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STANDARDIZING THE SELECTION OF SEASONAL-PUMPED STORAGE PROJECTS

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Abstract. *Brazil has just came out of a severe energy crisis and several regional water crisis, which started in 2013 and lasted until the end of 2015. The electricity supply and demand imbalance will further deteriorate with the operation of new dams in the Amazon that will generate most of their energy during the wet period. Seasonal-Pumped-Storage (SPS) is a solution to increase energy storage in a seasonal fashion. SPS stores potential energy during the wet season, when there is excess flow in the river, or when there is excess energy in the grid, pumping water to an upper reservoir. During the dry season, or when there is lack of flow in the river, or when there is lack of energy in the grid, the stored water generates electricity in the SPS and in the dams in cascade. This paper implements an integrated tool and decision support framework to approach complex, long-term problems involving the selection of Seasonal-Pumped Storage projects. The framework is embedded in an integrated tool called OUTDO (Oxford University Tool for Decision Organization). This analysis shows that the South region of Brazil should be selected region to build the first SPS project in Brazil.*

Keywords: *Pumped-Storage, Energy Storage, Energy Security, Decision Support Systems.*

1 INTRODUCTION

Brazil has just came out of a severe energy crisis and several regional water crisis, which started in 2013 and lasted until the end of 2015. The level of the stored energy in the reservoirs was reduced to a 19% of total capacity in January 2015 (National Electric Grid Operator, 2016). The energy crisis resulted in an average 52% increase in energy prices between October 2014 and October 2015 (Silva, 2015), which influenced on worsening the economic crisis in the country. In the end of 2015, the rain returned to the South of Brazil and an average of 3 GWmed1 of hydropower potential bypassed the dams without generating electricity in the Iguaçu River during 4 months. As the economic crisis reduced the electricity consumption in 2015 by 0.6% in comparison to 2014 (National Electric Grid Operator, 2016). It is expected that more water will bypass the dams in 2016 without generating electricity due to the low electricity demand during the next few years. The electricity supply and demand imbalance will worsen with the operation of new dams in the Amazon that will generate most of their energy during the wet period (Fearnside, 2015). The Government has stated that there is the need to increase the storage capacity (Energy Research Company, 2015), however no viable solution to increase the countries energy storage potential has been proposed. Electricity demand is set to increase by 44.9% and energy storage will increase by only 0.9% over the next 10 years (Energy Research Company, 2015).

An efficient solution to the frequent variation between low electricity generation and excess of energy for any country is to increase its energy storage capacity. This paper develops and discusses different projects for the implementation of Seasonal-Pumped-Storage (SPS). SPS is an innovative technology, firstly proposed in Hunt et al. 2014 (Hunt, et al., 2014; Hunt, et al., 2014), to increase energy storage in a seasonal fashion. It stores potential energy during the wet season, when there is excess flow in the river, or when there is excess energy in the grid, pumping water to an upper reservoir. During the dry season, or when there is lack of flow in the river, or when there is lack of energy in the grid, the stored water generates electricity in the SPS and in the dams in cascade (two or more hydroelectric dams in series). Although, a conventional pumped-storage plant has an average energy efficiency of 75%, the combination of a SPS with hydropower dams in cascade, can increase the total storage efficiency to around 90%, without including the reduction of spillage in the dams in cascade. In cases where a SPS decreases the spillage or evaporation in the hydropower dams in cascade, the SPS may result in an overall energy gain, rather than a loss to the system.

The aim of this paper is to find the most appropriate location to implement a SPS plant to reduce the vulnerability of a country's energy sector, increasing its energy storage capacity. On the resolution of such complex decision, various different aspects of a problem must be taken into account to find the most appropriate solution. Some of these aspects are trade-offs, for example, project costs against the environmental impact, long term climate changes against immediate benefits to the electricity sector. Thus, the choice of methodology to manage the influence of these aspects in the decision process is of para mount importance. Multi-Criteria Decision Analysis was implemented in OUTDO with the intent to keep the decision process transparent and to simplify its resolution. No less important than the identification and quantification of criteria in a decision process is the capability to foresee how the world is going to behave after a decision has been made. It

[1] 1 GWmed is equivalent to an average generation of 1 GW during a month.

can be the case that with a change in the value of a parameter in time (e.g. oil price or CO2 emissions cost) the best solution to a problem may also change.

At the same time OUTDO supports decision-making processes, the decision rationale (reasons behind the decisions and the justification for these reasons) is also documented. There are many benefits to document the decision rationale. In many cases, the reasons and concepts behind decisions are not formally recorded, and are forgotten. Frequently, if the same decision process used to find a previous decision is reused in a different place, circumstance or time, the outcome of the decision could be very different from what was decided previously. In addition, the management of knowledge and information is not easy to achieve. Communication between different groups of people working on the same project can be difficult because each person has a perspective on the project that fits with their own activities in the project (Selvin & al, 2001). OUTDO addresses this issue by enabling dialogue mapping (a technique for recording meeting discussions) (Conklin, 2005) and the linking of different sources of project information to further clarify the decision process. The combination of MCDA, decision rationale capture and Probabilistic Forecasting makes OUTDO a tool appropriate to aid long term and complex decision making which takes into consideration the change in external variables and involve a variety of conflicting criteria, interacting decisions, and different stakeholders.

This tool is applied to find the recommended location for the construction of the first SPS plant in Brazil. This is presented in the following sections.

2 METHODOLOGY

This section presents the Oxford University Tool for Decision Organization developed by main author with the intention to standardize decision making processes. The tool is then applied to support the selection of the most appropriate region to build the first SPS project in Brazil.

2.1 Oxford Tool for Decision Organization (OUTDO)

OUTDO is a tool that integrates Multi Criteria Decision Analysis, Rationale Management, Forecasting into a single framework (Hunt, 2013). MCDA is a structured methodology for supporting decision making that is suitable for addressing complex problems, that is, problems featuring high uncertainty, different forms of incommensurable data, long term consequences, multiplicity of interests and conflicting assessments (Cavallaro, 2009; Wang, et al., 2009; Roy, 1990; Zankis, et al., 1998). As many decision makers might be involved in the decision process, MCDA allows the representation of multiple and possibly conflicting views in the form of different criteria weight sets, thereby allowing the identification of important conflicts and/or opportunities for compromise (Linkov & Seager, 2011). MCDA may be applied using a variety of methods; some of them are reviewed in (Wang, et al., 2009; Belton & Stewart, 2002; Parlos, 2000).

Decision rationale is concerned with the explicit representation of decisions and with the systematic presentation of the reasons why the decisions were made (Moran &

Carroll, 1996; Jarczyk, et al., 1992). Among the existing decision rationale methodologies, Issue Based Information Systems (IBIS) is the one with the strongest intellectual appeal in the research community due to its combination of simplicity and expressive power (Bracewell, et al., 2009; Theissen & Marquardt, 2008) and, thus, was included in the framework. IBIS graphically represents decision processes. Issues in the decision process are linked to possible solutions (called options). In order to find the most appropriate solution, arguments are added to support or oppose each option. Once an option is recommended other issues might arise from the recommended option and these issues are then treated the same way. This process, therefore, results in a hierarchy of issues. A change in one decision may trigger a series of ripple effects to other parts of the decision space. With IBIS, it is possible to trace back an invalid decision and correct it (Douglas, 2005).

Having a process for documenting the rationale for an important decision helps in the quality control of the decision process, keeps track of possible effects when requirements for an artefact change (an artefact is anything created by a human that does not exist in nature, including abstract things such as decision processes (Westerberg, et al., 1997)), and provides useful information to people who may seek to reuse solutions (Douglas, 2005; Ramesh & Sengupta, 1995; Bañares-Alcántara & King, 1997; Theissen & Marquardt, 2008).. It is still often the case that large amounts of information relevant to decision processes are never documented and are stored only in the heads of the decision makers (Lee, 1997). Often, working groups repeatedly discuss the same issues that had been re solved earlier, as the justifications for a given decision might not have been clearly understood by all members of the group, or possibly the project group changes over time. If no comprehensive record of these discussions exists, the context in which key decisions were made may be lost (Ramesh & Sengupta, 1995). Lastly, a variety of stakeholders involved in decision processes often have different sets of objectives and priorities, capturing the decision rationale makes the process explicit and supports a consistent view among stakeholders.

Forecasting is an essential skill in the majority of decision making processes because all actions take time to implement and uncontrollable external variables inevitably change (Makridakis, et al., 1998). A decision taken today may not be the recommended decision in a month's time, and the ability to anticipate changes or analyse risks is key to empowering people to make better decisions in the present. Often, there will be great uncertainty in how a variable will behave in the future. The use of confidence intervals opens a door for the creation of a range of predicted values and their probabilities. There is no guaranteed ‘correct’ method of computing confidence intervals, although some methodologies are assumed appropriate for certain forecasting approaches. For OUTDO, Hanbury (Hanbury, 2010) has established a method for the creation of confidence intervals (see Appendix A). This method has the advantage of being applicable to any forecasting technique, and to estimate confidence intervals using the mean error when the forecast is compared with the actual data. The next section presents the decision framework to be used in OUTDO.

OUTDO (version 1.0) is a user-friendly, integrated decision support tool suitable for complex decision making. OUTDO provides tools to support and record the decision process allowing the decision maker to develop its own personalised system for decision support, suitable for his/her particular interests and context. Its use is suggested for long term, complex and interacting decisions that involve a number of different issues and conflicting criteria.

The Compendium software (version 1.5.2) was used as the basis for the development of OUTDO as it is an open-source application in Java and has an active development community (Compendium Institute, 2012). OUTDO is the result of more than 15 years of research (King & Bañares-Alcántara, 1997; Bañares-Alcántara, 1995; Bañares-Alcántara & Lababidi, 1995), firstly in Edinburgh University and later at the University of Oxford in collaboration with Oxford Brookes University. The initial development of OUTDO was made by Skrzypczak (2007) (Skrzypczak, 2007; Aldea, et al., 2012). The features of the current version are explained in (Hunt, et al., 2013).

2.2 Seasonal-Pumped-Storage

SPS involves the construction of an upper reservoir, with a stable geological formation, connected by a tube to a reservoir located near the top of a river with a series of hydroelectric dams in cascade downstream. The SPS reservoir should be at 200 meters or more above the lower reservoir height. This is because the upper reservoir should store as much water as possible, so that it would flood a small area and storage a lot of energy.

A cascade of hydropower dams works as shown in Figure 1 (a) where the blue arrow represents the direction and the flow of water. The dams with reservoirs has the potential to store water and energy, altering the normal flow of the river, the run-of-the-river dams do not change significantly the river flow. The planning of reservoirs and turbines takes into account the optimum power generation during the year with the lost cost.

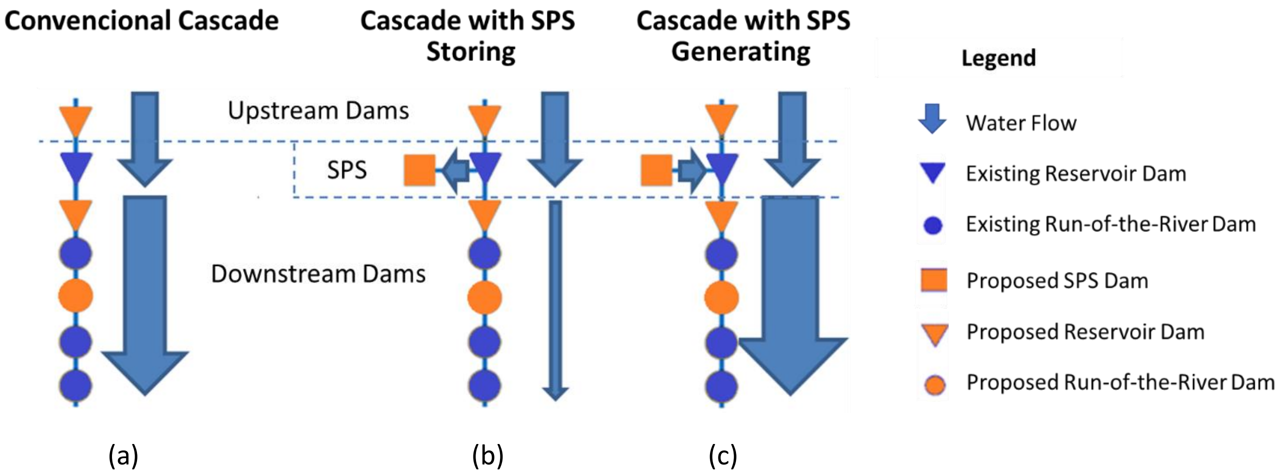


Figure 1. Operation of (a) conventional hydroelectric plants (b) SPS during periods of high water availability (c) SPS during periods of low water availability. Note that the same legend is used in other figures.

With the combination of a SPS and hydroelectric dams in cascade, in Figure 1 (b) and (c), it is possible to change the flow of a river basin in accordance with the need for energy storage and power generation (Hunt, et al., 2014). Figure 1 (b) represents the energy storage process that happens when there is high water availability in the basin in question and/or when there is excess energy in the National Interconnected System (SIN). The excess energy of the grid is used to pump water for the SPS upper reservoir with the consequent reduction of the generation of electricity in the cascade. The energy storage in SPS has a 70-75% efficiency. With the inclusion of the cascade, the overall storage efficiency increases considerably and may even result in a net generation gain. This happens if the increase in storage reduces the water spillage or water evaporation of the dams in cascade. During periods of low water availability in the basin or when there is a shortage of energy in the grid, SPS generates electricity using the stored water and increases the generation of the dams in cascade downstream, as shown in Figure 1 (c).

Table 1 shows a summary of the operating characteristics of a SPS plant. A SPS systems add several benefits to the operation of the dams in cascade downstream. Apart from the inherited benefits of PS such as to store energy from renewable sources, generate electricity during peak hours, and reduce transmission costs, SPS project adds further benefits to the system.

Table 1: Operation Scheme for SPS.

	Wet Period High Water Availability in the Watershed High Energy Availability in the SIN		Dry Period Low Water Availability in the Watershed Low Energy Availability in the SIN	
	No SPS	With SPS	No SPS	With SPS
Dams in Cascade Generation	High	Low (Energy is Conserved)	Low	High (Generate in scarcity)
Losses due to Spillage	High	Low (Water is Stored)	Low	Low
Losses due to Pumping	Zero	25% (Energy Losses Reduced)	Zero	Zero
Losses with Smaller Head	Low	Low	High (Less Power per Flow)	Low (Efficient Generation)

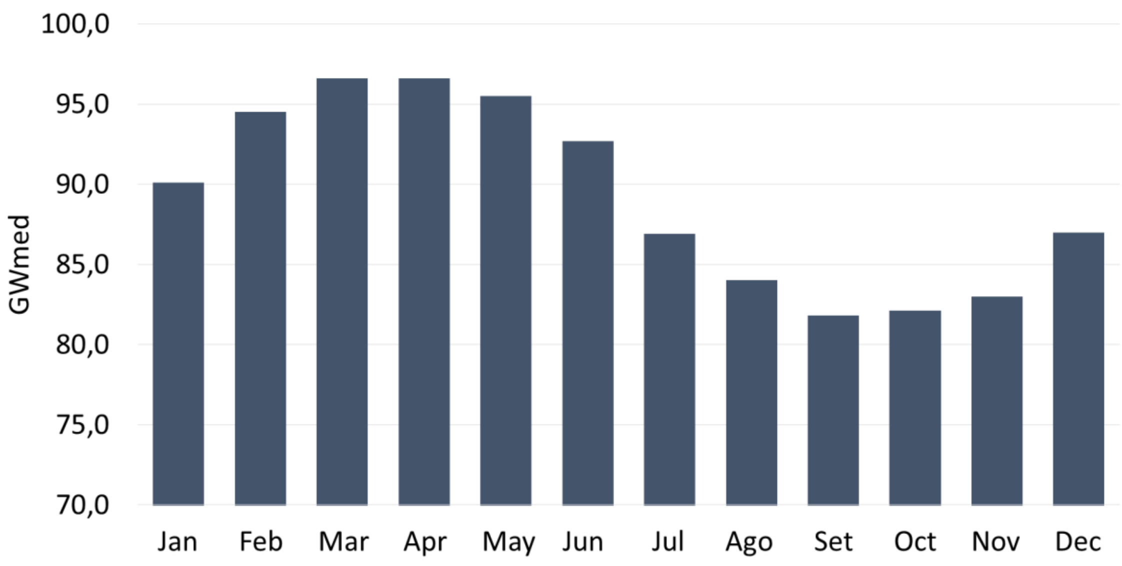


Figure 2: Predicted hydropower generation in 2023 (Empresa de Pesquisa Energética, 2013).

The main objective of SPS in the Brazilian energy sector is to complement the highly seasonal hydroelectric generation profile, which is foreseen to have a similar patterns in 2023 as shown in Figure 2. A SPS with 3 GW of installed capacity could be used to store 5.5 GW of energy during the wet period, when there is excess of energy in the system, and increase the generation during the dry period up to 6 GW, when there is lack of energy in the grid. This way, a SPS project could change the Brazilian hydropower profile to the generation profile shown in Figure 3. This way the seasonality caused by the hydropower generation in the Amazon region, without storage, can be resolved with one SPS project with 3 GW capacity.

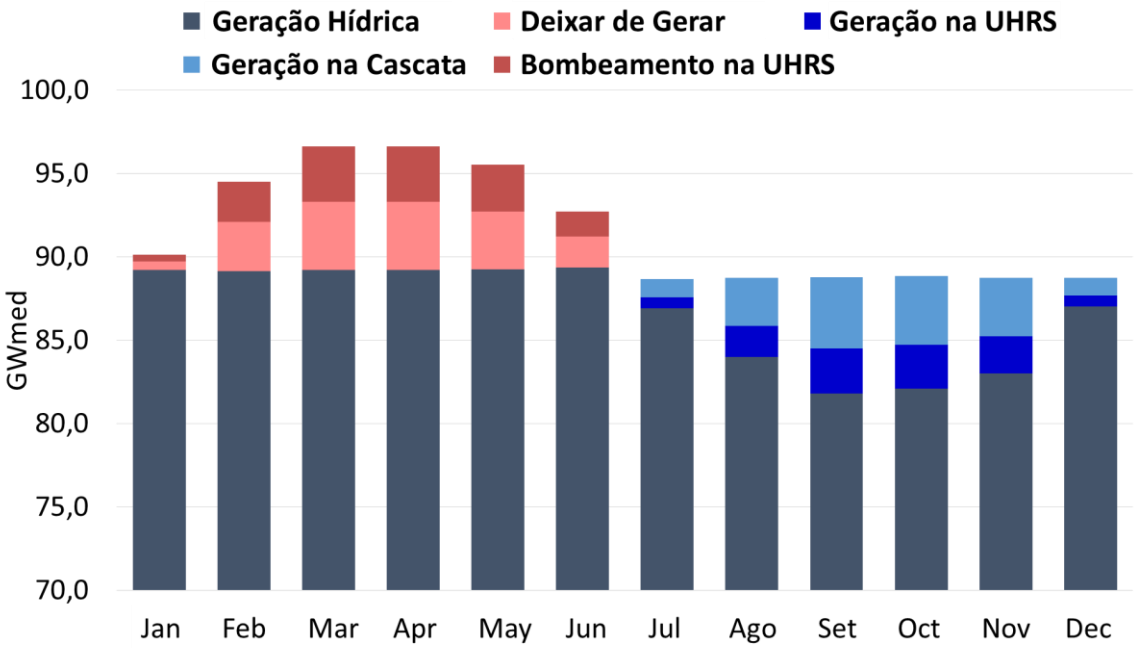


Figure 3: Estimated hydropower generation with a SPS project.

3 RESULTS

This section shows the reasons why a SPS project was selected with the support of the OUTDO software.

3.1 Decision Configuration: Why Seasonal-Pumped-Storage?

Firstly, it is important to present all the alternatives considered for the expansion of electricity generation sector. Figure 4 shows the decision rational used to select a list of alternatives.

The Brazilian energy sector has a variety of alternatives to expand. Run-of-the-river dams in the Amazon region, wind power in the Northeast and South regions, and decentralized solar power are going to be implemented in Brazil due to its costs and manageable environmental impacts. Conventional dams with reservoirs in the Amazon region are not applicable because, firstly, a huge flooded area is required to store a very small amount of energy. Secondly, the variation of the reservoirs result in a huge desert area between the river and the forest, during the dry season. This desert area can reach 10 to 20 km and have a severe impact to the ecosystem around the reservoir. For instance, animals and plants that rely on the river from drinking water will be dramatically affected by such a project.

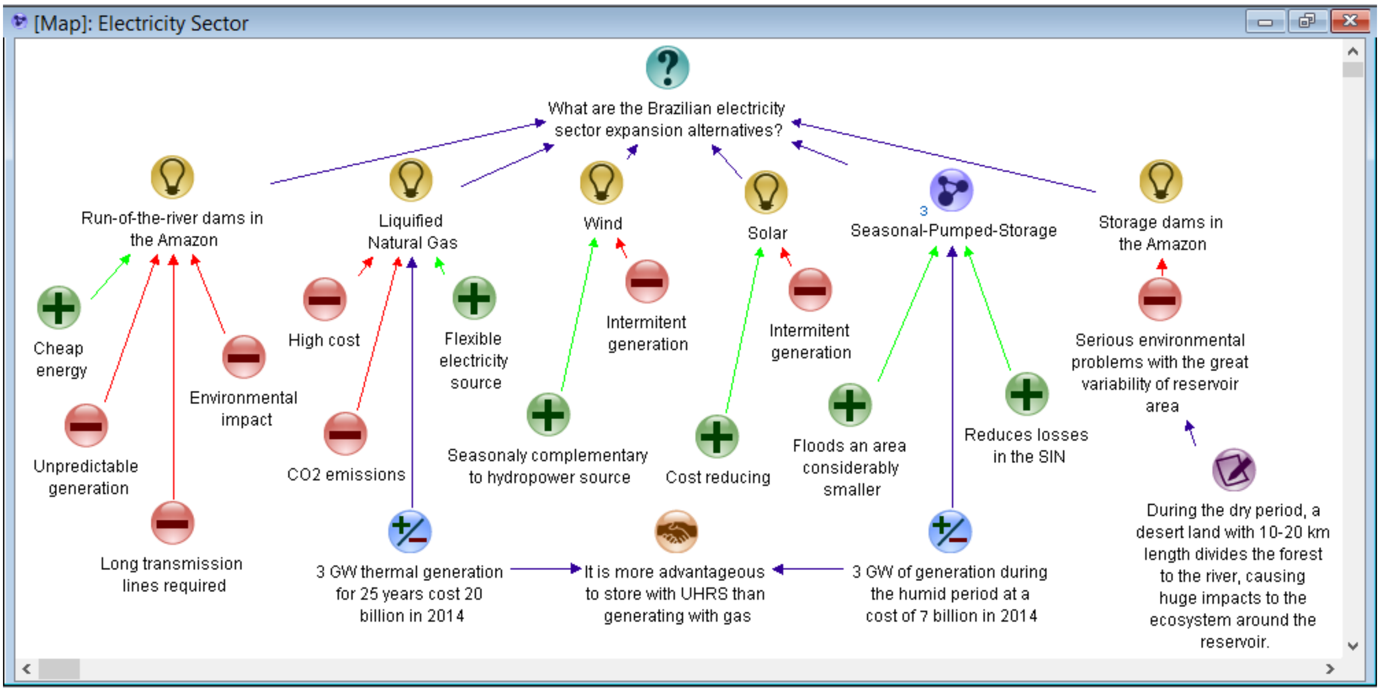


Figure 4: Decision rationale for the selection of SPS instead of thermoelectricity.

However, run-of-the-river dams, wind and solar power are unpredictable and intermittent sources of energy. Thus, the system requires generation alternatives which are capable of providing electricity when you cannot rely on these sources.

Two alternatives to guarantee the supply of electricity are Natural Gas and Energy Storage. Natural Gas emits CO_2 and is a scarce and expensive commodity in Brazil. The most acceptable alternative is to buy LNG from other countries, which is expensive and risky. SPS is an alternative with small environmental impact, as the flooded area is around 50 times smaller than conventional dams. The final and most important aspect is the cost. To guarantee 3 GW of generation during the dry period with LNG costs R$ 20 billion and with SPS costs R$ 7 billion, i.e. around three times cheaper that LNG. Thus, SPS should the technology selected to guarantee electricity generation in the future in Brazil.

3.2 Solution Development: Where to Build the SPS Project?

The selection of the location of a SPS plant is very complicated because there are several variables that influences on the decision. Figure 5 shows some of the pros and cons of the development of SPS in different regions of Brazil. With the intention to quantify the pros and cons in an effective way so that a rational decision is made, this section develops a MCDA for the selection of the region to implement the first SPS project in Brazil.

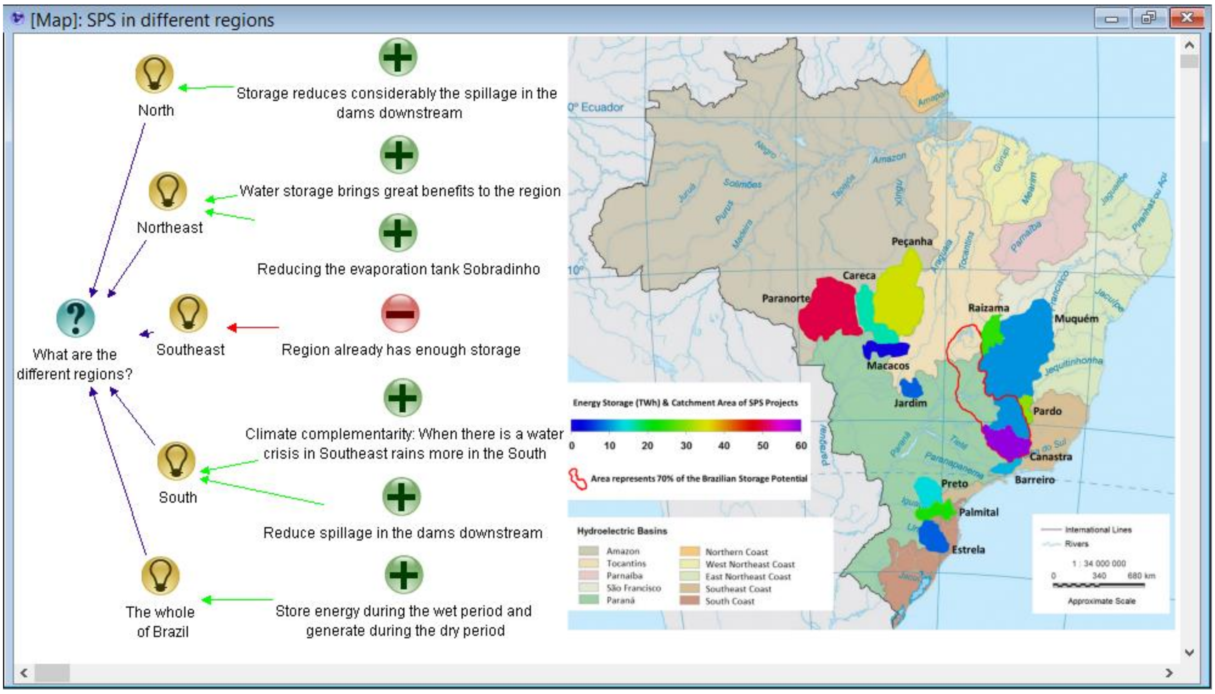


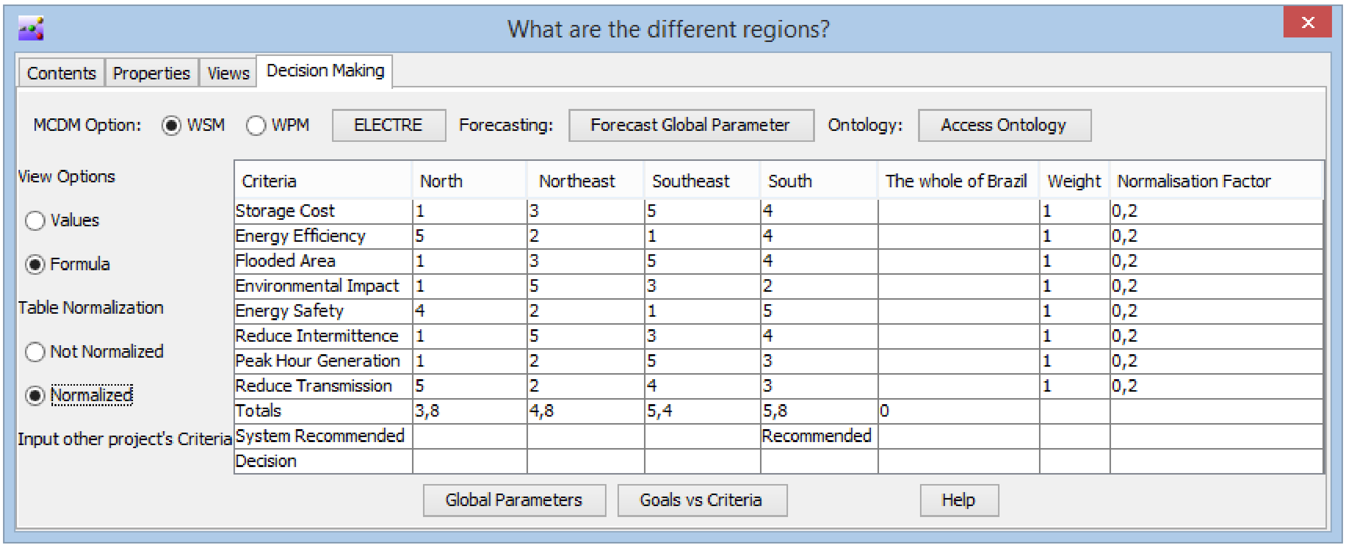
Figure 5: Description of the pros and cons of developing SPS projects in different areas of Brazil.

Table 2: Criteria used to compare different SPS projects.

Criterion	Description	Score	Weight
Storage Cost	Compares the SPS storage costs	QL	1
Energy Efficiency	SPS projects have a high overall efficiency reaching higher than 100%. This criterion compares the overall efficiency of SPS projects. It specially considers the reduction of water bypassing the Dam without generating electricity.	QL	1
Flooded Area	Compares the flooded area of the SPS projects	QL	1
Environmental Impact	Compares the environmental impact of the projects.	QL	1
Energy Safety	Compares which SPS project contributes the most to increase the security supply of the Brazilian electricity sector.	QL	1
Reduce Intermittence	Compares the SPS projects that contributes with the reduction of the intermittence of renewable energy sources.	QL	1
Peak Hour Generation	Compares the SPS projects that contributes with the increase of peak hour generation.	QL	1
Reduce Transmission	Compares the SPS projects that contributes with the reduction of future investments in transmission lines.	QL	1

The first step for developing a MCDA is to create and describe the criteria used to compare the alternatives. Each criteria can be quantitative (units are used to compare the alternatives or a function) or qualitative. A qualitative criterion scores 0 if it is contribution to the decision is very low, 1 if it is low, 2 medium, 3 high, 5 very high. Then a scenario for each criteria is built where the best and worst situations are set by the criteria scores. Secondly, the weight of criteria dictates the most and least important criteria. The higher the weight of criteria the most influence it has to the decision. In this example, the criteria have the same weight to reduce the influence of the decision maker in the decision. The scores were taken from the results presented in (Hunt, et al., 2016).

Table 2 presents the criteria used in the MCDA and Figure 6 shows the decision analysis for the selection of the first region to have a SPS project in Brazil.



Criteria	North	Northeast	Southeast	South	The whole of Brazil	Weight	Normalisation Factor
Storage Cost	1	3	5	4		1	0,2
Energy Efficiency	5	2	1	4		1	0,2
Flooded Area	1	3	5	4		1	0,2
Environmental Impact	1	5	3	2		1	0,2
Energy Safety	4	2	1	5		1	0,2
Reduce Intermittence	1	5	3	4		1	0,2
Peak Hour Generation	1	2	5	3		1	0,2
Reduce Transmission	5	2	4	3		1	0,2
Totals	3,8	4,8	5,4	5,8	0		
System Recommended				Recommended			
Decision							

Figure 6: Decision analysis to select the location to build the first SPS project.

According to Figure 6 the decision analysis shows that the South region of Brazil is the selected location to build the first SPS project. This is because:

- The SPS project has a reasonable cost, as most of the dams in cascade are already built.
- The efficiency of the SPS plant is high, as its operation would reduce the water spilled without generating electricity in the dams downstream.
- The flooded area is small as the level of the upper reservoir can vary more than 150 meters.
- The environmental impact is the second highest, just smaller than the dams in the Amazon.
- The SPS project would considerably increase the energy security of Brazil. This is because when there is a drought in the Southeast region, where most of the energy storage in Brazil is located, there is an increase in rain patterns in the South region.
- The South region has a big wind power potential a SPS plant can adapt its operation according to the wind generation and reduce the impact of its intermittence in the grid.
- The peak demand in the South region is not a big concern, however, the SPS can increase electricity generation during peak hours.
- The SPS project in the South region can store the wind energy generated and this way reduce the need of transmission lines to transmit the wind energy from the South region to the Southeast region.

4 CONCLUSION

Documenting the decision process and applying MCDA instead of simpler assessments can be very resource-intensive. However, this paper foresees the importance of a flexible framework that, in the context of uncertain technology deployment, records the essence of decision processes and aids decision making with in-depth multi criteria analysis. This, results in robust and transparent solutions for complex, long-term decision processes.

With the intention of selecting the most appropriate technology for the expansion of the electricity sector, OUTDO was used to present the pros and cons of each technology. It was pointed out that run-of-the-river dams, wind and solar power should contribute to the expansion of the electricity sector due to its low costs and manageable environmental impacts.

However, these technologies are unpredictable and intermittent. Thus, there is the need for a generation technology that can guarantee the supply of electricity. Comparing LNG based generation and storing energy with SPS, it was found that SPS should be the selected technology to guarantee the supply of electricity because it is around three times cheaper than LNG based electricity generation.

The study presented in this paper is a preliminary qualitative analysis. A more detailed quantitative analysis of each criteria would be necessary to make a more robust and final decision. In addition, in order to make a more thoughtful decision, forecasting should have been used to take into account future scenarios into the decision.

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