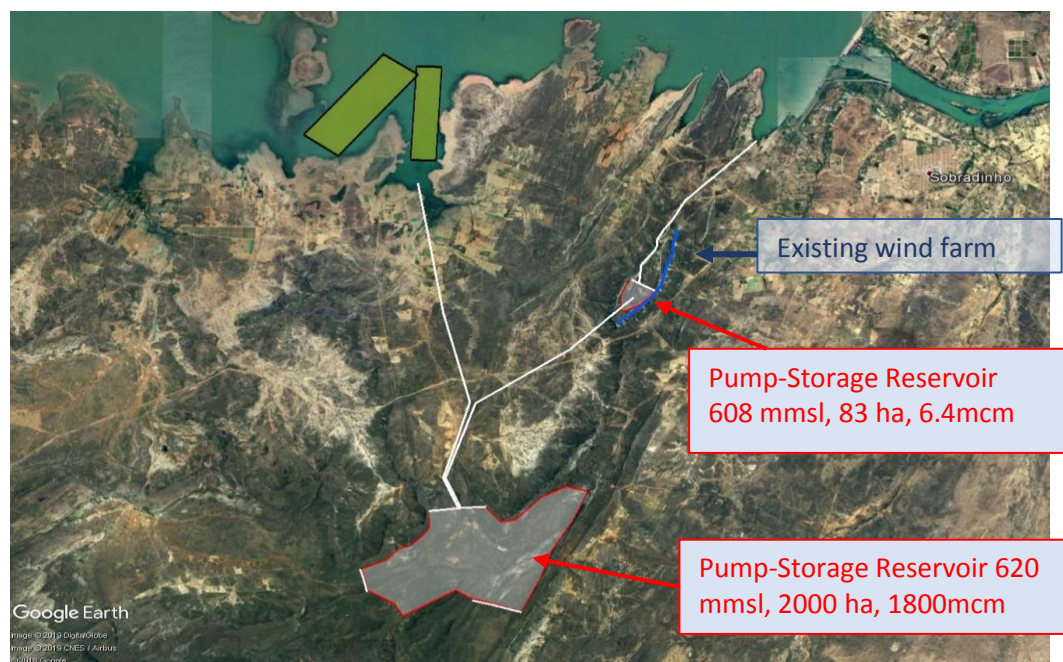
**Fig. 13 - Sobradinho hybrid – short term storage, near Saco da Arara**

### ***Sobradinho reservoir potential hybrid project - long term Storage 620 mmsl***

Another hybrid complex offers some additional characteristics that could complement Sobradinho operations. First, there is a short-term storage option with a constructed reservoir of 6.4 mcm volume, located at 608 mmsl. With an average head of 200 m it could provide 530 MW for 6 hrs, presumably designed to provide daily back up for variable solar. Second, it is a much larger storage unit, located further to the south, at 620 mmsl. This site, constructed with excavation and embankments, would provide as much as 1800 mcm. If this were allocated for 12 hours/day, it could provide long term backup, for example for as much as for 40 days, and could be sized for as much as 1440 MW. In addition, the two reservoirs could be interconnected, using the large one, 620 mmsl, to refill the smaller one, 608 mmsl, daily. This could provide firming for the 530 MW unit for as much as 280 days. Clearly there are several operating scenarios to be examined.

The major drawback to this site is the long distance to the Sobradinho reservoir; penstock costs may put these out of reach. But the value of long-term flexible energy to assist Sobradinho operations, as well as the large amount of potential VRE energy in this region, may warrant a detailed examination of these options. The distance from the upper reservoir 620 mmsl to the smaller reservoir 682 mmsl is 11km. The distance from the smaller, 608 mmsl, to Sobradinho Reservoir is 7 km.

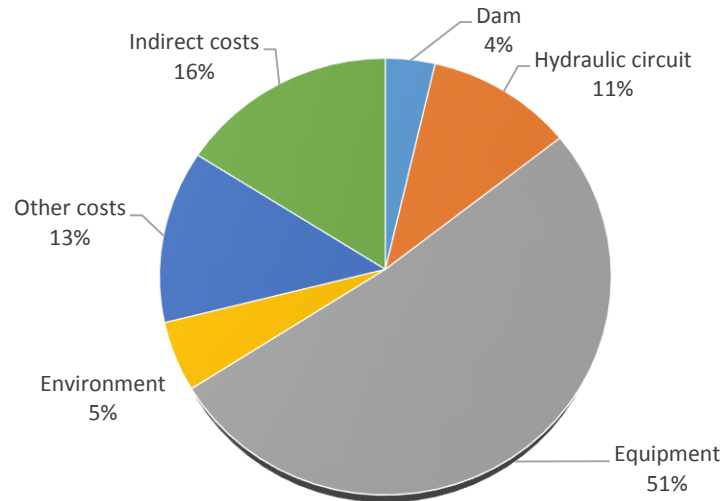
The case shown has 900 ha of flotovoltaiic units, presumably providing 600 MW of capacity, although the ultimate amount of theoretical flotovoltaiic capacity on Sobradinho Reservoir is practically unlimited. Interestingly the satellite image for this case shows an existing wind farm adjacent to possible pump storage reservoir 608 mmsl.



**Fig. 14 - Sobradinho hybrid – long term storage**

## 6. Preliminary Results

We worked on a rough estimate of the CAPEX for the Saco da Arara site and reached \$815/kW with the following breakdown of costs.



**Fig. 15 – PHS Cost breakdown**

We then investigated if PHS projects with 6 hours of capacity-worth of storage and 70% “round-trip” efficiency (generation/pumping cycle) would be selected by PSR’s Integrated Resource Planning model OptGen. We parametrized the process by selecting candidates with these characteristics and CAPEX varying from \$500 to \$1500 per kW for the various regions where VRE is expected to grow in Brazil (wind: South and Northeast; solar PV: Southeast, Center-West and Northeast).

A configuration of the Brazilian power system was used based on a project sponsored by GIZ through the Brazilian-German technical cooperation and developed by PSR, Lahmeyer International and Tractebel. This configuration is based on a strong penetration of VRE in the country for a system whose demand will be twice the amount observed in 2017. The expansion is based on optimization of investment and operation costs, including reserves. Candidates projects considered by Optgen are VRE, transmission reinforcements and fossil fuel projects (e.g. using coal, natural gas) and storage.

We started running a case with PHS candidate projects with CAPEX of \$1500/kW. No projects were selected. We lowered the CAPEX to \$1000/kW and, again, no projects were selected. Interestingly, PHS CAPEX breaks-even around \$800/kW, which is the cost level of the Saco de Arara PHS in our exercise. At this cost level there is some selection of PHS in the Northeast. When we ran a case with OptGen considering a CAPEX of \$600/kW there were strong investments of PHS and the natural gas fired projects were all discarded by this optimization model in the final configuration.

Naturally, these results depend on several other assumptions, such as the cost of other resources, cost of fuels, technological advances per source, evolution of distributed generation. These results indicate that there is merit in exploring this alternative of a power sector expansion based on VRE and PHS. It also shows that there is a lot of work that will need to be made for selecting good sites for PHS and preparing engineering solutions that can be used for cost estimate before being conclusive about the possibilities.

## **7. Conclusions**

Brazil is moving into a period of rapid and extensive expansion of Variable Renewable Energy sources of electrical generation, motivated largely by the ever-decreasing cost of these sources, but also by a general move to reduce carbon emissions.

It has been demonstrated that these VRE sources can be readily integrated into the existing grid system. For the next several years these variable sources can be absorbed just by system operation, largely on the back of the extensive and widespread hydropower capacity Brazil has developed. In a few years, however, there will start to be issues calling for the addition of energy storage into the integrated grid system.

There is already the problem of seasonal and multi-year water shortages. The dependence on reservoirs has already left the system vulnerable, and increasingly dependent on fossil fuel thermal-electric generation – at higher cost to the consumer and higher carbon emissions. The expansion of VRE's appears to be the logical way to add capacity that can complement hydropower and provide energy during droughts. However, this will further stress the existing system's ability to absorb variability.

As the default, it would be expected that the integration of VRE's into the system would involve significant expansion of thermal-electric capacity, primarily natural gas turbines, closed and open cycle systems. These function well to balance the system, but are vulnerable to future fuel costs, and involve continued carbon emissions.

Pumped Storage Hydropower offers a proven and reliable technology to complement other storage options and to provide capacity to integrate VRE's. Historically PHS was developed in much of the world to provide power during peak demand while complementing base-load, inflexible thermal generation (coal, nuclear, etc.) mostly from 1960-1980 period. There is now an increasing interest for the purpose of mitigating the short-term variability of renewables, providing flexible sources, as well as supporting the overall performance of the power system, such as stability and resilience. The inclusion of PHS in the power system in Brazil is a very promising possibility, one that calls for research and development at the scale of the interconnected grid. Using available tools such as the HERA model, it is suggested that a grid-wide survey be undertaken, defining and evaluating candidate PHS project opportunities.

It is suggested that such a survey start with a review of existing hydropower reservoirs because of likely synergies with existing projects. Using an existing reservoir as one of the two storage units will minimize the direct footprint, as would piggy-backing on existing electrical works and

transmission corridors. In addition, most projects have some amount of unused transmission and switching capacity that may be able to be taken advantage of.

In addition to grid wide applications of PHS, it is possible to increase the performance of the system by developing hybrid projects, adding pumped storage and solar components to existing hydropower projects. These systems would be designed to feed firm energy into the grid. Each of them would be optimized at project level to provide stable, reliable, robust and resilient supplies.

Performance of projects supplying the grid are evaluated by key attributes, for example, stability, reliability, flexibility, robustness, and resiliency. It is possible that a power system designed for those attributes would be enhanced by the addition of projects that were themselves designed and optimized for those attributes. A “system of systems” may provide increased stability, reliability, robustness, flexibility and resiliency. This calls for research and development to investigate if in fact this approach can improve performance of the interconnected grid in Brazil, and at what cost. This paper illustrated the possibility of hybrid projects with two existing Brazilian hydropower facilities, based on a high-level conceptual examination of the local topography and preliminary calculations. Both examples involve the use of reservoirs of existing dams as lower reservoirs.

It is suggested that these examples and others indicate a value for a system-wide survey of potential applications. A possible approach would be to systematically “screen” many more potential sites including the use of existing dams and possibly closed PHS systems, with the aid of specialized geoprocessing algorithms that operate on a digital terrain model. An engineering module would then be devised to design PHS projects in selected sites and estimate corresponding cost; then a study would be conducted as to which of the prepared PHS candidate projects would be “selected” in the system expansion with the use of an Integrated Resource Planning exercise for the Brazilian grid. Based on an understanding of how PHS would fit into the overall system, it would be possible to assess the potential value of a “system of systems” based on hybrid projects.

There remains an interesting area of inquiry, largely beyond the scope of this paper, regarding the regulatory and market structure in Brazil, as to how the services of PHS are to be valued and paid for. Payments for energy and capacity may not be enough for PHS to be competitive, because they do not recognize other services provided by the PHS. If an integrated cost optimization model, when executed, “selects” some of the candidate hybrid projects against possible alternatives (such as natural gas fired plants or batteries), what are potential regulatory and market conditions necessary to be resolved?

In the case of Brazil, the economic value of assets is largely linked to their ability to provide firm energy. Not even capacity payments are in place currently, much less payments for ancillary services for frequency control or secondary control. In the long run, such services (flexibility, reserves, capacity, peak shaving, etc.) would need to be properly remunerated for the advancement of PHS and hybrid projects. It is possible that a first step in this direction would be movement toward an auction based on performance attributes. Bids would be solicited for X megawatts of firm energy, with specified stability and reliability requirements. Thus, the values of ancillary services and firmness that a hybrid might bring would be internalized into the integrated bid.



There is a long way to go in terms of regulatory change, but we should not jump ahead of time; first things first. To begin, a screening of hybrid projects (PHS + VRE) needs to be done with project preparation and budgeting. Then, the “system of systems” concept needs to be evaluated in terms of economic benefits versus costs.

The Brazil example presents a very interesting case. The potential for expanding and integrating VRE's is at hand. The tools are available for research and development work to be done in the area to support decision makers – politicians, developers and society as a whole - to make rational decisions moving in the direction of a zero-carbon power sector.

## References

- [1] B. Lu, M. Stocks, A. Blakers, K. Anderson. Geographic information system algorithms to locate prospective sites for pumped hydro energy storage. *Applied Energy*, 222 (2018) pp 300-312.
- [2] Wänn A, Leahy P, Reidy M, Doyle S, Dalton H, Barry P. Facilitating energy storage to allow high penetration of intermittent renewable energy: Environmental performance of existing energy storage installations. *Deliv. D.3.1*; 2012.
- [3] Ram M, Bogdanov D, Aghahosseini A, Oyewo AS, Gulagi A, Child M, et al. Global energy system based on 100% renewable energy – power sector. Lappeenranta University of Technology and Energy Watch Group; 2017.
- [4] D. Connolly, H. Lund, B.V. Mathiesen. Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renew Sust Energ Rev*, 60 (2016), pp. 1634-1653.
- [5] A. Blakers, B. Lu, M. Stocks. 100% renewable electricity in Australia. *Energy*, 133 (2017), pp. 471-482.
- [6] M.E. Khodayar, M. Shahidehpour, L. Wu. Enhancing the dispatchability of variable wind generation by coordination with pumped-storage hydro units in stochastic power systems. *IEEE Trans Power Syst*, 28 (2013), pp. 2808-2818.
- [7] G. Caralis, D. Papantonis, A. Zervos. The role of pumped storage systems towards the large-scale wind integration in the Greek power supply system. *Renew Sust Energ Rev*, 16 (2012), pp. 2558-2565.
- [8] G. Vojvodic, A.I. Jarrah, D.P. Morton. Forward thresholds for operation of pumped-storage stations in the real-time energy market.
- [9] S. Zhang, P. Andrews-Speed, P. Perera. The evolving policy regime for pumped storage hydroelectricity in China: a key support for low-carbon energy.
- [10] D.G. Larentis, W. Collischonn, F. Olivera, Tucci, C.E.M. GIS-based procedures for hydropower potential spotting. *Energy*, 35 (2010), pp. 4237-4243
- [11] B.C. Kusre, D.C. Baruah, P.K. Bordoloi, S.C. Patra. Assessment of hydropower potential using GIS and hydrological modeling technique in Kopili River basin in Assam (India). *Appl Energy*, 87 (2010), pp. 298-309
- [12] C.S. Yi, J.H. Lee, M.P. Shim. Site location analysis for small hydropower using geo-spatial information system. *Renew Energ*, 35 (2010), pp. 852-861

- [13] C. Petheram, J. Gallant, A. Read. An automated and rapid method for identifying dam wall locations and estimating reservoir yield over large areas. *Environ Modell Softw*, 92 (2017), pp. 189-201
- [14] D.G. Hall, R.D. Lee. Assessment of opportunities for new United States pumped storage hydroelectric plants using existing water features as auxiliary reservoirs. Idaho National Laboratory (2014), p. 95
- [15] M. Gimeno-Gutierrez, R. Lacal-Arantequi; Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs. *Renew Energ*, 75 (2015), pp. 856-868
- [16] J.A.J. Capilla, J.A. Carrion, E. Alameda-Hernandez. Optimal site selection for upper reservoirs in pump-back systems, using geographical information systems and multicriteria analysis. *Renew Energ*, 86 (2016), pp. 429-440
- [17] N. Fitzgerald, R.L. Arantequi, E. McKeogh, P. Leahy. A GIS-based model to calculate the potential for transforming conventional hydropower schemes and non-hydro reservoirs to pumped hydropower schemes. *Energy*, 41 (2012), pp. 483-490
- [18] S. Kucukali. Finding the most suitable existing hydropower reservoirs for the development of pumped-storage schemes: an integrated approach. *Renew Sust Energ Rev*, 37 (2014), pp. 502-508
- [19] X. Lu, S.H. Wang. A GIS-based assessment of Tibet's potential for pumped hydropower energy storage. *Renew Sust Energ Rev*, 69 (2017), pp. 1045-1054
- [20] Gribbin C. Snowy Hydro scheme boost to secure electricity supply on east coast: Government. ABC News; 2017.
- [21] Botterud A, Levin T, Koritarov V. Pumped storage hydropower: benefits for grid reliability and integration of variable renewable energy. Argonne National Laboratory; 2014.
- [22] The world's water battery: Pumped hydropower storage and the clean energy transition, IHA working paper December 2018.
- [23] World Energy Outlook, IEA Nov 2018
- [24] Innovation Landscape for a renewable-power Future IRENA 2019
- [25] The Power of Rivers – a Business Case, The Nature Conservancy, <https://global.nature.org/content/power-of-rivers>
- [26] EPE-DEE-NT-006/2019-50; Feb. 2019, *Estudos de Inventário de Usinas Hidrelétricas Reversíveis* (in Portuguese)
- [27] [www.irena.org/publications/2018/Mar/Renewable-Capacity-Statistics-2018](http://www.irena.org/publications/2018/Mar/Renewable-Capacity-Statistics-2018)
- [28] Bloomberg NEF (BNEF), available at <https://about.bnef.com/clean-energy-investment/>
- [29] E. Gomes - *Potencial de Repotenciação de hidrelétricas no Brasil e sua viabilização*, MSc dissertation, UNICAMP, 2013
- [30] S. Baruch-Mordo et al 2018 - *Environ. Res. Lett.* in press <https://doi.org/10.1088/1748-9326/aaf6e0>