FEDERAL UNIVERSITY OF ITAJUBÁ
INSTITUTE OF ELECTRICAL SYSTEMS AND ENERGY
GRADUATION PROGRAM IN ELECTRICAL ENGINEERING

GABRIEL NASSER DOYLE DE DOILE

AN INTEGRATED FRAMEWORK FOR OVERALL ASSESSMENT OF UNDERGROUND PUMPED STORAGE HYDROPOWER

ITAJUBÁ – MG
2025

PPG-EEL – ACADEMIC DOCTORATE

GABRIEL NASSER DOYLE DE DOILE

AN INTEGRATED FRAMEWORK FOR OVERALL ASSESSMENT OF UNDERGROUND PUMPED STORAGE HYDROPOWER

Doctoral Thesis[1] presented to the Federal University of Itajubá – Unifei, as part of the requirements of the Graduate Program in Electrical Engineering – PPG-EEL at the Institute of Electrical Systems and Energy – ISEE, concentration area in electrical power systems, to obtain the Ph.D. Degree.

Supervisor

Ph.D. Professor Pedro Paulo Balestrassi

Co-supervisor

Ph.D. Professor Antonio Carlos Zambroni de Souza

ITAJUBÁ – MG
2025

[1] British English grammar and spelling are used in this thesis.

Index card prepared by Mauá Library – UNIFEI

Librarian: Geraldo Carlos da Silva – CRB6/1653

D657e Doile, Gabriel Nasser Doyle de.
An integrated framework for overall assessment of underground pumped storage hydropower / Gabriel Nasser Doyle de Doile. – Itajubá (MG): [s.n.], 2025.

127 f. ; 30 cm.

Orientador: Pedro Paulo Balestrassi.
Coorientador: Antonio Carlos Zambroni de Souza
Tese (doutorado) – Universidade Federa de Itajubá.

1. Armazenamento de energia. 2.Empilhamento de receitas. 3.Energias intermitentes. I. Balestrassi, Pedro Paulo, orient. II. Souza, Antonio Carlos Zambroni de. III. Universidade Federal de Itajubá. IV. Título.

CDU: 621.311.21(043)

GABRIEL NASSER DOYLE DE DOILE

AN INTEGRATED FRAMEWORK FOR OVERALL ASSESSMENT OF UNDERGROUND PUMPED STORAGE HYDROPOWER

Doctoral Thesis presented to the Federal University of Itajubá – Unifei, as part of the requirements of the Graduate Program in Electrical Engineering – PPG-EEL at the Institute of Electrical Systems and Energy – ISEE, concentration area in electrical power systems, to obtain the Ph.D. Degree.

APPROVED on May 5th, 2025

Ph.D. Professor Miguel Castilla	UPC
Ph.D. Professor Paulo Rotella Junior	UFPB
Ph.D. Professor Benedito Donizeti Bonatto	Unifei
Ph.D. Professor Eliane Valença Nascimento de Lorenci	Unifei

Supervisor

Ph.D. Professor Pedro Paulo Balestrassi

Co-supervisor

Ph.D. Professor Antonio Carlos Zambroni de Souza

ITAJUBÁ – MG
2025

ACKNOWLEDGMENTS

I am very thankful to Brazilian citizens for maintain and strengthen the free of charges public schools and universities where people from impoverished families, like me, can study and graduate!

I am so grateful to my wife, Isabel Teresinha de Souza Peixoto de Doile, my loyal companion to everything, everywhere, every time!

Thanks so much to my Supervisor, Ph.D. Professor Pedro Paulo Balestrassi, for his thoughtful suggestions and guidance throughout my research process, and for challenging me to think deeply about this issue. I am so grateful for the practical inputs and insights of my Second Supervisor, Ph.D. Professor Antonio Carlos Zambroni de Souza. I am, also, grateful to Professor Miguel Castilla for his valuable support during my internship at the Polytechnic University of Catalonia – Spain

Thanks to Ph.D. Professor Paulo Rotella Junior and to Ph.D. Professor Benedito Donizeti Bonatto and his team for their contribution to the development of this Thesis.

“*A people that does not invest in science and technology, who does not put money into research, will never be a nation. It will just be a mass of people with no prospects for the future and no prospect to competing in an increasingly competitive world.*”

Luiz Inácio Lula da Silva

ABSTRACT

There is a worldwide growing claim for the elimination or, at least a drastic reduction, in the consumption of fossil fuels that could contributes by decreasing the greenhouse effect. In this compass, renewable sources, such as wind and solar photovoltaics, have grown exponentially in several countries. Even with the predominance of hydroelectric power plants, Brazil also presents a rapid growth of these new sources of electric energy production, largely thanks to subsidies offered by the Federal Government. However, the intermittency of these sources, which depend directly on variations in wind speed and solar radiation, is an undesirable characteristic that needs to be overcome through energy storage. Thanks to the large volume of storage available in hydraulic power plants reservoirs, Brazilian power system has been operated without other types of energy storage. Nevertheless, this storage volume is finite and due to socio-environmental barriers, the construction of new reservoirs through dams is unfeasible in most cases, which leads to the need for the development and use of other energy storage technologies. To face socio-environmental barriers, the construction of underground reservoirs or even, in a more optimized way, the use of deactivated mines or natural caverns to implement Underground Pumped Storage Hydropower – UPSH, might be a solution, instead of large battery banks, which also face socio-environmental barriers, in addition to economic unfeasibility. The main purpose of this Thesis is to draw the attention of the academic community, decision makers, sectoral planners, entrepreneurs and governments to study, understand and develop UPSH technology, through the demonstration of its technical and economic viability, considering that this technology has great potential in the world and, especially in Brazil where there is hydrological abundance and many deactivated deep underground mines. To achieve such an objective, a comprehensive review of the literature, legislation and regulations was carried out to present **an integrated framework for general assessment of UPSH**. This framework is composed of 5 phases: (i) prospecting, where the availability of resources is assessed, such as water availability, soil survey, demand for energy storage, among others; (ii) design, where the dimensioning of machines, underground reservoirs, penstocks, among others, is refined; (iii) business plan, where the business model is defined based on the size of the plant and its compliance with current regulations. At this stage, an economic feasibility analysis is carried out, for which revenue stacking, combinatorial auction, among other innovations for the economic regulation of Energy Storage Systems – ESS were proposed; (iv) implementation, where the actual project is put into practice; and (v) decommissioning, where the closure of activities is defined, as well as the destination of unusable facilities and the recovery of the degraded environment. The integrated framework for general assessment of UPSH was applied to two case studies, concluding by the technical and economic feasibility of a μUPSH with 500 kW power and 1500 kWh capacity, taking advantage of the potential of the lake on the campus of Federal University of Itajubá. The plant was classified as Distributed Generation – DG and inserted in the

Electric Energy Compensation System – SCEE. Also, the technical and economic feasibility of an ultra-deep UPSH in Lake Mundaú, state of Alagoas, with 1000 m depth, 500 MW nominal power and 1 GWh capacity was attested. In this case, the economic regulation proposed in this Thesis was used. Also, the regulation for hydroelectric plants and underground mines was used, by similarity when applicable, in both case studies. It is concluded that UPSH technology is technically and economically viable and lacks adequate legislation and regulation to provide legal security to entrepreneurs interested in the technology. Further studies are needed to consolidate the regulatory proposal presented in this Thesis, as well as for comparisons with other technologies.

Keywords: business models, combinatorial auction, deactivated underground mines, economic regulation, energy storage, intermittent energies, revenue stacking, reversible power plants, underground reservoirs, UPSH.

RESUMO

Há uma crescente reivindicação a nível mundial para a eliminação ou, pelo menos uma redução drástica, no consumo de combustíveis fósseis que possa contribuir para diminuir o efeito estufa. Neste compasso, as fontes renováveis, tais como eólicas e solar fotovoltaica, têm crescido de forma exponencial em diversos países. Mesmo com a predominância de usinas hidrelétricas, o Brasil também apresenta um rápido crescimento dessas novas fontes de produção de energia elétrica, graças em grande parte a subsídios oferecidos pelo Governo Federal. No entanto, a intermitência dessas fontes, que dependem diretamente das variações do vento e da radiação solar, é uma característica indesejável que precisa ser contornada através do armazenamento de energia. Graças ao grande volume de armazenamento disponível nas usinas hidráulicas, o sistema elétrico brasileiro tem prescindido de outros tipos de armazenamento de energia. Porém, esse volume de armazenamento é finito e, devido a questões socioambientais, está praticamente inviável a construção de novos reservatórios por meio de represas, o que leva a necessidade do desenvolvimento e emprego de outras tecnologias de armazenamento de energia. Uma solução que contorna as barreiras socioambientais é a construção de reservatórios subterrâneos ou mesmo, de uma forma mais otimizada, o aproveitamento de minas subterrâneas desativadas ou cavernas naturais para implantação de Usinas Hidrelétricas Reversíveis Subterrâneas – UHRS, ao invés de grandes bancos de baterias, que também enfrentam barreiras socioambientais, além da inviabilidade econômica. O principal propósito desta tese é chamar a atenção da comunidade acadêmica, tomadores de decisão, planejamento setorial, empreendedores e governantes para que estudem, entendam e desenvolvam a tecnologia de UHRS, através da demonstração da sua viabilidade técnica e econômica, considerando que esta tecnologia tem grande potencial no mundo e, especialmente no Brasil onde há abundância hidrológica e muitas minas subterrâneas profundas desativadas. Para atingir este objetivo, foi feita uma ampla revisão bibliográfica, legislativa e regulatória para apresentar **uma estrutura integrada para avaliação geral de UHRS**. Tal estrutura é composta de 5 fases: (i) prospecção, onde é avaliada a disponibilidade de recursos, como disponibilidade hídrica, pesquisa de solo, demanda por armazenamento de energia, entre outros; (ii) projeto, onde o dimensionamento das máquinas, reservatórios subterrâneos, dutos-forçados, entre outros é refinado; (iii) plano de negócios, onde o modelo de negócios é definido com base no tamanho da usina e seu enquadramento na regulação vigente. Nesta fase é feita a análise de viabilidade econômica, para qual foram propostos o empilhamento de receitas, leilão combinatório, entre outras inovações para regulação econômica dos sistemas de armazenamento de energia. (iv) implementação, onde o projeto real sai do papel; e (v) descomissionamento, onde o encerramento as atividades é definido, bem como a destinação das instalações inservíveis e a recuperação do ambiente degradado. A estrutura integrada para avaliação geral de UHRS foi aplicada a dois estudos de caso, tendo-se concluído pela viabilidade técnica e econômica de uma µUHRS de 500 kW pico e 1500 kWh de capacidade, aproveitando o potencial do lago existente no campus de Itajubá. A planta foi enquadrada como Geração Distribuída – GD e inserida no Sistema de Compensação de Energia Elétrica – SCEE. Também, atestou-se a viabilidade técnica e econômica de uma UHRS ultra profunda no Lago Mundaú, estado de Alagoas, com 1000 m de profundidade, 500 MW de potência nominal e 1 GWh de capacidade. Neste caso foi utilizada a regulação econômica proposta nesta tese. Também, foi utilizada a regulação para hidrelétricas e minas subterrâneas, por similaridade no que coube, em ambos os estudos de caso. Conclui-se que a tecnologia de UHRS é técnica e economicamente viável e carece de adequada legislação e regulação para dar segurança jurídica aos empreendedores interessados na tecnologia. Estudos mais aprofundados são necessários para consolidar a proposta regulatória apresentada nesta tese, bem como para comparações com outras tecnologias.

Palavras-chave: armazenamento de energia, empilhamento de receitas, energias intermitentes, leilão combinatório, minas subterrâneas desativadas, modelos de negócio, regulação econômica, reservatórios subterrâneos, UHRS, usinas reversíveis.

RESUMEN

Existe una creciente demanda a nivel mundial por la eliminación o, al menos, una reducción drástica, en el consumo de combustibles fósiles que pueda contribuir disminuyendo el efecto invernadero. En este compás, las fuentes renovables, como la eólica y la solar fotovoltaica, han crecido exponencialmente en varios países. Incluso con el predominio de las centrales hidroeléctricas, Brasil también presenta un rápido crecimiento de estas nuevas fuentes de producción de energía eléctrica, gracias en gran medida a los subsidios ofrecidos por el Gobierno Federal. Sin embargo, la intermitencia de estas fuentes, que dependen directamente de las variaciones en el viento y en la radiación solar, es una característica indeseable que debe superarse mediante el almacenamiento de energía. Gracias al gran volumen de almacenamiento disponible en las centrales hidráulicas, el sistema eléctrico brasileño prescindió de otros tipos de almacenamiento de energía. Cabe señalar que este volumen de almacenamiento es finito y, por cuestiones socioambientales, la construcción de nuevos reservorios a través de represas es casi inviable, lo que genera la necesidad del desarrollo y uso de otras tecnologías de almacenamiento de energía. Una solución que supera las barreras socioambientales es la construcción de reservorios subterráneos o incluso, de forma más optimizada, el uso de minas desactivadas o cuevas naturales para implementar Centrales Hidroeléctricas Subterráneas Reversibles – CHSR, en lugar de grandes bancos de baterías, que también enfrentan barreras socioambientales, además de la inviabilidad económica. El objetivo principal de esta tesis es llamar la atención de la comunidad académica, tomadores de decisión, planificación sectorial, empresarios y gobiernos para estudiar, comprender y desarrollar la tecnología CHSR, a través de la demostración de su viabilidad técnica y económica, considerando que esta tecnología presenta un gran potencial en el mundo y especialmente en Brasil donde hay abundancia hidrológica y muchas minas subterráneas profundas desactivadas. Para lograr este objetivo, se llevó a cabo una extensa revisión bibliográfica, legislativa y regulatoria para presentar un **marco integrado para la evaluación general de CHSR**. Esta estructura se compone de 5 fases: (i) prospección, donde se evalúa la disponibilidad de recursos, como disponibilidad del agua, investigación de suelos, demanda de almacenamiento de energía, entre otros; (ii) proyecto, donde se afina el dimensionamiento de máquinas, reservorios subterráneos, ductos forzados, entre otros; (iii) plan de negocios, donde se define el modelo de negocio en función del tamaño de la planta y su cumplimiento de la normativa vigente. En esta etapa se realiza un análisis de viabilidad económica, para lo cual se propuso apilamiento de ingresos, subasta combinatoria, entre otras innovaciones para la regulación económica de los sistemas de almacenamiento de energía. (iv) implementación, donde el proyecto real se despega; y (v) desmantelamiento, donde se define el cierre de actividades, así como el destino de las instalaciones inutilizables y la recuperación del medio ambiente degradado. La estructura integrada para la evaluación general del CHSR fue aplicada a dos estudios de caso, concluyendo que una µCHSR con 500 kW de pico y 1500 kWh de capacidad es técnica y económicamente viable, aprovechando el potencial del lago existente en el campus de la Universidad Federal de Itajubá. La central fue clasificada como Generación Distribuida – GD e incluida en el Sistema de Compensación de Energía Eléctrica – SCEE. También se confirmó la viabilidad técnica y económica de una CHSR ultra profunda en el lago Mundaú, estado de Alagoas, con 1000 m de profundidad, 500 MW de potencia nominal y 1 GWh de capacidad. En este caso se utilizó la regulación económica propuesta en esta tesis. Asimismo, se utilizó la regulación para centrales hidroeléctricas y minas subterráneas, por similitud en lo aplicable, en ambos casos de estudio. Se concluye que la tecnología CHSR es técnica y económicamente viable y carece de legislación y regulación adecuada para brindar seguridad jurídica a los empresarios interesados en la tecnología. Son necesarios estudios más profundizados para consolidar la propuesta regulatoria presentada en esta tesis, así como para realizar comparaciones con otras tecnologías.

Palabras clave: almacenamiento de energía, apilado de ingresos, CHSR, energía intermitente, minas subterráneas desactivadas, modelos de negocio, plantas de almacenamiento por bombeo, regulación económica, reservorios subterráneos, subasta combinatoria.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ACL	Free Contracting Environment
ACR	Regulated Contracting Environment
ANEEL	National Electric Energy Agency
ANM	National Mining Agency
ART	Note of Technical Responsibility
CCEE	Electrical Energy Trading Chamber
CCP	Common Coupling Point
CEMIG	Energetic Company of Minas Gerais State
CEP	Clean Energy Package
CERH-MG	Minas Gerais State Council for Water Resources
CGH	Central de Geração Hidráulica (used to very small hydropowers)
CONAMA	National Environmental Council
COPAM	State Council for Environmental Policy of Minas Gerais State
DG	Distributed Generation
DISCO	Distribution Company
DMRE	Department of Mineral Resources
DNPM	National Department of Mineral Production
DPP	Discounted Payback Period
DRA	Auction Eligibility Registration Order
DRI	Order of Registration of Intent to Grant Authorization
EIA	Environmental Impact Study
EIH	Hydroelectric Inventory Studies
EPC	Engineering, Procurement and Construction
EPE	Energy Research Company
ESCO	Energy Storage Company
ESS	Energy Storage Systems
EVTE	Technical and Economic Feasibility Studies
FEAM	Minas Gerais State Environmental Foundation
FERC	Federal Energy Regulatory Commission
FWR	Far West Rand gold mines region in South Africa Republic
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
IBGE	Brazilian Institute of Geography and Statistics
ICMBio	Chico Mendes Institute for Biodiversity Conservation
IEA	International Energy Agency
IEEE	IEEE Xplore database (in this Thesis)
IEEE	Institute of Electrical and Electronics Engineers
IEF	Minas Gerais State Forestry Institute
IGAM	Minas Gerais Water Management Institute
IMA	Alagoas State Environmental Institute
INPE	National Institute for Space Research
IRR	Internal Rate of Return
LI	Environmental Installation License
LO	Environmental Operating License

LP	Environmental Preliminary License
LPI	Environmental Unified Preliminary and Installation Licence
MARR	Minimum Attractiveness Return Rate
MCS	Monte Carlo Simulation
MMA	Ministry of the Environment
NPC	Net Present Costs
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NRM	Mining Regulatory Standard (issued by ANM)
O&M	Operation and Maintenance
OF	Objective Function
ONS	National Electrical System Operator
OPGW	Optical Ground Wire
PBA	Basic Environmental Project
PCH	Pequena Central Hidrelétrica (meaning small hydropower)
PDF	Probability Density Functions
PFM	Mine Closure Plan
PHS	Pumped Hydroelectric System
PIE	Independent Energy Producer
PLD	Difference Settlement Price
PNE	National Energy Plan
PMMG	Minas Gerais Military Police
PNLA	National Environmental Licensing Portal
PNMA	National Environmental Policy
PRODIST	Distribution Procedures
PRORET	Tariff Regulation Procedures
PSH	Pumped Storage Hydropower
RAG	Annual Generation Revenue
RAP	Permitted Annual Revenue
RAS	Simplified Environmental Report
RASA	Energy Storage Service Annual Revenue
REN	Normative Resolution (issued by ANEEL)
RES	Renewable Energy Sources
RQx	Research Question (x is a real number)
RIMA	Environmental Impact Report
SC	Scopus database
SCEE	Electrical Energy Compensation System
SEMA	Special Secretariat for the Environment
SEMAD	MG State Secretariat for the Environment and Sustainable Development
SEMMA	Municipal Secretariat for the Environment of Itajubá municipality
SIGA	ANEEL’s Generation Information System
SIN	National Interconnected System
SISEMA	System of Environment and Water Resources of Minas Gerais State
SISNAMA	National Environmental System

SLR	Systematic Literature Review
TCO	Transmission Company
TLD	Definitive Release Term
TLP	Preliminary Release Term
TLT	Testing Release Term
TR	Term of Reference for environmental studies
UHE	Usina Hidrelétrica (used to large hydropowers)
UPHS	Underground Pumped Hydroelectric System
UPSH	Underground Pumped Storage Hydropower
WACC	Weighted Average Cost of Capital
WoS	Web of Science database

Greek letters

η	Overall hydroelectric yield
γ	Overall PSH yield
ε	Solar PV panels yield
ρ	Specific mass of water of 1,000 kg/m³ at 4°C
ω	Angular speed
σ	Hydro-turbines dimensionless coefficient
δ	Hydro-turbines diameter number

Chapter 1 – Introduction

One of the 21st century main global concerns is the global warm caused mainly by emissions of greenhouse gases. Gallagher et al. (2019) said that Renewable Energy Sources – RES are the way to reduce the greenhouse gas emissions and provide the necessary energy matrix changes. González et al. (2020), in other hand, state that the advent of RES, replacing the fossil fuel, is becoming crucial to alleviate such an issue. Nevertheless, the global energy consumption still being dominated by fossil fuels, that are step by step losing ground to the new kinds of clean energies. The new kind of energy resources, as solar photovoltaic, wind, hydro, and biofuels, among others are the transition core to a less carbon-intensive and environmentally sustainable energy systems (GOLDEMBERG, 2020).

The share of RES has been growing exponentially around the world and will reach 46% of electricity matrix by 2030, becoming the largest source of electricity production, according to the International Energy Agency – IEA. The Brazilian wind production grew from 27 MW in 2005 up to 33.2 GW by the end of 2024, while solar photovoltaic – PV generation have achieved 52.6 GW, including 17.5 GW of utility-scale and 35.1 GW of Distributed Generation – DG. There is an expectation in Brazil to reach 100 GW installed capacity of new renewables sources through 2030, excluding the large hydropower (ANEEL, 2025a; DOYLE DE DOILE, 2016; IEA, 2025).

1.1 Research theme

The electrical system operation is become more and more difficult due to the seasonal and intermittent characteristics of RES, especially wind and solar power plants. Such a problem leads to the need for Energy Storage Systems – ESS to regulate both the intermittence and the seasonality of generation (PEARRE; SWAN, 2020).

There are several technologies for energy storage, some of them in mature stage and others under development, as presented in Figure 1.1. The three more mature technologies are Compressed Air Storage Systems – CAES, lead-acid batteries, and Pumped Storage Hydropower – PSH. CAES is a well-studied alternative worldwide, especially using caves for underground air or other gases storage (RABI; RADULOVIC; BUICK, 2023).

Some authors, as Dias et al. (2023), have studied salt caves in Brazil to store air, CO_2, and in particular hydrogen. There are also several studies related to batteries, their applications, and technologies. However, they are well known for their short life cycle and chemical waste making them a not environmentally friendly alternative (DA COSTA et al., 2011; MAIA DA COSTA et al., 2019; YANG et al., 2018).

In all situations, one of the critical aspects in ESS is the investment cost. As can be seen in the Figure 1.1, PSH also named as Pumped Hydroelectric Systems – PHS by some authors, is the more mature technology presenting less risk and capital requirement. Technologies in the beginning of deployment or research and development require more capital and are subject to more risk (ROTELLA JUNIOR et al., 2021).

Therefore, the proposed theme for this Thesis is the **Underground Pumped Storage Hydropower – UPSH**, that is an evolution of PSH technology not studied in Brazil yet, as will be demonstrate in next chapter.

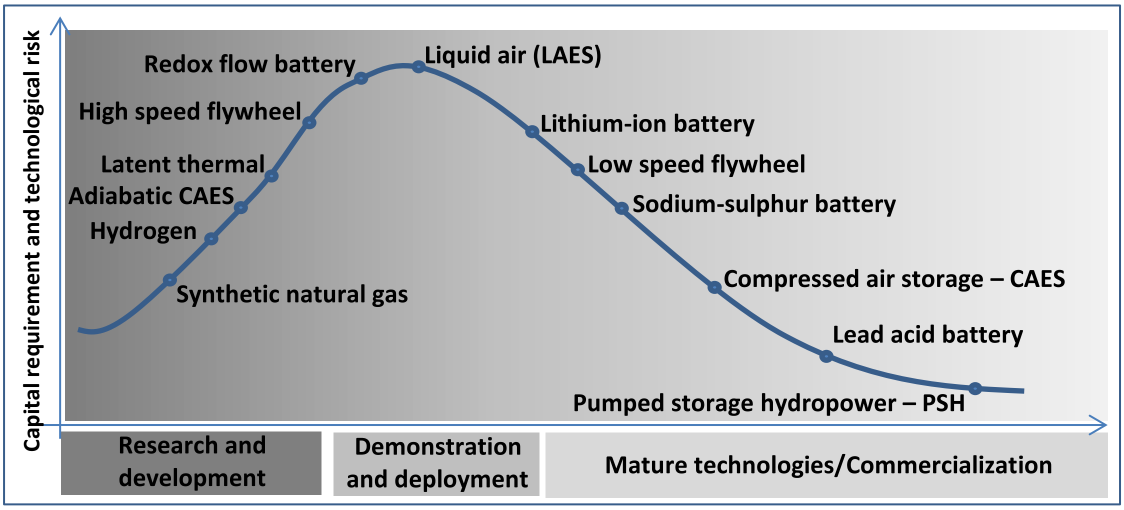


Figure 1.1 – Maturity of energy storage technologies. PSH is the more mature technology and presents less risk and less capital requirement.

1.2 Research problem

Brazil has a continental area with an extensive river network and adequate relief for the construction of dams, making the country as the largest water reservoir in the world. However, the socio-environmental barriers, that have emerged in the second half of last century, make it difficult to build new reservoirs and the trend is that the current reservoirs will run out in the not-so-distant future. The depletion of hydroelectric reservoir capacity will leave the national electrical system without sufficient storage capacity, leading to the investment need in other energy storage technologies (ZAMBON; BARROS; YEH, 2019).

UPSH presents itself as a solution for this issue. However, to make a holistic assessment is not an easy task and was not well studied yet. This Thesis focuses on an **integrated framework for overall assessment of UPSH**, that is a specific PSH case with at least one below ground reservoir. The UPSH can be deployed using an available superficial water body as upper reservoir and an underground lower reservoir or even both, lower and upper, underground reservoirs. Decommissioned mines, natural caves, or man-made excavated reservoirs are all options for these solutions. First ones, in general, are available for both lower and upper underground reservoirs in the same site.

1.3 Objectives

The general objective is to present **an integrated framework for overall assessment of UPSH**. Such a framework will be composed by five phases: (i) prospecting, (ii) design, (iii) business plan, (iv) execution and commissioning, and (v) decommissioning. Each phase can be seen as a specific objective, as explained below. The proposal is to study and detail each phase applied to Brazil. There were no specific regulations for energy storage in the country by 2025, when this Thesis was completed. Therefore, UPSH must be classified according to their rated installed power, just like hydroelectric plants. At each stage, applicable regulations will be studied based on similarity and, if necessary, new regulations will be proposed.

1.3.1 Prospecting

The main task in this phase is the site definition to build an UPSH. As an excavated UPSH can be built in almost any location, the emphasis in this phase will be in how to legalize the enterprise by similarity with current hydropower legislation, as there is no regulation for UPSH yet. Available sites will define the UPSH size and how it will be classified, type of grant, environmental licencing, and type of electricity trading. The procedures for legalizing each UPSH classification into current legislation for hydropower are presented here.

1.3.2 Design

This phase depends on assigned site. Reservoir projects should be developed. The power plant will be dimensioned based on volume and land levels of the reservoirs and/or availability of grid and energy and/or load to be attended. Deterministic studies should be carried out to determine the optimal use, if there are no limits to the reservoir. Stochastic studies can show the profit probabilities from the venture for the entrepreneur's decision. Another important issue in this phase is the grid connection. There are several regulations to be listed and detailed as grid connection depends on installed power, assured energy, voltage level, among other variables.

1.3.3 Business plan

The business models for generation, transmission, and distribution are presented in this phase as well as a proposal for ESS systems business plan. Some new concepts, as revenue stacking and combinatorial auction, and regulations, as revenue for energy storage services, should be presented and discussed to reach at such a proposal.

The economic assessment is the most important phase in a real case, however for this study an economic feasibility macro analysis is sufficient. Economic and financial tool are presented and used, as well as statistic and probability tools. The energy purchased for pumping and the energy generated and sold must be considered, as they have different regulations and prices. Related laws and regulation will be presented and discussed as well as financial and economic analysis tools and their potential results.

1.3.4 Execution and commissioning

There are five main tasks to be performed at this stage. Typically, all of them are carried out by an Engineering, Procurement and Construction – EPC company. (i) the executive project, where the basic design is refined; (ii) the studies for environmental licenses; (iii) the application for public permits; (iv) the works themselves, where construction and assembly are carried out; and (v) the presentation and discussion of procedures for commissioning with the National Electrical System Operator – ONS, Transmission Companies – TCOs and Distribution Companies – DISCOs.

1.3.5 Decommissioning

Nowadays, decommissioning issues are the main concern, especially in underground structures, as they can hide environmental damage that is difficult to reverse in the future. A well-structured decommissioning plan should be presented following all socio-environmental regulations provided for hydropower and underground mining, by similarity.

1.3.6 Other specific objectives

To reach previous specific objectives and achieve the final goal, some other intermediate studies must be carried out. A Systematic Literature Review – SLR is necessary to find related articles published in the main databases and prove the novelty of the proposed theme, as well as a legislative and regulatory review to find legislation that can be applied to UPSH by similarity. A technical review was also carried out presenting the history of reversible hydraulic plants, which gave rise to the UPSH, to find suitable machines and layout to compose the case studies. Two case studies were carried out to validate the main objective: a µUPSH on the Unifei campus and an ultra-deep UPSH in Lake Mundaú, Northeastern region.

1.4 Contributions

As stated before, UPSH can be from small size with a few kilowatts installed power to big ones reaching more than one gigawatt of installed power. Several laws and regulations for hydropower are related to licences and permits, energy trading, grid connection, among others. All of them depending on the power plant size, the installed power, and the voltage level. There will be different decisions to be made in each case. Some small plants may be under completely private decisions, however, from medium to large, public decision makers are necessary, as plants require public concession or public authorization. The **integrated framework for overall assessment of UPSH** proposed in this Thesis is a tool set for all decision makers. They will find in the same framework all necessary tools to make decision from site assignment until the power plant decommissioning, crossing by projects, business plan, and commercial operation. Additionally, this work brings contributions to the regulation of energy storage services, which is extremely necessary to create a safe and predictable energy storage market. The technical and economic feasibility of small and large UPSH is proven through two case studies presented.

1.5 Limitations

There are natural limitations due to the originality of the theme, as the lack of legislation, the lack of scientific studies, among others. However, the main limitation in Brazil is the lack of regulation for the use of decommissioned mines as energy storage plants, as well as general regulation for ESS (including UPSH), to remove barriers and create an energy storage market.

In-force legislation and regulation for hydropower plants, for the use of water resources, and for underground mining were used by similarity in this Thesis.

1.6 Methodologies

It is expected that the results of this study will be immediately applied to the solution of real problems, which characterizes it overall as applied nature research. Partially, it can be seen as normative research, characterized by an interest in developing regulatory policies, strategies, and actions to improve available results and find an optimal alternative for solving a new problem. Considering the case studies, this Thesis can be also partially considered experimental research, where causal relationships will be established. This technique allows the researcher to control the study variables, so that it is possible to change them according to needs.

Each specific objective requires a particular methodological approach. The first methodology applied in this study was the SLR. This type of study allows for transparency, replicability, and reduction of authors' bias, in opposition to traditional literature reviews. Kitchenham (2004) stated that an SLR allow us to identify, evaluate and understand all documents available for a particular study or research. According to Morioka, Bolis, and Carvalho (2018) the SLR allows us to focus on a global issue or on a collection of empirical results in a specific research. As a result, one can formulate a general concept, not just a summary. The method was applied first to find scientific documents related to the theme and prove the originality of the proposal. After that, the method was used to find applicable legislation and regulation by similarity in Brazil (TRANFIELD; DENYER; SMART, 2003).

Exploratory research was carried out to present the state of the art of PSH and UPSH technologies, their history and main physical laws applied. The same method was used to identify the Brazilian UPSH potential, as well as reversible pump-turbines and motor-generators suitable for UPSH. Such a methodology was also applied to identify the legislation and regulation applied to UPSH by similarity in the framework prospecting phase.

Engineering knowledges for dimensioning and statistical tools are used in the framework prospecting and design phases. Meanwhile, the business plan phase is mainly based on economic and statistic tools. Exploratory research was resumed at this phase to present the current regulation for the electrical sector and a proposal for ESS regulation.

The last two phases, project execution and decommissioning, are substantially based on engineering tools. However, exploratory research is still needed to define the project licensing, commissioning and deactivation stages.

In the prospecting and design phases of the case studies, field research was necessary to identify potentials and limitations, as well as data research to identify historical and current electricity production, demand and consumption data. Grid constraints and energy prices are also identified by this methodology.

1.7 Thesis structure

This Thesis is composed by six chapters. In this first chapter the research contextualization was presented as well as the objectives, contributions, limitations, and applied methodologies. The rest of Thesis is organized as follow:

An SLR on the proposed theme and its predecessor technologies are presented in the Chapter 2. A systematic review on applied laws and regulations in Brazil is also presented here. Finally, a technical and historical review on hydropower, PSH, UPSH, and their equipment are reported and the UPSH Brazilian potential is presented.

The main objective of this Thesis is presented in Chapter 3. The five phases of the **integrated framework for overall assessment of UPSH** are detailed. Current legislation and regulations applied by similarity are presented in each phase, as well as the step-by-step guide to using them in UPSH projects.

In the Chapter 4 is discussed a proposal for a µUPSH prototype on the Unifei campus of Itajubá. The micro power plant is primarily for study and research purposes, but it will also be able to reduce Unifei's energy bill.

A proposal for a large-scale ultra-deep UPSH is presented in Chapter 5, where its technical and economic feasibility is attested, using the economic regulation and the bidding methodology proposed in this Thesis.

Chapter 6 completes this Thesis, where final considerations, conclusions and suggestions for future research are presented.

1.8 Graphical summary

The entire thesis graph is presented in Figure 1.2. The graph is composed of five sections: (i) introduction, showing the motivation of the work; (ii) the gap, explaining where studies are needed; (iii) the main proposal which is to present **an integrated framework for overall assessment of UPSH**; (iv) two case studies, one presenting a proposal for a µUPSH at the Itajubá campus of Unifei and another presenting a proposal for a 1 GWh ultra-deep UPSH in the Northeast region, and (v) finally the conclusions stating that UPSH is a technically and economically viable technology in Brazil and some recommendations for new regulation, considering revenue stacking and combinatorial auctions.

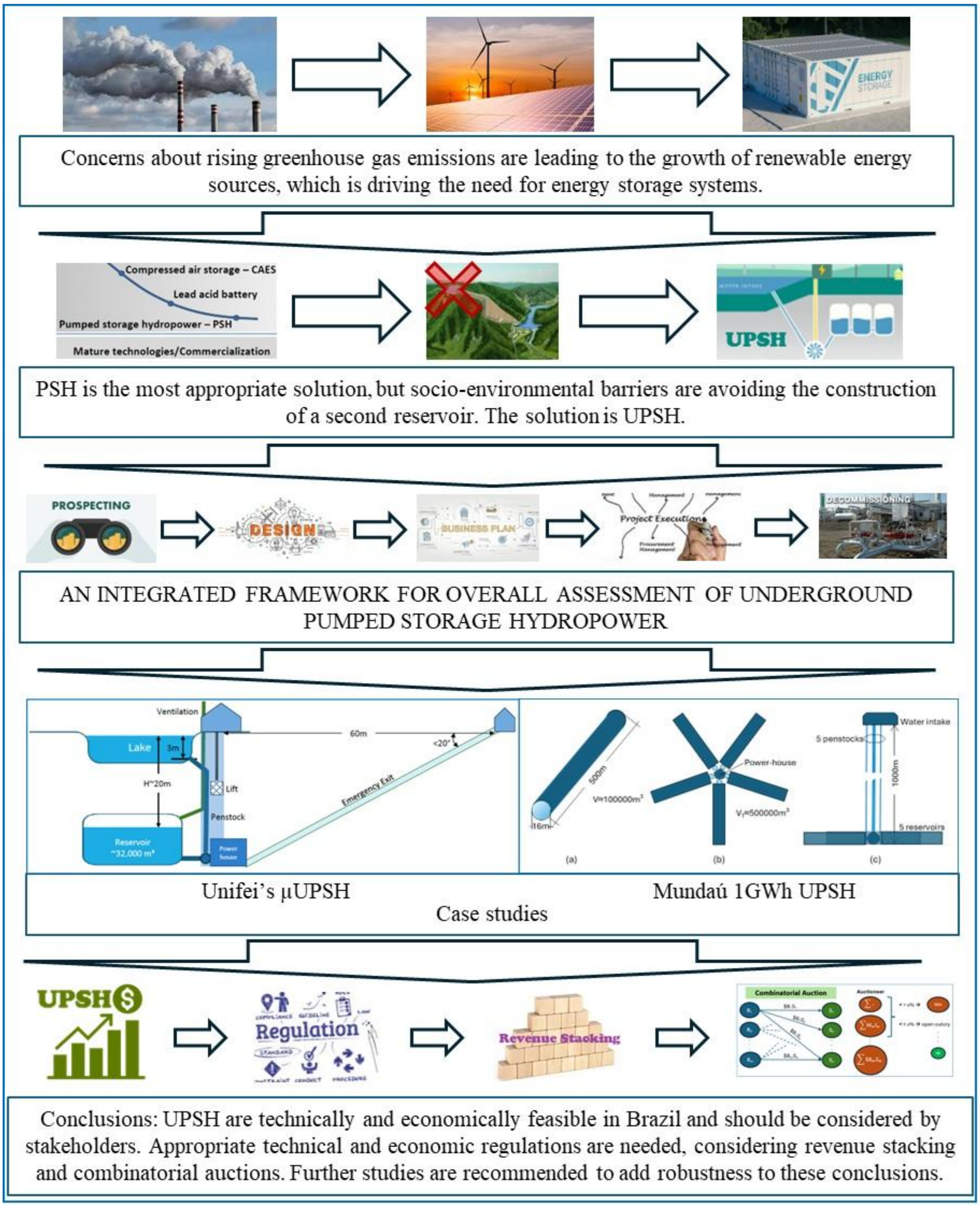


Figure 1.2 – Thesis' graphical summary. The graph has 5 sections: (i) introduction, (ii) the gap, (iii) the main proposal, (iv) case studies, and (v) conclusions.

Chapter 2 – History, literature, legislation, and technical reviews

Storing large amounts of electricity is a scientist community's dream since this kind of energy was discovered. However, it still being not possible, unless it is transformed into another form of energy. Based on this, many types of primary energy storage systems – ESS have been developed. The first one, after fuel storage for thermoelectric power plants, was the Pumped Storage Hydropower system – PSH. These systems have been in use since the ends of 19th century. Underground Pumped Storage Hydropower system – UPSH are more recent research field having few published studies and some projects being carried out. Based on a Systematic Literature Review – SLR, this chapter aims to present the PSH state of the art throughout the world, focused on studies addressed to Brazil, as well as those dedicated to UPSH. The same methodology was applied to identify and catalogue legislation and regulation to be applied in UPSH development. Finally, a history of hydropower technology and a review on hydropower equipment are presented.

2.1 Systematic literature review on PSH and UPSH technologies

Storing water in a high reservoir and then using its potential energy is perhaps the oldest method of energy storage, used for several activities, including powering water wheels. With the advent of electricity, hydroelectric power became a producing means of this form of energy and, the dams storing potential energy for later conversion into electrical energy became vital. The first PSH in Europe was Engeweiher power plant, in Switzerland, commissioned in 1909 (GETH et al., 2015; SUISSE ADMINISTRATION, 2021).

Several PSH were put into operation in the USA and in Europe before the 60s, with the vast majority located in mountainous regions where the construction of double superficial reservoir in different land levels is facilitated. PSH have had an accelerated growth between 1960 and 1980, the so-called PSH Golden Era, following the growth of nuclear power plants (BARBOUR et al., 2016; PICKARD, 2012).

With the fast growth of intermittent energies sources from the 1990's onwards, mainly wind and solar photovoltaic – solar PV, the subject of energy storage returned to the study benches, as in today's world the main objective is to provide clean energy access with clean technologies. However, electricity generated from renewable energy plants is difficult to forecast; therefore, large-scale ESS are required for balancing supply and demand. PSH system is a suitable technology for large-scale applications to cope with intermittency of renewable energy systems due to its plants capability of responding to huge electrical potential load changes in a very short period (KITSIKOUDIS et al., 2020; VAHIDINASAB; HABIBI, 2021).

In general, PSH can benefit the electrical system in several aspects as providing energy balance, energy security, storage capacity, and ancillary grid services like network frequency control and reserves. Although it is an ancient technology, the PSH encounters both environmental and technical problems. Pickard (2012) stated that an obvious solution for natural relief or environmental barriers is the UPSH with excavated underground reservoirs or using abandoned mines or, even, using natural caves. Unlike conventional PSH systems, UPSH plants are not limited by topography and produce low environmental impacts (MENÉNDEZ; FERNÁNDEZ-ORO; LOREDO, 2020).

Brazil has a continental area where there are many decommissioned underground mines and numerous natural caves. The Chico Mendes Institute for Biodiversity Conservation – ICMBio, a national body for environment protection, point that Brazil have cross the mark of 20 thousand mapped caves. The country has vast flat areas with lakes and big rivers, as São Francisco and Amazon. Based on previous statements, Brazil is a strong candidate to use UPSH (ICMBIO, 2021).

To understand the state of the art of previous statements, a well-structured literature research should be done. For this Thesis, it was chosen the SLR methodology.

An SLR should be organized in three stages, as show in Table 2.1: (i) planning, (ii) conducting, and (iii) reporting the research, to evaluate and interpret available studies on specific research questions and finally select the most relevant ones. These three stages are divided into five goals. Planning stage is divided into two objectives: the formulation of research questions and the formulation of strings. The conducting phase is, also, divides in two goals: to find the articles and the selection of interesting ones. The production of a review report is the final stage purpose (KITCHENHAM, 2004).

Table 2.1 – SLR stages and objectives

Systematic Literature Review	
Stage	**Objectives**
Planning	Research questions formulation
	Strings formulation
Conducting	Documents finding
	Documents selection
Reporting	Review report writing

2.1.1 Research questions formulation

The first step in conducting a literature review is to define the Research Questions – RQs to be answered. The RQs should specify the problem or population, the intervention that will be analysed, comparisons, if any, and the intended outcome (GALVÃO; RICARTE, 2019). In this study, firstly it was defined a RQ1 with a large population to discover the overall size of the intervention. From then onwards, in RQ2 up to RQ5, the population and the problem were reduced to the main question to be evaluated: UPSH related studies addressed to Brazil or written by Brazilian authors.

RQ1) What are the main data and characteristics of the literature regarding PSH worldwide?

RQ2) What are the main aspects studied around the world regarding UPSH?

RQ3) What are the main data and characteristics of the literature regarding PSH addressed to Brazil?

RQ4) Are there studies on UPSH dedicated to Brazil or Brazilian researchers addressing UPSH?

RQ5) What are the studies' remarks, and the research frameworks used to explore UPSH in Brazil?

2.1.2 Strings formulation

According to de Doile et al (2021), in the string formulation phase, it is crucial to choose adequate descriptors to make an SLR, addressing the answers for research questions. Four descriptors were defined to answer the five research questions as following:

D1) (“pumped hydro*” OR “pumped storage hydro*” OR “reversible hydro*”);

D2) (“underground pumped hydro*” OR “underground pumped storage hydro*” OR “underground reversible hydro*”);

D3) [(“pumped hydro*” OR “pumped storage hydro*” OR “reversible hydro*”) AND Brazil]; and

D4) [(“underground pumped hydro*” OR “underground pumped storage hydro*” OR “underground reversible hydro*”) AND Brazil]

Descriptors should be present in the title, abstract or keywords of books and article published in journals or international conference proceedings. The following restrictions were included: (i) type of document: “books”, “articles”, or “review”; (ii) language: English or Portuguese; (iii) publication year: no time frame restriction. The D1 descriptor was used to find all general articles covering the topic pumped hydropower, including those using the compound word pumped-hydro and words using the prefix hydro, such as hydroelectric, hydropower, etc. The D2 descriptor limits the search to underground systems and the D3 descriptor focus the large research on Brazil. To conclude, the D4 descriptor is a composition of the three previous descriptors, reducing the research focus on UPSH to Brazil through the key words “underground pumped hydro*”, “underground pumped storage hydro*”, and Brazil. It is noteworthy that all documents in the final sample will also be contained in the first two samples.

2.1.3 Documents finding and selection

The three of the most complete research databases in the engineering field, Scopus – SC, Web of Science – WoS and IEEE Xplore – IEEE platforms, stated by Visser, Van Eck, and Waltman (2019), were chosen for this research. The bibliographic search in such databases was carried out on two occasions. Firstly, at the beginning of the research development, mainly to prove the novelty of the proposed research theme, and then, four years after in the end of the work, to show the growth of studies and to present current data.

In Table 2.2 is presented the results of the first SLR carried out in the second half of 2021. As can be seen, there were no UPSH studies related to Brazil nor written by Brazilian researchers at that time. Some PSH studies dedicated to Brazil were found.

Table 2.2 – General results of the first SLR carried out in 2021. The lack of UPSH studies in Brazil is evident.

Phase	**Search**			**Selection**		
Descriptor	**SC**	**WoS**	**IEEE**	**Duplicated**	**Screened**	**Final Sample**
D1 (PSH all over the world)	1,666	1,179	675	989	0	2,531
D2 (UPSH worldwide)	135	57	12	28	94	82
D3 (PSH in Brazil)	24	10	20	11	20	23
D4 (UPSH in Brazil)	**1**	**0**	**0**	**0**	**1**	**0**

Analyses started by answering the RQ1, “What are the main data and characteristics of the literature regarding PSH worldwide”, to provide an initial and general understanding of this theme. The second SLR with D1 descriptor, carried out in 2025, presents a total of 6,793 documents found, with 3,942 in the SC database, 2,015 in the

WoS database and 836 in the IEEE database. The total sample is 5051, excluding duplicated ones in two or three databases, representing an almost 100% growth over the first SLR, carried out in 2021. The objective of this first sample is to demonstrate the evolution of PSH studies, which is the basis for the main theme of this Thesis: the UPSH. Therefore, it was not screened to separate articles with a superficial approach to the theme or even not well-focused on it.

These results show that there is a great academic interest in the PHS theme with several studies worldwide since the 40s, when Wilson (1948) presented a project for a hybrid irrigation and power generation system, in the Rocky Mountains, in the US state of Colorado, by pumping water from the Granby River dam to Big Lake at the top of Shadow Mountain and, by gravity from there, for irrigation in the Rocky Mountain National Park valley passing through a series of electric generators.

A PSH to meet the peak hours demand was placed in service at Buchanan dam, in the US state of Texas, in 1950. The operation of the plant with 14 MW installed power is detailed and discussed in a paper published in the same year (SCHMITT, 1950).

The first article found related to Europe was published in 1963. The paper is a review of the PSH state of the art in Europe, starting with a history that date back to the beginning of last century. All major pumping stations are listed and the possible arrangements of the machinery, the types of pumps and turbines available that time are assessed. Technical and economic analyses were carried out (HAPPOLDT; HARTMANN; WIEDEMANN, 1963).

Normally, scientific interest follows the technical needs, and this is the reason for the period between the end of 60s and the beginning of 80s to be called the PSH' Golden Era, Figure 2.1 (B). With the fast growth of nuclear power plants, noted in those decades, a complementary source was needed to attend the peak demand, making the PSH more popular worldwide that time (REHMAN; AL-HADHRAMI; ALAM, 2015).

Once again in the history, with the exponential growth of intermittent sources, as wind and solar PV from 2010, the scientific interest in PSH grows following the same pattern, Figure 2.1 (B). From now on, the scientific interest is beginning to include UPSH, mainly due to the socio-environmental problems faced by the need of new reservoirs construction.

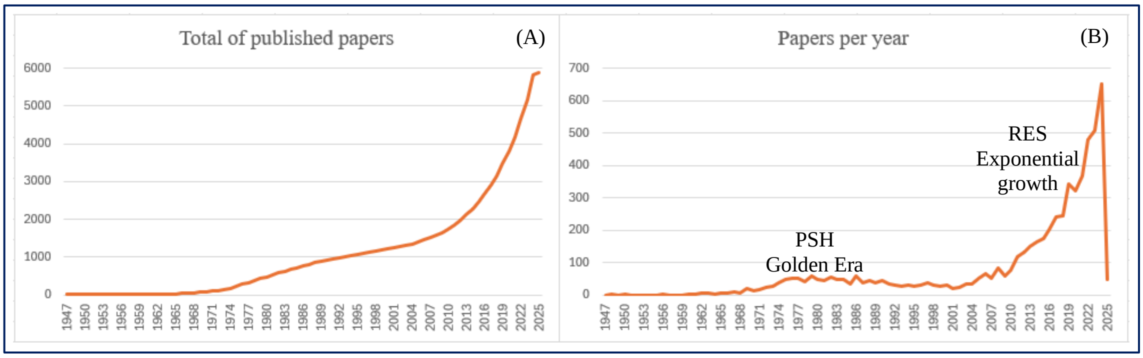


Figure 2.1 – SLR results. (A) presents the annual sum of previously published articles; (B) presents the total number of articles published in each year.

This SLR was focused on articles related to a specific technology named UPSH addressed to Brazil or written by Brazilian researchers. Therefore, two additional keywords set was included at the first descriptor, D1. First, the word underground was included in the D2 descriptor to answer the RQ2, "What are the main aspects studied around the world regarding UPSH", to found articles related to the topic around the world and then compare them with Brazilian papers, if they are found.

The second SLR with D2 descriptor presents a total of 224 documents found, being 150 in the SC database, 62 in the WoS database and 12 in the IEEE database. The total sample is 97, after screening. Duplicate articles and those in which the theme was not focused on UPSH were excluded during screening. The growth of UPSH studies did not follow the same pattern as PSH, as can be seen in Figure 2.2.

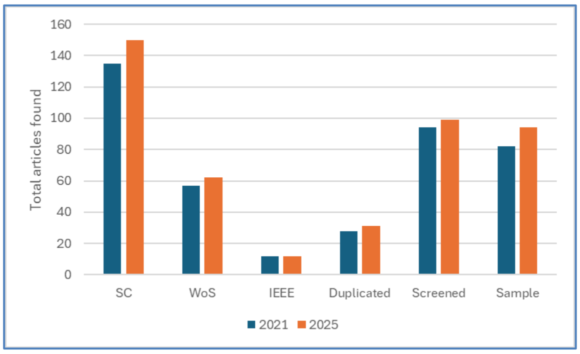


Figure 2.2 – SLR results for D2 descriptor, shown the growth of UPSH studies from 2021 to 2025.

The academic interest in the UPSH technology started in the late 70s with Schulz and Wall (1975) describing plans for an underground pumped storage hydroelectric plant, to be built by Jersey Central Power and Light, in the USA. After that, Allen (1977) studied the potential for conventional and underground pumped-storage in the USA. In 2012, also in the USA, Uddin (2012) have analysed geotechnical issues for underground reservoirs for UPHS. In the same year a review of history, present, and future of underground reservoir for bulky energy storage was published (PICKARD, 2012).

An overview of large-scale underground energy storage technologies for integration of renewable energies and criteria for reservoir identification, published by Portuguese researchers, is the most cited article in this research area. They stated that the use of subsurface for storing energy is based on oil industry experience and motivated by the socio-environmental impacts minimisation when compared to the large surface facilities required to store the same volume of energy (MATOS; CARNEIRO; SILVA, 2019).

Two important studies related to UPSH in Europe were published in 2020. First, Kramer et al. (2020) published a risk mitigation assessment of a UPHS project in the Netherlands. OPAC, Dutch acronym for Underground Pump Accumulation Plant, is an ambitious project with over 1,400 m of excavation depth, 1.4 GW of installed capacity and 8 GWh of energy capacity. Then, Spanish authors wrote a paper to assess the economic viability of UPSH plants providing ancillary services in Spain. The authors concluded that the investment cost of a UPSH plant is reduced by 46.6% when an existing underground infrastructure, such as an abandoned mine, is used as a lower reservoir (MENÉNDEZ; FERNÁNDEZ-ORO; LOREDO, 2020).

Hunt et al. (2023), from Austria, proposed using abandoned mines to store sand instead of water. According to the authors, the electricity production technology from the potential energy of sand is similar to the UPSH and mitigates any risk of contamination of underground water resources, in addition to not requiring a water upper reservoir, making any deactivated mine suitable for this.

Studies published by African authors are mainly technical and economic assessment conducted by Kusakana (2018, 2019b) and Shirinda, Kusakana, and Koko (2018, 2019, 2020) researchers. A study about feasibility of UPHS using abandoned gold mines in South Africa Republic is the first on the topic and the well-cited African article (WINDE; KAISER; ERASMUS, 2017).

Some studies were conducted to examines the feasibility of UPSH at the deep gold mines in the Far West Rand – FWR gold mines in South Africa Republic. Ultra-deep unflooded shafts, large underground reservoirs, and large amounts of water from the upper karst aquifer make the FWR region ideal for UPSH. With a generation capacity of over 1.5 GW per system, UPSH is not only potentially important for local gold mines affected by frequent power outages, but also fills the peak load gap in the country's grid (SHIRINDA; KUSAKANA; KOKO, 2019).

The growth of the renewable energy sector, in addition to UPSH systems, can avoid the high costs of water management for mines after closure, preventing flooding of mining spaces in an ecologically and economically sustainable way. UPSH also provides two of the most important factors for the successful development of cities after mining closure: energy and water. It protects water resources and generates electricity at peak loads. Based on this example, it can be stated that abandoned mines have a great potential for technical feasibility for the installation of UPSH (MENÉNDEZ et al., 2019).

The most recently published study presents an assessment of geological and mining factors that influence the feasibility of converting abandoned coal mines into underground storage reservoirs, focused on European continent. The study explores various reuse scenarios, including the use as a lower reservoir for UPSH plants, among other uses (COLAS et al., 2025).

This literature review allows to identify that around the world most scientific studies focus mainly on analyses and comparisons among diverse energy storage technologies. There are only few studies, less than 2% of the sample, focused on the UPSH. In fact, studies involving underground reservoirs are rare and need urgent academic attention, especially in Brazil as the country presents a great potential for that.

The word Brazil was added to compose D3 descriptor to answer the research question RQ3, “What are the main data and characteristics of the literature regarding PSH addressed to Brazil”. The total of 60 documents were found in the second SLR with D3 descriptor, withing 27 in the SC database, 13 in the WoS database and 20 in the IEEE database. The total sample is 23, after screening. Duplicate articles and those in which the theme was not focused on PSH dedicated to Brazil or written by Brazilian authors were excluded during screening. Results are summarized in Table 2.3.

The first article matching this descriptor was published in 2009, by Barin et el. (2009), in a Brazilian conference, dedicated to selection of storage energy technologies including PSH. Seven years later, it was published a study proposing to supply 100% of Brazilian electricity demand from renewable sources by 2030. To achieve such a goal, at least one GW of PSH would be needed, according to authors (BARBOSA et al., 2016).

A dedicated microgrid planning and operation approach for distribution network support considering PSH, and an integer programming problem for PSH siting that uses a digital elevation model to meet an energy storage requirement are addressed to Brazil.

Both are general studies that can be applied all over the world, however, the second one presents a Brazilian real case to illustrate the proposed methodology (ADEYANJU; SIANO; CANHA, 2022; ANDRADE et al., 2022).

Mensah *et all.* (2022) published an energy and economic study of using PSH with renewable resources to recover the Furnas reservoir, a big hydroelectric dam located in south-eastern region of Brazil. Authors have studied three scenarios and concluded that two of them are economically feasible with positive Net Present Value – NPV and, could recover around 0.5 m of Furnas' Lake level per year.

The last two paper related to PSH and dedicated to Brazil were published both in 2024. The first presents a proposal for the transformation of mining-degraded areas into renewable energy installations, converting deactivated mine pits, in the Quadrilátero Ferrífero region in state of Minas Gerais, into reservoirs for PSH. The second article introduces the PSH as responding to climate change impacts on the Brazilian electrical sector. The study presents an approach by developing an energy system model that optimizes PSH technology, considering the seasonal variability of renewable sources across three climate change scenarios (WEBER et al., 2024; GUIMARÃES et al., 2024).

Finally, D4 descriptor considers UPSH and Brazil to answer RQ4, "Are Brazilian researchers addressing UPSH" and RQ5, "What are the studies' remarks, and the research frameworks used to explore UPSH in Brazil". Three articles focused on Brazil containing the acronym UPSH were found. The first one, published in 2020, is not focused on UPSH, even though it dedicates a page to the subject. The second is a 2024 conference paper based on Chapter 4 of this Thesis, and the latest is an early access paper, not peer-reviewed as of the end of this work, based on Chapter 5 of this Thesis (VILANOVA; FLORES; BALESTIERI, 2020; DE DOILE; BALESTRASSI; ZAMBRONI DE SOUZA, 2024; DE DOILE et al., 2025).

Brazilian authors Vilanova, Flores, and Balestieri (2020) published a PHS literature review in 2020. The authors use the expression "pumped hydro storage plants" and the acronym PHS to refer pumped-hydro technology in general. They have dedicated a paragraph to stated that UPSH should be widely studied, since this technology can solve socio-environmental issues related to conventional reversible hydroelectric plants, among others. The results of the second SLR for descriptors D1 to D4 are summarized in Table 2.3. As the D1 descriptor is present in all other descriptors, articles in subsequent samples are also in the previous ones.

Table 2.3 – General results of the second SLR carried out in 2025. The lack of UPSH studies in Brazil is still present.

Phase	Search			Selection		
Descriptor	**SC**	**WoS**	**IEEE**	**Duplicated**	**Screened**	**Final Sample**
D1 (PSH all over the world)	3,942	2,015	836	1,742	0	5,051
D2 (UPSH worldwide)	150	62	12	31	99	94
D3 (PSH in Brazil)	27	13	20	14	23	23
D4 (UPSH in Brazil)	**1**	**1**	**1**	**0**	**3**	**0**

This final result demonstrates a literature gap in the area of UPSH in Brazil that deserves to be carefully studied right away, as the Brazilian potential for underground storage has already aroused the interest of foreign researchers such as Hunt et al. that published at least four articles on the theme since 2014. (HUNT et al., 2020, 2023; HUNT; FREITAS; PEREIRA JUNIOR, 2017, 2014).

Additionally, UPSH technology can appropriate of abandoned mines avoiding possible environmental issues as happen in the Brazilian northeastern region, where the ground is sinking due to the collapse of abandoned rock-salt mines (BRASIL, 2023; VASSILEVA et al., 2021).

2.2 Systematic review on legislation and regulation

As mentioned before, there is no specific legislation neither regulation for PSH and UPSH in Brazil, issued until 2024, which is the main limitation in the search for specific legislation and regulation. In this section, research on legislation and regulations that can be applied to PSH and UPSH by similarity is carried out based on SLR methodology. Four legislation bases, to cover all involved areas in the theme, were chosen to carry out this research: (i) National Electric Energy Agency; (ii) National Mining Agency; (iii) Brazilian Government; (iv) Brazilian environmental body (ANEEL, 2025b; ANM, 2025; BRASIL, 2025; IBAMA, 2025).

2.2.1 Research questions formulation

To be as comprehensively as possible, the following research questions were formulated:

RQ1) Is there legislation or regulation in force for PSH or UPSH in Brazil?

RQ2) With legislation or regulation in force for hydropower could be applied to PSH or UPSH?

RQ3) With other legislation or regulation in force could be applied to PSH or UPSH?

RQ4) With legislation or regulation in force for underground mining could be applied to UPSH?

2.2.2 Strings formulation

As legal documents are issued in local language, Portuguese was used to find documents in the Brazilian legislation bases. PSH in Brazil is called "usina reversível", meaning reversible power plant. UHE, PCH, and CGH are Portuguese acronyms for hydropower depending on their size and installed power. Four descriptors were defined to answer the four research questions as following:

D1) ("hidr* bombeada" OR "armazenamento bombeado" OR "usina reversível" OR "hidr* bombeada subterrânea" OR "armazenamento bombeado subterrâneo" OR "usina reversível subterrânea");

D2) (hidrelétrica OR hidroelétrica OR UHE OR PCH OR CGH);

D3) [(conexão AND rede) OR (licenc* AND ambient* AND energia)];

D4) ("min* subterrânea" OR "min* profunda")

Hydropower are called by their acronyms in several documents: UHE meaning hydropower over 30 MW installed power; PCH small hydropower, 30 MW and below; and CGH very small hydropower, less than 5 MW of power. Descriptors should be present in any part of documents. Documents should be in force in 2025.

A search for "hidr* bombeada" or "armazenamento bombeado" or "usina reversível" or "hidr* bombeada subterrânea" or "armazenamento bombeado subterrâneo" or "usina reversível subterrânea" was carried out by D1 descriptor to confirm that there is no legislation neither regulation in force about PHS or UPSH in Brazil.

D2 descriptor limits the search to documents related to hydropower and the D3 descriptor searches for documents related to activities need for electric energy production, as grid connection, permissions and licensing. Finally, the D4 descriptor searches for mining regulations, especially those related to underground mines and deep mines, with possible application by similarity in UPSH.

2.2.3 Documents found and selection

The search was carried out in the beginning of 2025 and as expected, no one document related to PSH or UPSH was found by D1 descriptor. In other hand, D2 descriptor searched for hydroelectric energy in two Portuguese spelling formats, hidrelétrica and hidroelétrica, or its acronyms UHE or PCH or CGH allowing to find several legislation and regulations for hydropower. Such documentation was assessed and only that possible to use by similarity with UPSH was considered and detailed in Table 2.4.

Table 2.4 – Documents related to hydropower found by D2 descriptor.

Document	Number	Year	Summary
National Law	9,074	1995	Establishes rules for granting of concessions and permissions for public services, including hydropower.
National Law Water Resources Law	9,433	1997	Establishes the national water resources policy, creates the national water resources management system.
REN ANEEL	875	2020	General regulation for hydropower.
REN ANEEL	957	2021	Establishes the Electric Energy Trading Convention and creates the CCEE.
REN ANEEL	1,030	2022	Regulates, among others, the provision and payment for ancillary services provided by hydropower.
REN ANEEL	1,080	2023	Approves the electricity trading rules to be adopted by the CCEE.

The Brazilian general regulation for hydropower is in the Normative Resolution – REN nº 875. Based on national Law nº 9,074, the resolution defines the classification by the installed power, the kind of granting, and how to study and register a power plant at National Electric Energy Agency – ANEEL. The law also created the figure of the Independent Energy Producer – PIE, which can sell energy freely in both regulated and unregulated markets. Power plants dispatched by the National Electrical System Operator – ONS must provide ancillary services, when requested by the Operator, according to REN nº 1,030 (ANEEL, 2020, 2022a; BRASIL, 1995a).

The Water Resources Law establishes the National Water Resources Policy and creates the National Water Resources Management System. The first one establishes criteria and priorities for the rational use of water resources, how they are classified and when is need a grant for private exploitation. The latter aims to coordinate and monitor actions to comply with the National Water Resources Policy (BRASIL, 1997).

The energy trading rules, proposed by Electrical Energy Trading Chamber – CCEE and approved by REN nº 1,080, as well as the energy trading procedures, deal with the trading of electrical energy produced by all existing sources in the country. However, since hydroelectric power is responsible for most of the energy produced in Brazil, these rules and procedures consider the peculiarities of this energy source. REN nº 957 establishes a convention for electrical energy trading and creates the CCEE. This convention provides, among other things, that electric power plants with installed capacity of 30 MW or more must be associated with the CCEE, as well as small-scale power plants that intend to sell energy in the Regulated Contracting Environment – ACR (ANEEL, 2021a, 2023a; CCEE, 2024a, 2024b).

Possible legislation to use in UPSH from other areas, found through D3 descriptor, are listed in Table 2.5. The search through D3 descriptor allowed to find documents containing the strings (conexão and rede) or (licenc* and ambient* and energia) meaning (connection and grid or network) or (all words beginning with licens* and environment* and energy). Most of the documents are related to environmental aspects and, subsequently, to grid connection and concession grant rules.

Table 2.5 – General documents that can be applied to UPSH found by D3 descriptor.

	Document	Number	Year	Summary
Environmental licencing legislation and regulation	National Decree	73,030	1973	Creates the Special Secretariat for the Environment
	National Law	6,938	1981	Provides for the National Environmental Policy
	CONAMA Resolution	001	1986	Provides basic criteria and general guidelines for the environmental impact assessment
	CONAMA Resolution	006	1987	Provides for the environmental licensing of works in the electricity generation and transmission sectors.
	CONAMA Resolution	237	1997	Establishes criteria, types, power to issue, and deadlines for environmental licensing.
	CONAMA Resolution	279	2001	Disciplines the simplified environmental licensing process.
	Complementary Law	140	2011	Establishes rules for cooperation between the Union, states, and municipalities governments in administrative actions related to the National Environmental Policy.
	National Decree	8,437	2015	Regulates the provisions of nº 140 to establish which enterprises must be licensed by the Union.
	[1] MG State Law	21,972	2016	Provides for the State Environmental and Water Resources System of Minas Gerais State.
	[1] MG State Decree	47,383	2018	Establishes, among other things, standards for environmental licensing in Minas Gerais State.
	[1] Itajubá Municipal Law	3,353	2019	Disciplines the land use and provide for ventures that must be licenced by the municipality of Itajubá
	IBAMA Ordinance	924	2021	Establishes the environmental licencing standard operational procedure.
	National Decree	10,935	2022	Regulates the use of natural caves.
Grant, connections, and procedures	National Law Granting Law	8,987	1995	Provides for the concession and permission regime for the provision of public services.
	REN ANEEL	1,000	2021	Establishes the rules for providing public electricity distribution services, The Distribution Procedures.
	National Law DG Law	14.300	2022	Establishes the legal framework for distributed generation and the Electric Energy Compensation System – SCEE.
	REN ANEEL	1,059	2023	Amends REN nº 1,000 to, among others, allow the installation of energy storage equipment in DG.
	REN ANEEL	1,071	2023	Regulates the authorization and registration processes of power plants up to 50 MW installed power.
	Distribution Procedures	Module 3	2021	Rules issued by ANEEL for new facilities integration in the distribution grid.
	Grid Procedures	Module 7	2023	Rules issued by ONS for new facilities integration in the National Interconnected System – SIN.
	[2] DG Handbook		2024	Cemig's Distributed Generation Handbook

Trade	National Energy Trading Law	10.848	2004	Establishes rules for commercialization of electrical energy, created the free and the regulated energy markets.

[1]. All of 27 Brazilian states have their own environmental legislation, as well as most of the 5,568 municipalities.
[2]. The 131 Brazilian Distribution Companies – DISCOs have their own distributed generation rules.

The environmental protection policy movements have been prominent worldwide since the 60s and 70s. In Brazil, there was no legal requirement regarding environmental control of potentially polluting activities until the issuance of Decree nº 73,030 in October 1973, which created the Special Secretariat for the Environment – SEMA, whose role was to propose standards against pollution, giving rise to the so-called Brazilian Environmental Right (TONIDANDEL; PARIZZI; LIMA, 2012).

However, the foundations that define environmental protection in Brazil were only established in 1981 with the publication of Law nº. 6,938, which instituted the National Environmental Policy – PNMA, whose main objective is to reconcile economic and social development with the preservation of environmental quality and ecological balance. This law provides for rights and duties, among which the following stand out: the establishment of environmental quality standards, environmental zoning, environmental impact assessment, environmental licensing and review of effective or environmentally polluting activities, as well as the obligation to repair environmental damage.

The 6,938 Law also provides that the bodies and entities of the Union, states and municipalities, as well as the foundations established by the Government, responsible for the protection and improvement of the environment quality, will constitute the National Environmental System – SISNAMA. The National Environmental Council – CONAMA, a body of SISNAMA, has the purpose of advising, studying and proposing guidelines for government policies for the environment and natural resources and deliberating on norms and standards compatible with an ecologically balanced environment (BRASIL, 1981).

The Environmental Impact Study – EIA and its minimum content are defined by CONAMA Resolution nº 01, and it is up to the state and municipal licensing agencies to establish their own criteria, given the peculiarities of each federative entity, as long as criteria established in the federal norm are respected. In other hand, the CONAMA Resolution nº 06 deals with environmental licensing for works in hydroelectric and thermoelectric plants and transmission lines, establishing additional content to that one provided for in Resolution nº 01 for the EIA (CONAMA, 1986, 1987).

The use of Standard Operating Procedure nº 1, which constitutes the Term of Reference – TR structure to prepare the EIA and the respective Environmental Impact

Report – Rima, for the environmental licensing is regulated by IBAMA Ordinance nº 924 (IBAMA, 2021).

CONAMA Resolution nº 237 provides for the procedures and criteria for environmental licensing, establishing the license types: Preliminary License – LP, Installation License – LI, and Operating License – LO; the government bodies powers to issue them; deadlines for issuance and which economic activities must be licensed. Conversely, CONAMA Resolution nº 279 provides for simplified environmental licensing, applied to electrical projects with a small potential for environmental impact. Such projects must present a Simplified Environmental Report – RAS, with the minimum content set forth in this Resolution, and the deadlines are shorter than those of the ordinary procedure (CONAMA, 1997, 2001).

Complementary Law nº 140 establishes, among other rules, which projects must be environmentally licensed by the Union, states and municipalities. The National Decree nº 8,437 regulates the 140 Law and, among other things, establishes that hydroelectric plants with a capacity equal to or greater than 300 megawatts must request environmental licenses from the Union, even if located in a single state or municipality (BRASIL, 2011, 2015).

The state of Minas Gerais was chosen to represent all of 27 Brazilian states, as it has one of the most complex legal frameworks for regulating activities with potential environmental impact. This framework began with the creation of the State Council for Environmental Policy – COPAM, in the 70s, and several other government bodies and entities over the years. Through State Law nº 21,972/2016 the State System of Environment and Water Resources – SISEMA – was stablished. Such a system is the set of government bodies and entities responsible for environmental and water resources policies, with the purpose of conserving, preserving and recovering environmental resources and promoting sustainable development and improving the environmental quality of the Minas Gerais State (MINAS GERAIS, 1977, 2016).

The SISEMA is made up of (i) the State Secretariat for the Environment and Sustainable Development – SEMAD , which will coordinate it; (ii) the State Council for Environmental Policy – COPAM; (iii) the State Council for Water Resources – CERH-MG; (iv) the State Environmental Foundation – FEAM; (v) the State Forestry Institute – IEF; (vi) the Minas Gerais Water Management Institute – IGAM; (vii) the Minas Gerais Military Police – PMMG; (viii) the environmental management centres of the other State

Secretariats; (ix) the river basin committees; and (x) the river basin agencies and entities equivalent to them. All these government entities have different responsibilities depending on various characteristics of the projects. In terms of environmental licenses, State Decree nº 47,383 establishes that it is up to COPAM and SEMAD to analyse and decide on requests for environmental licensing, hearing the other bodies within their respective competences (MINAS GERAIS, 2018).

Itajubá, home of Unifei, was chosen to represent all Brazilian municipalities. According to Municipal Secretariat for the Environment – SEMMA of the municipality, the general environmental licensing procedures are similar to those of the State of Minas Gerais, especially those relating to licensing modalities, types of studies required, public consultation and applicable exemptions. In addition to the ventures whose licensing is delegated to the municipality by National Complementary Law nº 140 and the State of Minas Gerais, through COPAM resolutions, the Municipal Law nº 3,353/2019 defines other activities that must be licensed by SEMMA (ITAJUBA, 2019, 2024).

Natural caves are potential candidates for the implementation of UPSH. However, environmental legislation makes this almost impossible. Even with the provision that activities considered effectively or potentially polluting or degrading natural underground cavities and their area of influence will depend on prior licensing, the National Decree nº 10,935 establishes that natural underground cavities must be protected to allow, as a priority, scientific studies and research and activities of a speleological, ethnic-cultural, touristic, recreational and educational nature (BRASIL, 2022a).

Additional environmental regulation can be found at National Environmental Licensing Portal – PNLA, that is a tool made available by the Ministry of the Environment – MMA to disseminate information related to environmental licensing procedures (MMA, 2024).

The Grants Law (Law nº 8,987) provides for public service granting regimes: (i) the concession is the strongest regime delegated through bidding; (ii) and the permission regime for the provision of public services, that is formalized through an adhesion contract, which can be unilaterally revoked by the granting authority. This 8,987 Law also provides for service adequacy, user rights and duties, tariff policy, bidding rules, and contracts (BRASIL, 1995b).

Through REN nº 1,059, issued in the beginning of 2023, the previous resolution for Distributed Generation, REN nº 482/2012, was revoked. The new rules for Distributed Generation – DG were included into the REN nº 1,000, the general rules for distribution services. The Energy Storage Systems – ESS installed in DG systems, permitted since 2022 by DG Law nº 14,300, were finally regulated by ANEEL, being the main novelty brought by REN 1,059 (ANEEL, 2023b; BRASIL, 2022b).

The REN nº 1,071 establishes the requirements and procedures necessary to obtain authorization for power plants, except hydropower, between 5 and 50 MW installed power and communication of the implementation of generating plants with reduced capacity, up to 5 MW (ANEEL, 2023c).

The regulation for grid connection at the National Interconnected System – SIN is in the Module 7 of Grid Procedures, the national grid code issued by national operator of the electrical system – ONS. The SIN is composed by generators from 30 MW installed power and by the transmission system of 230 kV and above (ONS, 2024a).

The connection to the distribution grid, below 230 kV, is regulated by Module 3 of Distribution Procedures – PRODIST, issued by ANEEL, and by each of 131 Distribution Companies – DISCO procedures, like the Distributed Generation Handbook, issued by Energetic Company of Minas Gerais State – Cemig (ANEEL, 2021b; CEMIG, 2024).

The Free Contracting Environment – ACL and the Regulated Contracting Environment – ACR were created by Law nº 10,848, the Energy Trade Law. In the ACR are the DISCO and their captive consumers. In such an environment, energy purchase is made through public auctions held by the CCEE. In other hand, free consumer can buy energy directly from the producer or through a trade company in the ACL (BRASIL, 2004).

Legislation applied to mining and possible to use by similarity in UPSH are presented in Table 2.6. Such documents were found by the D4 descriptor, where documents contain the words “min* subterrânea” or “min* profunda”, meaning "underground min*” or “deep min*" were searched.

Table 2.6 – Documents for mining that can be applied to UPSH found by D4 descriptor.

Document	Number	Year	Summary
DNPM Ordinance	237	2001	Approves the Mining Regulatory Standards – NRM 01 up to NRM 22.
NRM	01	2001	General rules for mining
NRM	04	2021	Provides for underground openings
NRM	05	2001	Provides for support systems and treatments

NRM	06	2001	Provides for mines ventilation
NRM	07	2001	Provides for emergency routes and exits
NRM	08	2001	Provides for the prevention of fires, explosions, gases and floods
NRM	11	2001	Provides for mining sites lighting
NRM	20	2001	Provides for the suspension, closure of mine and resumption of mining operations
NRM	21	2001	Provides for the rehabilitation of researched, mined and impacted areas
ANM Resolution	68	2021	Provides rules regarding the Mine Closure Plan – PFM

The Ordinance nº 237, issued by the National Department of Mineral Production – DNPM in 2001 is the first specific act to regulate mining activities. Such an ordinance created 22 Mining Regulatory Standards – NRM, some of them useful by similarity in UPSH. The NRM nº 01 provides for general rules of mining activities, among them the rights and duties of mining entrepreneurs and mining workers (DNPM, 2001).

The rules for underground opening are provided for in NRM nº 04. The standard provides, among others, that each level of an underground mine must have at least two accesses, adequately separated, observing the technical conditions essential to the safety and stability of the opening, as well as the safety and health conditions of workers.

The NRM nº 05 provides for support and treatment systems of underground openings, that must be assessed and suitably treated or supported according to their hydro-geo-mechanical characteristics and intended purposes. While NRM nº 06 provides for rules and minimum requirements for mine ventilation.

Active underground mines must have at least two access routes to the surface, a main route and an emergency route, separated from each other and connected by secondary routes so that the interruption of one of them does not affect traffic on the other, according to NRM nº 07. The norm also provides rules for the use and maintenance of the mines exits.

NRM nº 08 establishes rules for signalling, equipment installation, and worker behaviour to prevent fires, explosions, gas production or leakage, and flooding inside of underground mines. NRM nº 11 states that a fixed lighting system is mandatory in underground mines, establishing the minimum levels of lighting. Finally, NRM nº 20 provides rules for the mine closure and NRM nº 21 provides for rehabilitation of impacted areas.

These rules remain valid even after the extinction of the DNPM and the creation of the National Mining Agency – ANM in 2017. However, items 20.4 and 20.5 of NRM nº 20 which provided for the definitive closure of mines were revoked by ANM Resolution nº 68 in 2021. The resolution 68 created the Mine Closure Plan – PFM to replace the NRM 20.4 and 20.5 (ANM, 2021).

From this brief excerpt of the laws and regulations applicable by similarity to UPSH, it can be stated that Brazilian legislation and regulations are abundant, which makes it difficult for lay people to interpret this legal framework. It is expected that the legislation and regulation of energy storage, when issued, will also be complete and comprehensive.

2.3 PSH and UPSH technologies

The water potential energy is probably one of the humanity's first sources of mechanical energy. There is clear evidence that the wooden paddles waterwheels were already used in the ancient Roman, Egyptian, and Greek empires by the first millennium BC. The use of a waterwheel coupled to an electrical generator began in the late 19th century in the USA and Europe, thanks to mastery of the iron usage (BREEZE, 2018).

The hydropower, as seen nowadays, was born in 1820's by the French engineer Benoît Fourneyron. In 1881 Niagara Falls Hydropower, using a Fourneyron turbine, was commissioned being the first one operating in the USA (BLALOCK; WOODWORTH, 2008).

With the largest generation park today, China put into operation its first hydroelectric plant, located at Shilongba, only in 1912 (DE DOILE, 2018; GHOSH, 2022).

During the 1910's, four large hydropower were commissioned in Brazilian states of São Paulo and Rio de Janeiro, introducing Brazil to the large power plants era (SAES, 2013).

2.3.1 Pumped storage hydropower systems

PSH is a technology that can be used from small to large energy volume, short to long storage period, high efficiency, and low capital cost per unit of energy. Such a technology is based on the use of two water reservoirs located at different land levels, Figure 2.3: the upper reservoir and the lower reservoir separated by a suitable level for power generation, the waterhead, represented by the H factor in the general power equation for hydroelectric plants, Equation 2.1 (BROCKSCHINK; GURNEY; SEELY, 2001).

$$P = \eta g \rho Q H \quad (2.1)$$

where P is the produced power in [W]; η is the dimensionless power station efficiency; g is the earth gravity constant in [m/s²]; ρ is the specific mass of water in [kg/m³], Q is the water flow through the turbine in [m^3/s], given by Equation 2.2; and H the water level difference (waterhead) between upper reservoir and the turbine in [m].

$$Q = V t^{-1} \quad (2.2)$$

where V is the available volume of water in cubic meters and t is the time in seconds.

Firsts PSH used to have two separate systems: a turbine-generator set, and a motor-pump set. This arrangement is still being used to adapt an existing hydropower without change the original turbine-generator set. Nowadays, the concept of reversible power plants with a single motor-generator and pump-turbine set is widely used. In this case, to adapt an existing hydroelectric plant, the existing machine set should be adapted or even changed in some cases.

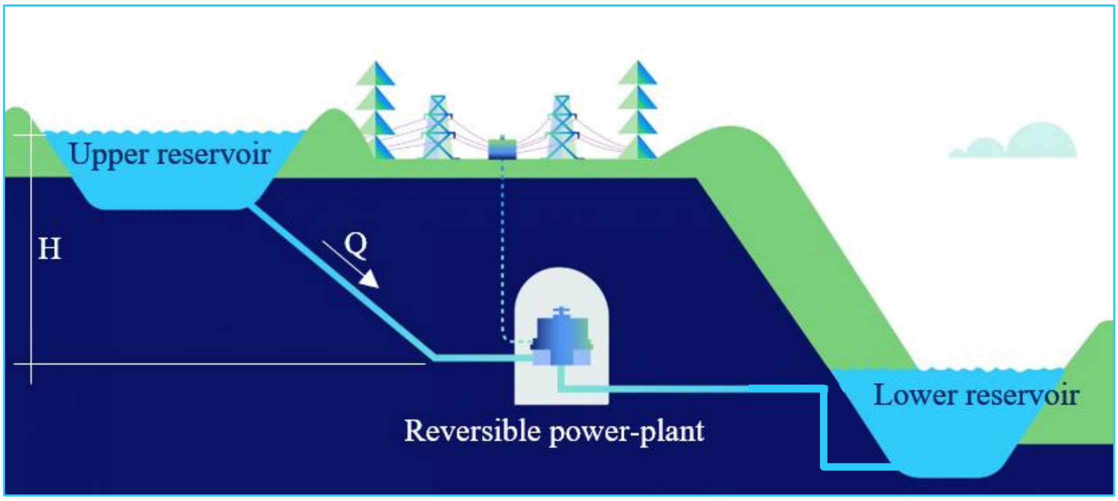


Figure 2.3 – Standard schematic of a PSH. When there is power excess on the grid, the power is used to pump water from the lower to the upper reservoir using reversible machine as a water-pump. When demand is high, the water is down released into the lower reservoir, through reversible machine now working as a turbine.

PSH technology was born shortly after conventional hydroelectric power plants. The Engeweiher PSH, in Switzerland, was the first one implemented and still being in operation since 1909. However, firstly PSH were used for water management rather than supporting power generation. Brazil was the world pioneer using reversible PSH for both reasons, electricity generation and flood control (DE DOILE et al., 2022; PECZKIS, 2021).

A large-scale project was planned in late 1930's, involving several installations on the Tiete and Pinheiros rivers to integrate a complex system of dams and hydroelectric plants, ensuring the domain of water and electricity in the São Paulo metropolis, as shown in Figure 2.4. In operation since 1940, the Traição pumping plant had the objective of partially reversing the course of the waters of Pinheiros and Tiete rivers, to be sent to Pedreira pumping plant, the world first reversible plant operating since 1939, and then to Billings reservoir, a dam serving the Henry Borden hydropower (EMAE, 2023).

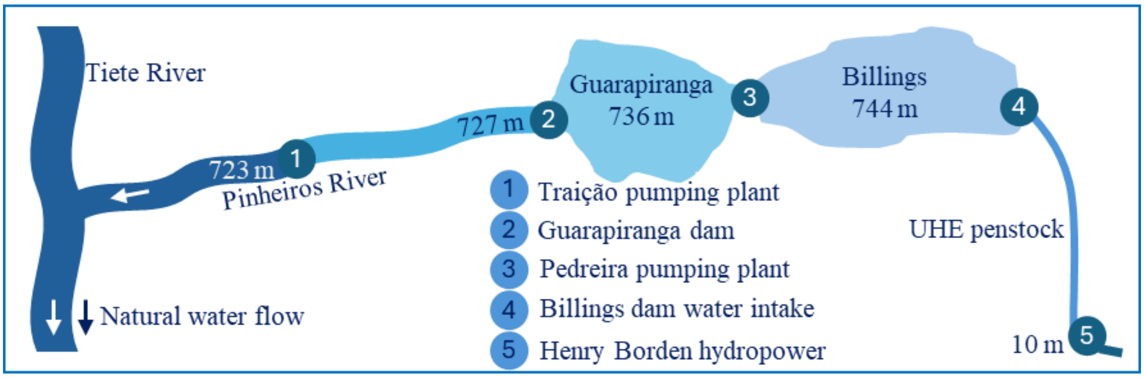


Figure 2.4 – Traição-Pedreira pumping system. Traição (1), 727 m above mean sea level, pumps to Guarapiranga reservoir and, then Pedreira (3) pumps to Billing reservoir, 744 m amsl, that serves Henry Borden hydropower (5). Henry Borden is an 889 MW power-plant with a waterhead over 700 m. Guarapiranga and Billings also serve as drinking water reservoirs for the São Paulo metropolis.

In the 1950s, a similar pumping system was built in the state of Rio de Janeiro. Santa Cecília power plant on the Paraíba do Sul River and Vigário power plant on the Piraí River Figure 2.5. Both, Traição-Pedreira and Santa Cecília-Vigário systems, that were designed to maximize electricity production, are nowadays being used only for water management due to environmental issues (EPE, 2021).

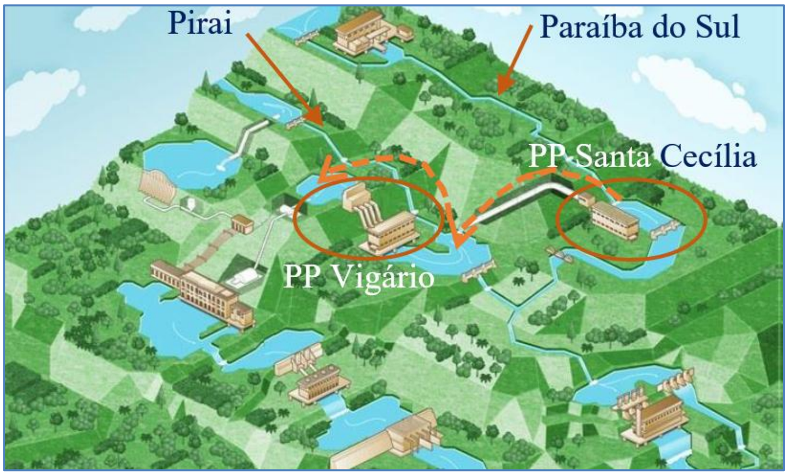


Figure 2.5 – Santa Cecília-Vigário pumping system. Santa Cecília pumps to Vigário lower reservoir and, then Vigário pumps to its upper reservoir, that serves 5 hydro-powers in cascade.

The wide use of PSH to support for electricity generation started with the growth of nuclear power plants in the 1970's and 1980's. Such a time was known as the PSH'

Golden Era. Nuclear plants operate at baseline with constant generation, while PSH adjust the load, generating in peak periods and storing in out-of-peak periods.

Plants can be categorized based on different criteria such as storage capacity, pump-turbine rotation speed, storage need, and arrangements. The services to be provided by a PSH depend on its reservoir size, that can vary from 0.001 hm^3 up to 100 hm^3. PSH and UPSH are classified according to the service and size in five categories: (i) hourly, (ii) daily, (iii) weekly, (iv) seasonal, and (v) pluriannual. Small reservoirs are mainly used to provide ancillary services such as frequency balancing, harmonic removal, backup power in case of minor disturbances. These **hourly** systems should operate in short periods and can do several reversals per day (HUNT et al., 2020).

The most frequent PSH application are **daily** systems to day-night energy arbitrage, being the second size of reservoir. The third size is used in **weekly** mode storing energy from intermittent sources as wind and solar PV. Big reservoirs can provide all previous described services and, also, can be used for **seasonal** and **pluriannual** storage systems. However, they are not widely used yet (NIKOLAOS; MARIOS; DIMITRIS, 2023).

2.3.2 Underground pumped storage hydropower systems

The main difference between a PSH and an UPSH is related to civil structures. Based on this, the entire project must be optimized to reduce costs in reservoirs construction or adaptation, when natural cavities or other decommissioned ventures are used, such as deep mines. Both the upper and lower reservoirs may be constructed by excavation; however, it is customary to use an existing structure for at least one of them.

The ideal situation for an UPSH is the presence of a water body close to an abandoned mine or natural cave, avoiding excavation costs, Figure 2.6 (A). However, in some cases, a mineral may have multiple mineable seams, and certain abandoned mines have two or more free underground spaces at different levels. This situation makes possible the construction of both upper and lower reservoirs underground, Figure 2.6 (B).

The UPSH exploitation has already started in China where several coal mines were or are being decommissioned. Other countries with large mine activities as the USA and South Africa are studying their respective potential, as presented in the subsection 2.1.3 (YANG et al., 2023).

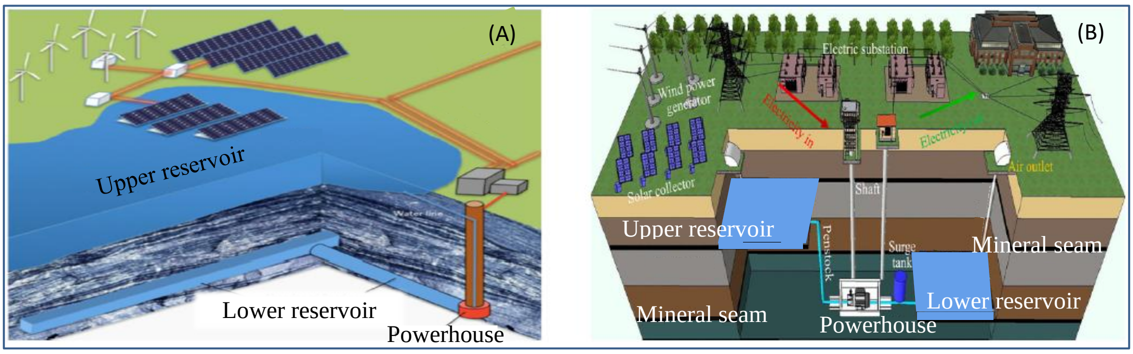


Figure 2.6 – UPSH layout for abandoned mines. A) There is a surface water body close to the abandoned mine; B) The abandoned mine has exploited two mineral seams at different levels, making possible the two underground reservoirs.

2.3.3 *Brazilian potential for UPSH*

As a continental country, Brazil has thousands of water bodies such as rivers, lakes, and dams. According to National Information System on Dam Safety – SNISB, in its Portuguese acronym, there was 24,467 registered dams in the country by 2023, from the smallest ones with 0.001 hm^3 to the Sobradinho dam, the largest one with 34,116 hm^3. Itaipu reservoir has a volume of 29,000 hm^3. Even with many of them being run-of-river dams, they represent a great potential for PSH and UPSH. (ANA, 2023; SNISB, 2023).

The country has more than 10,000 registered mineral exploration sites. Of these, only 1.4% correspond to the extraction of valuable minerals such as gold, copper, aluminium, uranium, and coal, the so-called mineral commodities. Many of them are open pit mines, that should be studied on a case-by-case basis for PSH applications. However, there are dozens underground mines, some of them out of operation, available for UPSH studies. According to ANM, there were 92 deep underground mines in operation in 2022 and 4 at a standstill operation. These mines are mainly coal mines in the south region, gold mines in the southeast region, copper and potash mines in the northeast region, and some others scattered throughout the country (ANM, 2024; MELFI et al., 2016).

A single coal mine may have several "mine-mouths", as stated by Krebs *et al.* (2010). A mine-mouth can be the main entrance, or a shaft used for ventilation or electrical cable entry and many other accesses to the mine. The authors found hundreds of them in abandoned mines in the coal region of Santa Catarina state. These abandoned mines cause several environmental problems such as acid drainage, which can contaminate the waters of rivers and underground aquifers. As shown in the paper, many mine-mouths are close to water bodies, making them potential for UPSH enterprises.

Brazil also has 23,378 natural caves registered at Chico Mendes Institute for Biodiversity Conservation – ICMBio, the national body for environmental reserves administration. Natural caves are environmental areas protected by Brazilian laws; therefore, it is extremely difficult to develop other commercial activities in them besides scientific research or tourism. Due to such environmental issues, natural caves should not be studied while other options for UPSH exist (CECAV, 2022).

According to ONS, the Brazilian electrical system operator, there are more than 70 hydroelectric reservoirs. These dans with reservoir capacity should be studied to PSH or UPSH ventures in future works. Urban lakes may be another alternative to be studied, as well as abandoned underground coal and gold mines and, especially, the rock-salt abandoned mines in Alagoas state. These abandoned rock-salt mines, located next to a very large lake, have not been decommissioned properly and are collapsing, causing the ground to sink in an urban area (ONS, 2023; VASSILEVA et al., 2021).

2.3.4 PSH pump-turbines

The turbine is one of the main hydropower elements converting the water energy into mechanical rotational energy, that is used to drive a generator to produce electricity. The most common hydro turbines are Francis, Pelton, Deriaz, Kaplan and others propeller turbines. They can be split into reaction turbines and impulse turbines and, also, by the waterhead height that each one operates with greater efficiency (BREEZE, 2018).

A reaction turbine works from the potential energy of water pressure, the water mass itself, and kinetic energy of moving water, both combined. The water flows over the blades or paddles rather than striking each one individually. Among this kind of turbine, Kaplan and other propellers are generally used for sites with lower head and higher flows, and the Francis turbine for sites with medium and high head. Francis turbine has fixed blades while propellers, including Kaplan and bulb turbines, have adjustable paddles.

An impulse turbine uses the water speed, the kinetic energy, to move the machine and discharges the water at local pressure. A water stream hits each spoon-shaped paddle on the runner, with no suction on the downside of the turbine. The two main types of these turbines, that are generally suitable for high-head with low-flow applications, are Pelton and crossflow turbines. Pelton are among the most efficient hydro turbines available nowadays. Unfortunately, this kind of turbine cannot be reverted to work as a pump.

Turbines can operate at different speeds, limited by generator technology. Synchronous generators need a fixed speed, while asynchronous generators, as induction motors, can operate at different speeds. Second ones can be more efficient; however, they frequently need an ac-dc-ac converter to grid connection.

2.3.4.1 Francis turbine

Accounting for 80% of all hydro turbines in operation worldwide, the Francis turbine, developed by James Bichens Francis in 1855 in the USA, is suitable for almost all projects, however, it is preferred for medium and hight waterheads. These turbines operate immersed, and water flow enters in the radial direction flowing towards its axis, and, after interacting with the turbine blades, it exits along the axis direction, as a mixed-flow turbine, Figure 2.7. The water flow is controlled by a casing which curls around the turbine in a spiral shape making the water reach all blades equally. In general, for great projects, the blade shape and size are particularly designed based on the waterhead available and the flow volume of the project site. The largest Francis turbines in operation, 700 MW each one, are in Itaipu and Three Gorges power plants, in Brazil and China respectively. This kind of turbine coupled to a motor can operate as water pump, that is: it can be reversible.

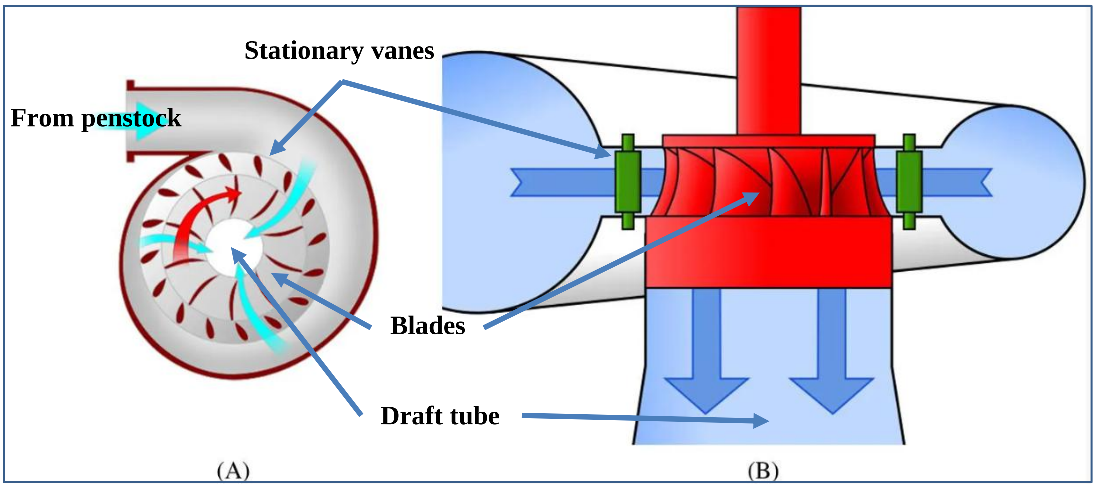


Figure 2.7 – Francis turbine top view (A) and side view (B). The water flows from the penstock to the draft tube through the set of blades transferring the water energy to the turbine rotor, in red colour, causing it to turn. The draft tube is designed to introduce a suction force, improving the machine efficiency.

2.3.4.2 Kaplan turbine

Propeller turbines, as that one developed by Viktor Kaplan in 1915, are suitable for low waterheads where Francis turbines' efficiency falls. The operating principle of such a turbine is like a ship propeller operating in a reverse mode. In general, power plants using propeller turbines, have several ones in parallel, as their efficiency drops rapidly when water flow drops below 75% of the design rating. In this case, some units are shutdown to maintain the others in the optimal operation point. The Kaplan turbine primary feature is a set of paddles that can be adjusted to maximise efficiency for different flow conditions, Figure 2.8. Based on its operating principle, this kind of turbine coupled to a motor can be reversible, too.

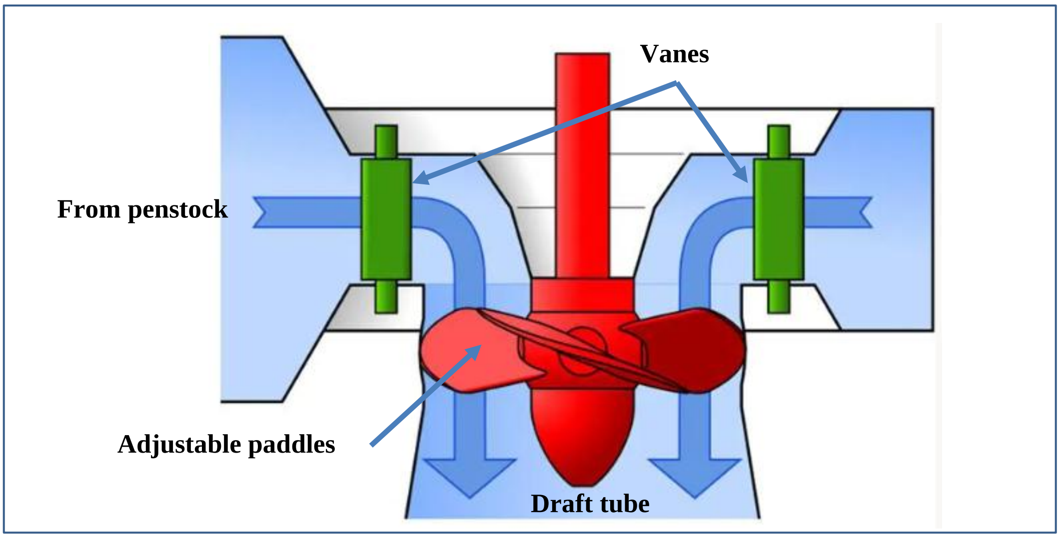


Figure 2.8 – Kaplan turbine side view. The water flows from the penstock to the draft tube through the propeller transferring the water energy to the turbine rotor, in red colour, causing it to turn. The draft tube is designed to introduce a suction force, improving the machine efficiency.

2.3.4.3 Pelton turbine

Directly descendant of the waterwheel, the turbine developed by Lester Allen Pelton in 1889 is an impulse machine powered only by the kinetic energy of a powerful jet of water that is generated from a high waterhead. Newest Pelton turbines have a set of spoon-shaped paddles mounted on the rotor as shown in Figure 2.9. The paddles are formed so that the water from the jet entering changes direction and exits on the opposite side, transferring its momentum to the rotor as it does so. A simple Pelton turbine will have one jet nozzle; however, power output can be increased by using up to six nozzles, equally spaced, directed at the same wheel. In most of the cases, Pelton turbine will have two paddle rows mounted side by side around the rotor, and these will be driven from two or four jets. As Pelton turbines must operate in free air, with no part of the wheel submerged, to avoid drag on the wheel and waste energy, they cannot be reversible to operate as water-pumps.

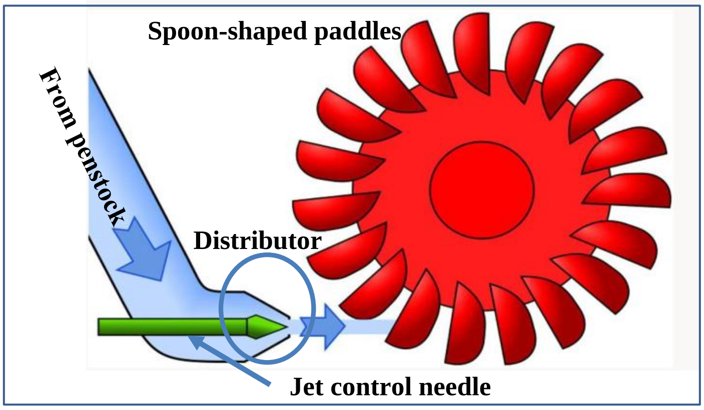


Figure 2.9 – Pelton turbine side view. The water flows from the penstock to the distributor, where its flux is controlled by the needle. The water jet hits the paddles transferring the energy of the water to the turbine rotor, in red colour, making it turn and then return to its natural flow with no draft tube.

2.3.4.4 Other turbines

There are many other types of commercial turbines; however, all of them are based on these three kinds presented here. The Knight turbine is the predecessor of the Pelton and use the same principle. Turgo turbine is a more complex Pelton and has a few applications, only in a waterhead not enough hight for a Pelton turbine and not enough low for a Francis turbine. Among reaction turbines, the Deriaz is a modified Francis with adjustable blades that make it more flexible. The bulb turbine is a fully immersed turbine-generator set that uses the same Kaplan principle. It is suitable for very low headwaters and generally applicable in run-of-river power plants.

2.3.5 PSH motor-generator

Generators and electric engines have more than 150 years of refinement, maintaining the same operating principle discovered by Michael Faraday during the 19th century. The electrical phenomenon, known as Faraday's principle, occurs when a metal moves through a magnetic field. Electrons are moved in such a metal causing a potential difference which, when in a closed circuit, produces an electrical current. This phenomenon is reversible, that is: when an electric current passes through a coil, a magnetic field is produced in its core. This is the principle used in generator poles, which are fed by a direct current called excitation current. The excitation current can be varied to control the power generated. Modern machines are sophisticated electromechanical devices and can achieve over 90% efficiency (CHIBA; WAKI, 2020; SHARLIN, 1961).

The generator is the second main element in a hydroelectric plant, which converts mechanical into electrical energy. Bulk power plants generally have individually designed generators, to take full advantage of plant site conditions. As most hydro turbines rotate at a low speed, synchronous generators are often designed with multiple poles, 36 or even more, to be able to produce energy at grid frequency, 50 or 60 Hz. Their rotors are usually constructed with salient poles, instead of smooth rotor used in high-speed machines. Variable speed generators, that are often synchronized using ac-dc-ac converters, are suitable for smaller hydroelectric projects, including reversible plants as PSH and UPSH.

Electric motors and generators have two main parts that can be described in both mechanical and electrical terms. In mechanical terms they have a rotating part called **rotor**, and the **stator** being the stationary part. Both electrical parts can be assembled in the rotor or in the stator: The **armature** is the power winding that produces electricity in a generator or consumes electricity in a motor. On the other hand, the **field** is the magnetic component, operating at low power and low currents or, even with no electrical current in case of permanent magnets. In general, the armature is mounted on the stator, as it must withstand high currents in large machines. Small machines may have the armature in the rotors and often permanent magnets in the stator as a magnetic field (BOSTIC, 2014).

2.3.5.1 Synchronous machines

Synchronous machines in general are designed for high power application, as medium and large hydropower, being the armature always mounted in the stator to avoid high currents passing in a moving part. A salient multipole rotor, Figure 2.10, is responsible by the field circuit. The primary machine operating speed defines how many poles will have the rotor. Synchronous speed will be controlled by primary machine, the turbine in a hydroelectric plant, and power output may be controlled by the excitation current injected into the rotor.

More than electricity production, synchronous generators, especially that big ones used in large hydropower, provide other important services to the grid. The power provided at grid frequency helps to maintain grid stability during fluctuations in both demand and supply from other small sources. The turbine-generator set provide inertia due to the momentum associated with its large spinning masses, helping the grid stability in case of transitory faults. Some generators can operate as a synchronous motor absorbing or injecting reactive power depending on its excitation current. For such an operation, the turbine casing is totally emptied. If the casing is flooded, the turbine will operate as a water-pump, as in a reversible power plant or PSH.

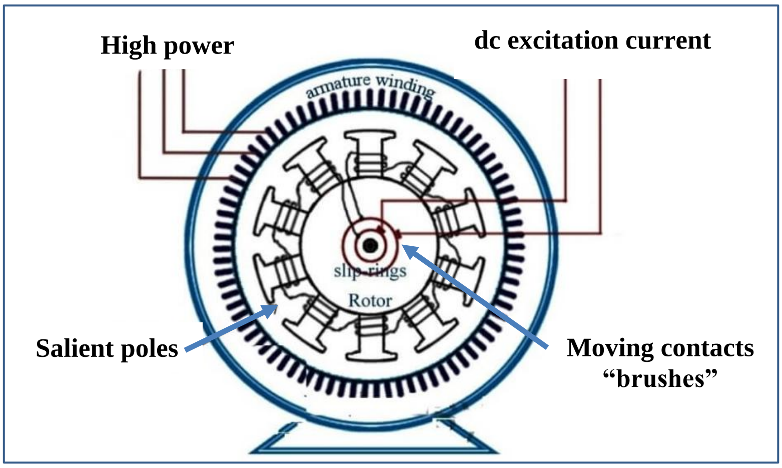


Figure 2.10 – Scheme of a salient pole rotor synchronous machine. The controlled excitation current feeds the pole winding through the moving contacts (slip ring-brush set), creating a magnetic field that will react with the armature winding in the stator.

2.3.5.2 Asynchronous machines

Asynchronous engines and generators can be wound-rotor induction or self-excited induction, the so-called squirrel-cage rotor machines or simply induction machines. The first one has moving contacts at the rotor and may be mounted in similar way of a synchronous machine. The main difference is that asynchronous machines can operate at variable speed, being voltage and frequency controlled by the grid or synchronized by an ac-dc-ac converter. Induction machines require an alternating energy source to provide the reactive power necessary for their magnetization, such as a bank of capacitors when operating in stand-alone mode. When connected in parallel to the grid, its magnetization current is supplied by the grid itself, leading to the need for power factor correction devices to meet grid standards. (BOLDEA, 2018).

One of the main characteristics of these machines is that the torque is proportional to the slip. The slip factor, s, is the difference between synchronous speed, ω, and the actual rotor speed, ω_R, divided by the synchronous speed, Equation 2.3. Small motors typical slip factor is in the range from 0.5% to 5% under full load conditions. Machines with high slip factor designed for specific applications may have slip values from 5% to 20%. Figure 2.11 represents a typical induction machine with slip factor of around ±10% under full load (AREE, 2018).

$$s = \frac{\omega - \omega_R}{\omega} \tag{2.3}$$

The slip factors in motor mode and generator mode are symmetrical to zero. The slip value for full load in motor mode is the pushover torque point in generator mode, when negative. At this point the mechanical torque, T_m, is maximum. Thus, the operating range of an induction generator varies in the linear region of the curve, from $s = 0$ to the pushover torque point. Since power is proportional to mechanical torque and generator speed, Equation 2.4, output power can be controlled by controlling generator speed within the machine's operating range (MARTINS; SOUSA, 2007).

$$P = T_m \omega \tag{2.4}$$

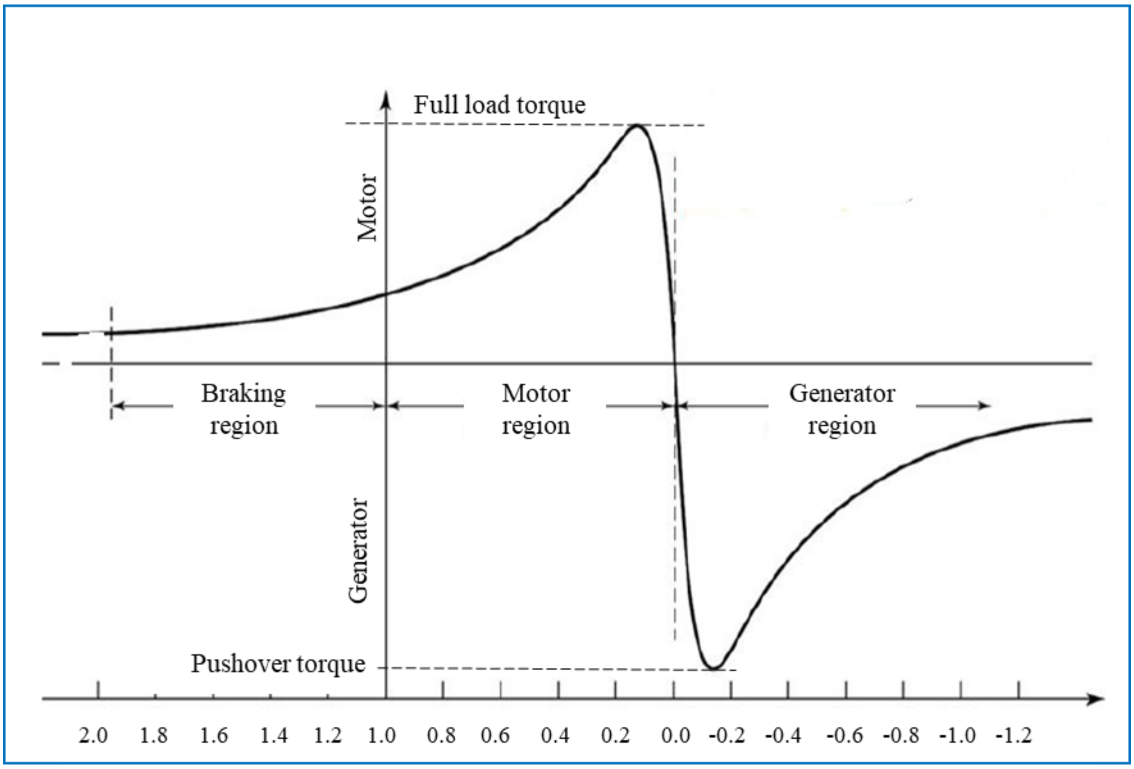


Figure 2.11 – Slip (speed) versus torque characteristic curve of an induction machine. From the pushover point the machine enter in the saturation region.

The squirrel-cage motor is the cheapest and most widely used electric rotating machine and has been used as generator. The three-phase winding is carefully mounted on the stator, with exactly 120º among phases, to create a rotating magnetic field. This rotating magnetic field is the basic principle of these induction machines. There are no windings or electrical connections on the rotor, Figure 2.12. The rotating magnetic field induces an electric current in short-circuited squirrel-cage bars. These induced currents produce an opposing magnetic force causing the rotor to turn. As there is not a controllable excitation current in this type of machine, they cannot operate as grid former generators and will be synchronized by the grid, grid follow mode, or connected through an ac-dc-ac converter to a powered grid (FIGUEIREDO, 2021).

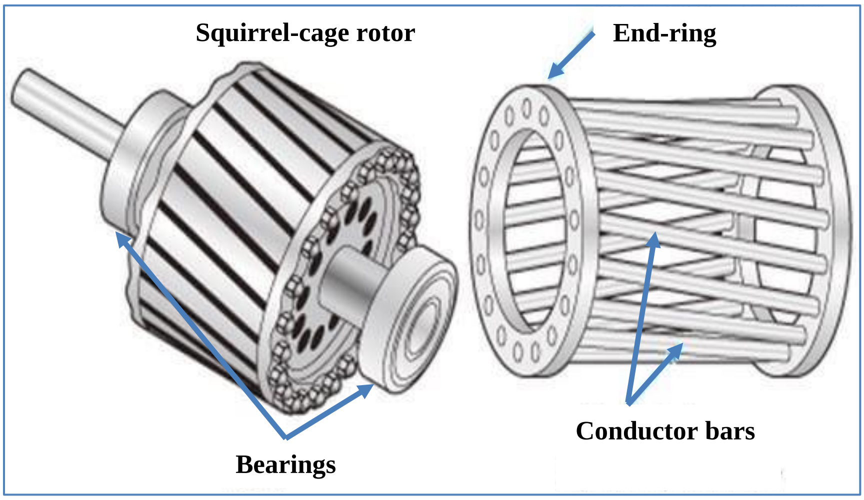


Figure 2.12 – Squirrel-cage rotor of an induction machine. The squirrel cage bars are mounted in grooves, insulated from the rotor core material, and short circuited by the end ring.

With the recent dissemination of power electronics, many small hydroelectric power plants are using asynchronous speed-variable generators to improve their efficiency, taking advantage of all the potential provided by water. However, these power plants tend to reduce grid stability rather than help it, if not synchronized through an ac-dc-ac converter. If connected through a converter, this type of generator also provides grid support in the same way as a synchronous generator. Almost all asynchronous engines can be reversed and operate as a generator at the cost of lower efficiency, which does not happen with those designed for this purpose.

2.3.5.3 Other electric engines and generators

There are many ways to classify electric machines, nevertheless by principle and by application are considered to be fully representative. The application depends on the power level and varies from very small machines with less than 1 Watt of power up to giant generators reaching 1 GW of power. Machines can be separated into three operating principles, as the fundamental one remains Faraday's principle for all. Synchronous and induction machines (asynchronous), where several sub-classifications may be done, and parametric machines.

While large multipole generators use conventional rotors, with salient poles and windings, some modern variable speed generators use multipole permanent magnet rotors, Figure 2.13. The so-called parametric machines use permanent magnets as a field, which causes them to have fewer electrical connections. These electric machines are built using rare earth magnets and is more efficient than a conventional one. Permanent magnet generators are being used in offshore wind power plants, where rotational speeds are often low, and the speed varies with wind. This technology can be applied to small hydropower and UPSH where the demands on the generator are similar.

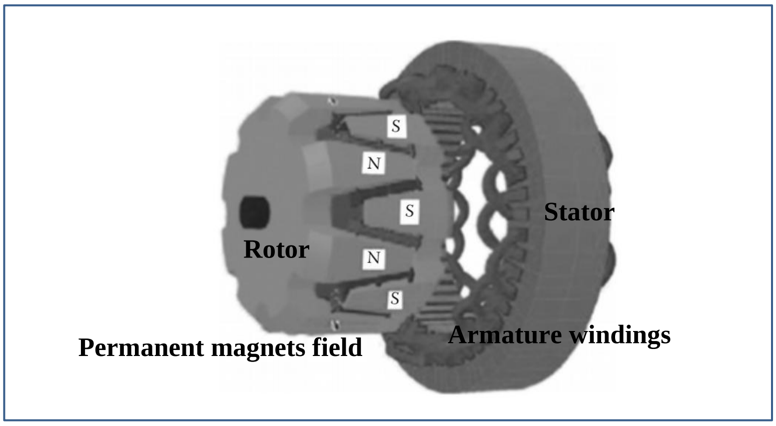


Figure 2.13 – Permanent magnets machine. The magnetic field present in the rotor react with the armature windings mounted in the stator. There is no electrical connection in the rotor.

Chapter 3 – An integrated framework for overall assessment of UPSH

As stated previously an UPSH is a PSH with at least one reservoir underground, leading to an underground powerhouse. This type of plant had not yet been studied in Brazil until 2025. Therefore, the objective of this chapter is to present an integrate framework for fully assessment of such a technology. The framework can be split into five phases: (i) prospecting, (ii) design, (iii) business plan, (iv) execution, operation, and maintenance, and (v) decommissioning.

3.1 Prospecting

Available sites will define the energy availability, the UPSH dimensions, and how it will be classified into current regulation. There was no specific regulation for energy storage in force in Brazil by the end of this Thesis, therefore UPSH will be named and classified, by similarity, following the hydropower classification, mainly that provided for in the REN nº 875 (ANEEL, 2020):

a) µUPSH, meaning micro UPSH, for plants with up to 5 MW of installed power classified as CGH (very small hydropower plant);
b) sUPSH, meaning small UPSH, for plants above 5 MW up to 30 MW of installed power classified as PCH (small hydropower plant); and
c) UPSH meaning big UPSH, for plants with installed power above 30 MW classified as UHE (hydropower plant).

µUPSH can be freely built, connected to distribution grid following the Distribution Procedures – PRODIST and Distribution Companies – DISCO's connection rules, and then registered at ANEEL. sUPSH must have an authorization granting issued by ANEEL. UPSH with an installed capacity exceeding 30 MW up to 50 MW will be subject to authorization whereas UPSH with installed power exceeding 50 MW will be subject to concession granting, assigned through public auction. All of power plants from 30 MW installed capacity will be part of National Interconnected System – SIN and dispatched by ONS. The type of granting that each power plant needs is summarized in the Table 3.1.

Table 3.1 – Power plants granting types.

Source	Capacity	Type of granting
Hydro	Over 50 MW	Public concession assigned through auction
Hydro	From 5 to 50 MW	Prior authorization from ANEEL
Others	Over 5 MW	Prior authorization from ANEEL
All sources	Up to 5 MW	Registration with ANEEL after plant conclusion

Before starting the design itself, it is necessary to complete some steps to legalize the project, which will again depend on the power plant size defined in this phase. µUPSH can be legalized as a DG or reduced installed capacity power plant; UPSH may hold an authorization, if the power does not exceed 50 MW, or a concession for power exceeding 50 MW; while mUPSH can only be legalized as authorized entity (ANEEL, 2020).

3.1.1 µUPSH as Distributed Generation

In this case, the entrepreneur must follow the PRODIST rules and the DISCO procedures, which generally, based on Cemig´s Distributed Generation Handbook, consist of:

a) Request of connection budget. The connection quote request is the request formulated by the consumer to the DISCO, in which the connection conditions and technical requirements that allow the consumer's facilities to be connected and the respective deadlines are informed.
b) DISCO approves the documentation and issues the connection quote, presenting the definitive technical and commercial conditions, which also guarantees the intended load reserve.
c) After finishing the power plant installation, the consumer must register the inspection request within the DISCO.
d) If the installation is approved, the consumer start being part of SCEE and being called prosumer (CEMIG, 2024).

3.1.2 µUPSH as power plant with reduced installed capacity

The registration with ANEEL of a plant with reduced installed capacity is provided for in two resolutions: REN 875 for hydroelectric plants and REN 1,071 for other sources. In both documents, registration must be done through the Agency's website, which guarantees the right to grid connection and sell energy from these projects. The powerplant must be ready to enter into operation following all sectoral regulations, such as project requirements, licensing, among others, for registration with ANEEL (ANEEL, 2020, 2023d).

3.1.3 mUPSH and UPSH with installed capacity up to 50 MW

This plant size will be subject to authorization from ANEEL to the interested party, whether an individual or legal entity, who must follow the steps below:

a) Registration with ANEEL to prepare Hydroelectric Inventory Studies – EIH. As defined in REN nº 875, a hydroelectric inventory study aims to identify, through the optimal use of hydraulic potential, hydropower in the river basin, with installed power exceeding 5 MW, which present the best cost-energy production relationship. Such a concept can be used by similarity to study the potential of UPSH. The approved EIH will compose the energy sector database, and the right of preference is guaranteed to its holder.
b) Requesting registration of intention to grant authorization from ANEEL. If approved, it will be issued an Order of Registration of Intent to Grant Authorization – DRI.
c) Presenting to ANEEL the executive summary of basic design. If the executive summary is approved, ANEEL will issue another Order that will allow the request for environmental licenses.
d) Requesting environmental licenses from the competent body: IBAMA if the plant is in two or more states; state environmental body if the plant is in two or more municipalities within the state; and municipal environmental body if the plant is entire in one municipality.
e) If the interested party demonstrates fiscal, regularity, technical, and legal qualifications, ANEEL will issue the grant act.
f) After the granting issue, the construction itself can be started based on an executive design. Such an executive design can be started before under entrepreneur risk.

3.1.4 UPSH with installed capacity greater than 50 MW

As provided by the Law 9,074/1995, large plants above 50 MW are subject to public concession through auction, regardless of the electricity trading environment chosen by the owner: public service, PIE, or self-producer. The steps to be followed to implement this type of plant are:

a) Registration with ANEEL to prepare Hydroelectric Inventory Studies – EIH. In some cases, the EIH may have been carried out by another entrepreneur previously.
b) Registration with ANEEL to prepare Technical and Economic Feasibility Study – EVTE. ANEEL will issue an Authorization Order to the applicant to

carry out the EVTE. The compatibility of the EVTE presented to ANEEL with the EIH will be attested through the issuance of another Order.

c) Requesting Environmental Preliminary License – LP from the competent body. After obtaining the LP, ANEEL will issue the Aptitude for Tender Registration Order – DRA, a document certifying that the project is eligible for bidding.

d) If the power plant is tendered, it will be guaranteed reimbursement for the costs incurred in preparing the EVTE and the EIH to their developers by the winner of the bid (BRASIL, 1995a).

Environmental licensing also depends on the size and location of the plant. As predicted in Complementary Law nº 140, enterprises located in one municipality will be licensed by that Municipality, in 2 or more municipalities, they will be licensed by the State authority, and in 2 or more states, they will be licensed by IBAMA, the national environmental authority. In general, small plants, considered to have a low probability of environmental impact, are allowed to present only a Simplified Environmental Report – RAS, whereas big ones, and those presenting great potential for environmental impact, need present an Environmental Impact Study and respective Environmental Impact Report – EIA/RIMA. (BRASIL, 2011).

There are four legal figures for electricity trading: (i) the concessionaire of public service, (ii) the Independent Energy Producer – PIE, (iii) the self-producer, and (iv) the Distributed Generation – DG. The first figure must be defined by long-term planning carried out by the Energy Research Company – EPE, a state-owned company in charge of energy sector planning. The concessionaire is assigned through a public auction where the price and minimum quantity of energy to be sold in the Regulated Contracting Environment – ACR are defined (BRASIL, 1995a).

The PIE can be from small to big ones and will receive the correspondent granting depending on its size. They can sell energy freely in both markets. In the Free Contracting Environment – ACL through bilateral contracts with buyers and in the ACR through public energy auctions.

The concept of self-producer of electrical energy was firstly defined in 1981, by a decree that has now been revoked. However, even without a legal definition, they are still included in other legal and regulatory instruments. They have an authorization to produce electricity for self-consumption exclusively. The power plant must have a size compatible with their demand and will eventually be able to sell surplus energy in the ACL.

Only µUPSH can be classified as DG and receive the benefits of Electrical Energy Compensation System – SCEE regulated by REN nº 1,000. Conversely, UPSH dispatched by ONS are allowed to provide ancillary services according to REN nº 1,039 (ANEEL, 2021, 2022)

3.2 Design

The first step is to define the size of the plant, that may be limited by water availability, grid availability or load to be attended. The reservoirs are then designed. At this moment, there are many possibilities, even if we are limited to at least one underground reservoir. The upper reservoir can be an existing water body, a dam, a lake, etc., or the upper part of a deactivated mine, or even being excavated. Knowing the upper reservoir, the lower reservoir can be designed. If an existing cavity is used, such as an abandoned mine, the waterhead will define the power of the plant, by general equation for hydropower, 2.1.

It can be seen in the equation 2.1 that there is a trade off among the three main variables that define a hydropower, *P*, the nominal power; *Q*, the water flow depending on reservoir volume, *V*; and *H*, the water head.

3.2.1 Deterministic approach

If there are no limits to the underground reservoir and enough water availability, a deterministic study can be carried out to size the UPSH. In this case, optimization tools can be used to find the optimal value for storage, maximum energy stored $ES(t)$, using the maximum of available resources, as water, *Q*, energy surplus, *S*, electrical consumption, *C*, or other variables to be defined by the designer, such as economic variables that will be discussed in the next section. The Objective Function – OF could be as in Equation 3.1.

$$\begin{aligned} &\operatorname*{Max}_{t \in Q^{+}} ES(t) \\ Subject\ to:\ &q(t) \leq 0 \\ &h(t) = 0 \end{aligned} \tag{3.1}$$

where $ES(t)$ is the energy stored function defined by the designer depending on available resources, $q(t)$ and $h(t)$ are constraint functions related to available resources.

An example could be the Northeast region of Brazil, where there is a surplus of energy from wind and solar power and large bodies of water such as the Sobradinho dam and the Mundaú and Manguaba natural lakes. In this case, the constraint functions would be first the volume of energy storage and, second, the availability of the transmission system. Finally, knowing the maximum possible size of the plant, an economic evaluation should be carried out to define the optimal size, considering at least initial investments, operation and maintenance costs, energy purchase and sale prices, taxes and eventual subsidies.

3.2.2 Stochastic approach

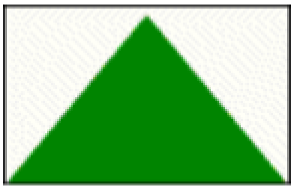
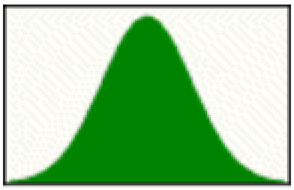
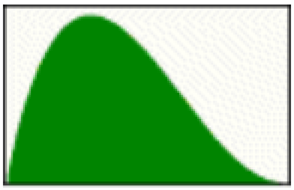
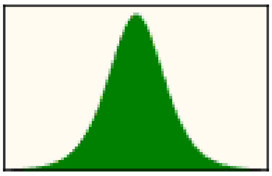
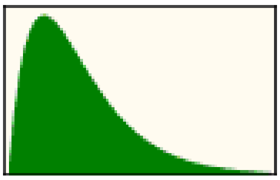
Sometimes an Energy Storage System – ESS is designed to store a known surplus generation or to meet an existing energy deficit. The energy surplus, $S(t)$, is given by the positive values of the integral of the difference between generation, $g(t)$, and consumption, $c(t)$, Equation 3.2. The deficit, $D(t)$, will be represented by the negative values of this same integral. The surplus or deficit during a specific time can be calculated by varying the limit T in such an integral.

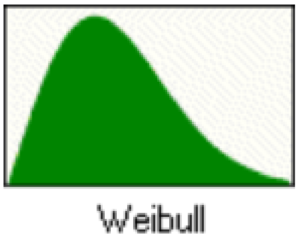
$$S = \int_{t=0}^{T} [g(t) - c(t)]dt \tag{3.2}$$

The next step is to adjust the project using statistical tools and long-term data. According to Raychaudhuri (2008), a useful mathematical tool to assess data behaviour with uncertain, providing probabilistic outputs, is the Monte Carlo Simulation – MCS. An MCS is used to model outcome probabilities in process that cannot easily be predicted due to the intervention of stochastic variables (stochastic inputs). It is a technique used to understand risk and uncertainty.

Uncertainties on inputs estimation can be incorporated into the studies through the MCS. The method is performed by numerous iterations, where the parameters uncertainties are entered from the selection of different random values. A probabilistic model is built, where parameters can assume a range of possible stochastic values. Such parameters are represented by Probability Density Functions – PDF based on measured or observed parameters. According to De Doile et al. (2023), a well-defined PDF is the core in a MCS study. However, to define a PDF is not an easy task as taught by Delaigle and Hall (2010) and Hernandez (2017). Fortunately, statistical software such as Crystal Ball®, among others, have PDF libraries available to the user. The following Table 3.2 presents a sample of PDFs useful for analyses of UPSH.

Table 3.2 – Sample of useful PDFs for UPSH analyses.

PDF	Description
 Uniform	The uniform distribution is continuous. In such a distribution, you know the range between the minimum and maximum values, and you know that all values in the range are equally likely to occur. It can be used to describe a condenser discharge or a leak in a pipe.
 Triangular	The triangular distribution is continuous. It describes a situation where you know the minimum, maximum, and most likely values to occur. It is useful with limited data in situations such as sales estimates, the number of goods sold in a week, inventory numbers, and marketing costs. For example, you could describe the electrical demand of a consumer per week when past demands show the minimum, maximum, and the demand that happened more times.
 Normal	The normal distribution is continuous and used when mean and standard deviation are known. Mean value is most likely and the function is symmetrical about the mean. It is the most important distribution in probability theory because it describes many natural phenomena. Decision-makers can use the normal distribution to describe uncertain variables such as the inflation rate or the future tariffs. Approximately 68% of normal distribution values are within 1 standard deviation of the mean.
 Beta	The beta distribution is continuous. It is commonly used to represent variability over a fixed range. It can represent uncertainty in the probability of occurrence of an event, as solar radiation. It is also used to describe empirical data; predict the random behaviour and can be used to represent the reliability of some devices. The parameter that must be known are minimum, maximum, alpha, beta, all then positives. Alfa and beta define the function shape. If the parameters are equal, the distribution is symmetrical. If either parameter is 1 and the other parameter is greater than 1, the distribution is J-shaped. If alpha is less than beta, the distribution is said to be positively skewed (most of the values are near the minimum value). If alpha is greater than beta, the distribution is negatively skewed (most of the values are near the maximum value).
 Logistica	Logistic distribution is often used to describe growth. It can also be used to describe chemical reactions and the course of growth for a population or individual. It is a continuous probability distribution with mean and scale parameters.
 Gama	The Gamma distribution is a continuous probability distribution applied to a wide range of physical quantities. It is used in meteorological processes to represent pollutant concentrations and precipitation amounts, and has other applications in economics, inventory, and insurance risk theories. The parameters need are location, scale, and shape. The location parameter lets us set up an exponential distribution to start at a location other than 0.0.

	The Weibull distribution is also continuous. It describes data resulting from fatigue tests and can be used to describe failure time in reliability studies or the breaking strengths of materials in reliability and quality control tests. Weibull distributions are also used to represent various physical quantities, such as wind speed. The parameters need are location, scale, and shape. This flexible distribution can assume the properties of other distributions. When the shape parameter is equal to 1.0, the Weibull distribution is identical to the exponential distribution. When the shape parameter is less than 1.0, the Weibull distribution becomes a steeply declining curve.

3.2.3 Machinery definition

The rated power defines the type of electric machine, synchronous for large powers or asynchronous for small powers. The type of machine can be defined by the price, in the case of medium powers, or by its function in the grid: synchronous machine for grid former, as they have strong frequency and voltage controllability, or asynchronous for grid follow plants.

Conversely, the first approach to defining a hydraulic machine is based on waterhead, H, water flow, Q, rotor speed, n, and nominal power, P, as shown in Table 3.3 (SANGAL; GARG; KUMAR, 2013).

Table 3.3 – Variables for preliminary definition of the hydro turbine type.

Turbine	Waterhead [m]	Water flow [m³/s]	Rotor speed [rpm]	Nominal power [kW]
Pelton	$100 \leq H \leq 1{,}400$	$0.1 \leq Q \leq 50$	$1{,}800 \leq n \leq 2{,}900$	$50 \leq P \leq 10{,}000$
Francis	$10 \leq H \leq 350$	$2 \leq Q \leq 100$	$200 \leq n \leq 3{,}600$	$200 \leq P \leq 700{,}000$
Kaplan	$2 \leq H \leq 60$	$2 \leq Q \leq 300$	$400 \leq n \leq 900$	$5 \leq P \leq 10{,}000$

Since the Pelton turbine is a 100% action turbine, taking energy from the water velocity, working in an open cavity at ambient pressure, it is not possible to reverse its cycle. Therefore, it cannot function as a hydro-pump which makes it inapplicable for UPSH. On the other hand, Kaplan is a 100% reaction turbine, which obtains energy from the difference in water pressure. Such a turbine operates in a closed casing where the inlet pressure, water coming from the penstock, is greater than the outlet pressure in the draft tube. As the propeller is constantly flooded, this process can be reversible, functioning as a water pump.

The Francis turbine works in a mix of action and reaction, being suitable for medium heads and high nominal powers. The turbine rotor also works in a closed casing completely flooded, making it a reversible turbine. Power control is achieved by closing and opening the water distributor. The main advantage of a Francis turbine is its robustness, which results in less maintenance, making it the most used turbine in the world, while the Kaplan turbine has more controllability due to the movement of the propeller blades, being adequate for medium and small power plants.

3.3 Business plan

The business plan strictly depends on the business model. Unfortunately, there is no economic regulation for energy storage in Brazil yet. There are three economic approaches on Brazilian electrical system: (i) for generation, (ii) for transmission, and (iii) for distribution.

3.3.1 Generation business model

Plants with installed capacity of up to 5 MW, classified as DG and members of the SCEE, are remunerated by this compensation system, as provided for in Law nº 14.300 and REN nº. 1,000. Initially, the SCEE allowed 100% of the surplus energy to be compensated, that is, used by the consumer during energy deficits. If the injected energy was greater than consumed energy, the surplus was considered as credit for next tariff period. Law 14,300 provided for a transition period until 2030, where each year a percentage of the Distribution System Usage Tariff – TUSD was discounted from the grid injected energy. After 2030, 100% of the TUSD, that according to de Doyle et al. correspond to around 43% of the tariff, would be discounted from the surplus energy (ANEEL, 2021c; BRASIL, 2022b; DE DOILE et al., 2023b).

The granting of the old hydroelectric plants, most of them state-owned, were extended by National Law nº 12,783 from 2012 onwards. Such an extension created the quota regime and the Annual Generation Revenue – RAG, regulated by ANEEL through Module 12 of the Tariff Regulation Procedures – PRORET (ANEEL, 2022b; BRASIL, 2013).

The RAG is the annual amount that a generator with an extended contract is entitled to receive for the provision of the physical guarantee of energy and power of the hydroelectric plant under the quota regime. This amount is paid in twelfth instalments and is subject to discounts for unavailability or bad generation performance. It is composed of the regulatory costs of operation, maintenance, administration, remuneration and amortization of the power plant, and is adjusted annually in July, in addition to being reviewed every five years.

The RAG, calculated by ANEEL, is then divided among the distribution companies in proportion to their markets (loads). These values are named quotas, of quota regime, to be paid by each DISCO. A similar quotas procedure is applied to energy from Itaipu binational hydropower and Angra nuclear power plants (ANEEL, 2022b).

New hydroelectric plants are in a competitive market, where they sell energy directly to free consumers or in public energy auctions held by the CCEE. The DISCOs inform the CCEE of the amount of energy needed for the coming years. This total amount of energy is not known to the sellers, who offer their bids in quantity and price. The auctioneer stacks bids from the lowest price until the total amount of energy informed by DISCOs is reached. Each energy package and price are then divided among the buyers in proportion to their informed energy need and will be reflected in a long-term bilateral contract between the seller and the buyer (CCEE, 2024c).

3.3.2 Transmission business model

The transmission business model is perhaps the simplest in the Brazilian electrical system, where Transmission Companies – TCOs receive a fixed annual revenue, the Permitted Annual Revenue – RAP, for the availability of the facilities, that is: the RAP is guaranteed regardless of the transmitted energy volume.

Electric energy transmission is characterized as a natural monopoly, since the construction of two or more lines to provide the same service is economically unfeasible. Thus, sectoral planning, carried out by EPE, defines the transmission facilities required in the medium and long term, which are then put out to tender by ANEEL. Competition for the right to build and operate new facilities only occurs at this point. After the signing of the public service concession contract, the monopoly is established and there is no longer any competition. Expansions and reinforcements defined by the operation planning, carried out by ONS, and short-term planning, carried out by EPE, will be determined by ANEEL to TCOs with RAP established by this regulatory agency, according to Module 9 of the PRORET (ANEEL, 2022b).

The auction for the concession of the public transmission service is of the decreasing type, where ANEEL calculates a ceiling RAP and the bidders offer lower values. The bidder who offers the lowest RAP value wins the auction and will sign a concession contract for a period of 30 years. The RAP is adjusted annually by the inflation rate and reviewed every five years, where administration, operation and maintenance costs are adjusted. A discount limited to 12.5% of the RAP is applied for unavailability of the facilities. This is a very good business model for conservative entrepreneurs, as the profit established at the auction is fixed for 30 years. However, the TCO is not authorized to carry out other economic activities. If authorized by ANEEL to carry out compatible activities, such as data transmission through Optical Ground Wire – OPGW, the profit will be captured to reduce tariffs to consumers.

3.3.3 Distribution business model

The distribution service can be divided into distribution grid and energy trading. However, such a division is not yet permitted for captive consumers in Brazil. The distribution grid service is also a natural monopoly by geographic regions. There are more than 100 DISCOs in Brazil, each operating in an exclusive concession area.

DISCOs receive a tariff set by ANEEL and paid by users. This tariff is made up of two parcels: (i) parcel A, which includes costs related to energy purchase, quotas of plants in the quotas regime, and transportation, in addition to sector charges and taxes; and (ii) parcel B, which includes typical costs of distribution activities, operation and maintenance, and commercial management of customers. Tariffs are adjusted annually based on inflation rate and reviewed periodically in accordance with concession contracts.

Parcel B includes costs that can be managed and optimized by DISCOs, such as administration, operation and maintenance costs; installation costs, including recovery of investments, remuneration of capital, and taxes; in addition to the X factor. The X Factor, composed of three components: (i) productivity gains, (ii) service quality, and (iii) operating cost trajectory, aims to ensure that the balance between efficient revenues and expenses is cancelled in subsequent tariff revisions.

The distribution tariffs regulation is in the Modules 2 up to 8 of PRORET issued by ANEEL (ANEEL, 2022b).

3.3.4 Energy storage proposed business model

As explained throughout this Thesis, ESS cannot be included in the current economic regulations of the Brazilian electricity sector, as they can provide services in the three application sub-sectors: generation, transmission and distribution. Therefore, a fourth segment of economic regulation should be created. The energy storage economic regulation, the fourth economic regulation segment, must consider all possible services provided by ESSs.

According to Hjalmarsson, Thomas, and Boström (2023), the number of services supplied by ESSs ranges from 10 to 30 and can be grouped into ten groups: (i) black start, (ii) energy arbitrage, (iii) frequency control, (iv) peak shaving, (v) outage mitigation, (vi) Renewable Energy Sources – RES integration, (vii) spinning reserve, (viii) Transmission and Distribution – T&D investment deferral, (ix) voltage support, and (x) self-consumption behind the meter. Possible ESS groups of services and the regulation segment they fall under, their application, are presented in Table 3.4.

Table 3.4 – Groups of ESS services and application.

Group	[1] Application	Description
Black start	G and T	Assisting re-energization after grid failure and supporting other generators with initial power.
Energy arbitrage	G	Optimizing energy demand through the electricity price difference in the spot market.
Frequency control	G	Balancing of deviations between generation and demand.
Peak shaving	G, T and D	Discharging during a specific time to meet the peak demand, decongesting the transmission and/or distribution grids.
Outage mitigation	G, T and D	Used to cover for outage of generators and also as a backup unit downstream the grid to cover for grid outages
RES integration	G	Providing firm capacity during intermittences, ramp rate control, energy time shifting, among others.
Spinning reserve	G	Rotating machines synchronized to the grid without injecting power to ensure grid stability.
T&D investments deferral	T and D	Used in a congested grid to reduce the infrastructure loading during peak load, postponing otherwise required investments.
Voltage support	G, T and D	Providing active and reactive power control to improve the local voltage quality.
Self-consumption	G and D	Meeting peak demand of DG connected users.

[1] G is generation, T is Transmission, and D is Distribution

As can be seen from the table above, most ESS applications are related to generation, with at least half of them providing transmission and/or distribution services together. However, the current economic regulation for generation is not suitable for ESSs, as these facilities do not produce energy. They need to buy energy and then inject it into the grid when requested by the system, making their energy price very expensive and economically unfeasible in the generation competitive market.

Conversely, economic regulation of transmission is the best for the ESSs from the point of view of a conservative businessman. However, this is not optimal for either the entrepreneur or the users. Under the economic regulation of transmission, the user pays for the availability of the facility, does not mattering whether the service is provided or not. This is understandable in the case of a transmission service, where there is no other service to be provided in parallel, but not where there are several services that are provided on grid demand. Paying for all these services, whether receiving them or not, will be very expensive for users. On the other hand, companies with less risk aversion might be more profitable taking advantage of multiple services provided by the ESSs in a competitive market.

The main advantage of distribution economic regulation is the management the amount paid by users related to parcel A. This is a large amount received by the DISCO and passed on to suppliers and the government, in the case of taxes and sectorial charges, in other words: this is an economic-financial service, similar to a banking service, provided by the DISCOs.

The parcel A of distribution tariffs cannot be managed by an ESS company due to the distribution monopoly. In other hand, the parcel B approach is similar to transmission economic regulation and will not be optimal for ESSs as explained in the previous paragraph.

Revenue stacking, also known as value stacking or service stacking, is a promising method to optimize and maximize all of ESS potentials, especially the economic potential to make these enterprises profitable. Revenue stacking may be defined as the bundling of services provides by an ESS and their respective revenues, creating multiple value streams, which can improve the facility economic feasibility. It can be implemented independently of technology, although the service portfolio depends on the ESS characteristics and grid connection point, as ESS services are location-sensitive (HJALMARSSON; THOMAS; BOSTRÖM, 2023).

The algorithm for implementing an ESS, and then a service stacking, could be as follows: in the first step the sectorial planning defines the main service to be provided by such an ESS and, eventually, one or more parallel service to be provided. The most common services provided by ESSs are energy arbitrage, RES integration, peak shaving, and frequency control. The planning can also define the optimal delivery point. This is the optimal grid connection point if there are no other services provided by the ESS. However, an entrepreneur can find other potential services and other optimal grid connection points. In this case, the contracted services defined by the planning will be delivered and measured at the delivery point, even if the facility is connected to another grid point.

The regulated remuneration for the services will have two or more instalments depending on how many services were defined by the planning and the investor should be free to sell other services on the free market. The first parcel should guarantee the return on investment. Therefore, it would be similar to the transmission's RAP. Such a parcel will be called in this Thesis Energy Storage Service Annual Revenue – RASA (in the Portuguese acronym). The RASA, in R$ per year, should be defined by regulation considering investments without capital remuneration, sectorial charges and taxes. Administration, operation and maintenance costs, as well as capital remuneration must come from the services provided revenue.

The other instalments will depend on what services were contracted. Services based on energy will receive a variable parcel in R$ per supplied MWh and services based on power will receive a parcel in R$ per available MW, both defined in competitive auctions. The entrepreneur's profit will come from these instalments and from other possible revenues obtained in the free market.

The company that will have the public granting to explore the ESS, called Energy Storage Company – ESCO in this Thesis, should be defined by a combinatorial public auction. The RASA ceiling and reserve prices should be calculated previously by the regulatory authority, and bidders will offer a RASA in R$/year and packages of energy in MWh and power in MW and the respective prices in R$/MWh and R$/MW/year. An algorithm will define which combination leads to a minimum tariff for users, and this will be the winning proposal of the auction.

Small ESSs, connected as DG, could be authorized for peak shaving service and, through an aggregator, provide other services. An aggregator is an intermediary entity between a group of small agents connected as DG (prosumers) and the electricity market, facilitating the buying and selling of energy services through competitive pricing (IRIA; SOARES, 2023).

3.3.4.1 Combinatorial auction system

As the design phase has been carried out previously, the magnitude of the facility, the power and energy to be supplied, is known at the auction, as well as the RASA ceiling. The reserve price of energy, the highest price that the consumer can pay, is not known to the bidders, as well as the total amount of energy and power being tendered. However, the minimal amount of energy and/or power to be supplied should be defined by the sectoral planning.

Most combinatorial auction schemes found in the literature are related to the sale of goods, where there is a series of goods at different prices and bidders offer bids for one or more goods. They can result in multiple winners, depending on the combination of bids, each one purchasing a certain number of goods (CRAMTON; SHOHAM; STEINBERG, 2007; LIU et al., 2022).

The proposed combinatorial auction has two or more energy storage services $S = \{S_1, S_2,..., S_i,..., S_n\}$ to be auctioned and multiple bidders $B = \{B_1, B_2,..., B_j,..., B_m\}$. Each bidder will offer a bid for one or more services $\$B_m = (\$B_mS_1 + \$B_mS_2 + \ldots + \$B_mS_i + \ldots + \$B_mS_n)$, with a bid being set to zero if a given service does not receive a bid from a bidder. The proposals must consist of the price and quantity of power or energy for services based on this, respectively. There will be only one winner, who will be the one whose sum of the bids for each service is the minimum, subject to the largest number of services contracted.

In practice, the auctioneer will receive all bids and check whether there is at least one set of bids for all the services being bid, or if not, check which sets of bids have bids for the largest number of services and disqualify the rest. Then, the auctioneer will stack the sum of bids (4) from the lowest to the highest. The winner will be the bid with the lowest value for the services tendered, if the other proposals are greater than a previously defined percentage of the lowest proposal (generally 5%). If there are bids equal to or lower than such a percentage of the lowest bid, the auction will continue with open outcry rounds, in which bidders may reduce their offers for each of the services tendered, until a bid is the winner. An illustration of the proposed combinatorial auction scheme is shown in Figure 3.1.

$$\$B_m = \sum_{i=1}^{n} \$B_m S_i \quad (4)$$

where $\$B_m$ is the sum of the bids offered by bidder m and $\$B_mS_i$ is the bid offered by the bidder m for service i, that can be the proposed value for RASA in R$/year, all proposed values for services based on energy in R$/MWh and respective energy amount in MWh/year, and all proposed values for services based on power in R$/MW and respective amount of power in MW/year.

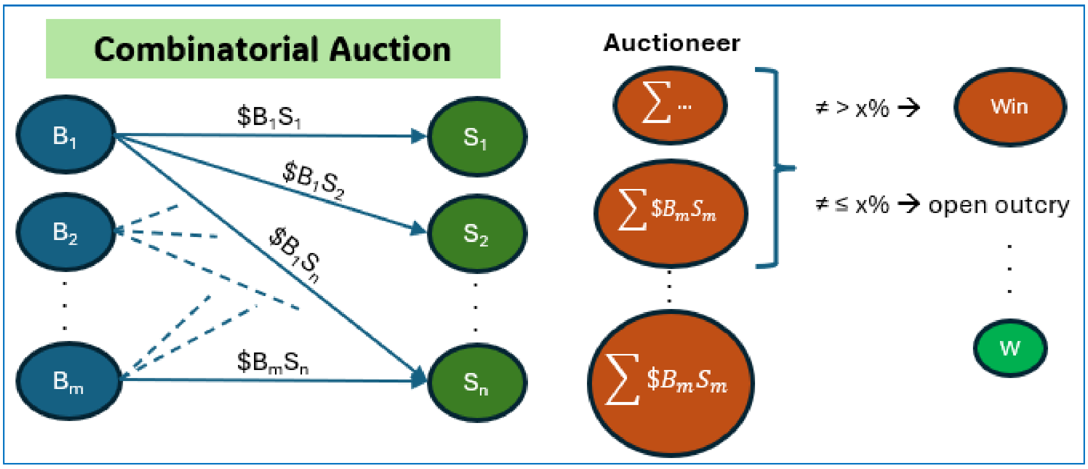


Figure 3.1 – Proposed combinatorial auction scheme. $\$S_i$ is the RASA (R$/year) or a MW amount times R$/MW or an amount of MWh times R$/MWh.

The revenue stack will be composed of n instalments, depending on how many services were defined by the sectoral planning and purchased at the auction, added to the instalments defined by the entrepreneur to be freely marketed in the ACL.

The first parcel, the RASA, should only provide the guarantee of the return on the initial investment without profits. Manageable activities such as administration, operation and maintenance must be remunerated by additional instalments to RASA. This is where the entrepreneur can maximize his profits.

3.3.4.2 RASA ceiling definition

To calculate the maximum RASA to be taken to auction, the initial investment must be known and then, a long-term cash-flow should be carried out. At this stage, only the expected inflation rate should be considered, as the capital remuneration comes from other revenues in this business model. If the concession contract has a clause that indexes the annual revenue correction to the inflation rate, the calculation of the RASA ceiling should not consider such a rate.

According to Teixeira and Viana (2013), the average long-term inflation rate in Brazil is about 4.5% per year. However, the same author stated that a long-term economic forecast is subject to notable errors and is full of uncertainty. Therefore, the probability of having larger and smaller values of inflation rate should be considered through stochastic analyses.

Planning should use actual prices from official databases or even through research prices from suppliers. However, for academic studies, prices from research databases or published articles can be used.

Hydropower are normally designed for an operating lifetime of about 50 years, and their lifespan can reach more than 100 years with proper operation and maintenance. A useful life of 50 years for cash flow studies is acceptable in this case (VORLET; DE CESARE, 2024).

3.3.4.3 Reserve price definition

There are four types of auctions in terms of reserve price: (i) simple bidding without a reserve price, (ii) bidding with an announced reserve price, (iii) bidding with a secret reserve price, and (iv) bidding with a secret reserve price, but with the possibility of ex post negotiation if the winner has a bid above the reserve price. Forgoing a reserve price can lead to purchasing the energy at a very high price. However, in a competitive market where there are several potential bidders, such a risk is quite low, making a reserve price unnecessary. Even so, auctioneers often have a reference price to check if bids are too high in relation to it (BUGARIN; PORTUGAL, 2022).

A reference price might be calculated to be used in the economic assessment studies. Such a reference price must remunerate the invested capital and cover all expenses, such as energy acquisition, administration, operation and maintenance, taxes and sector charges.

At least, six inputs are necessary for this calculation: (i) the initial investment used to consider the capital remuneration only, since the return on investment is already in the RASA; (ii) the amount of energy dispatched, where the amount to be freely negotiated in the ACL and a reserve amount should be discounted; (iii) the operation and maintenance costs; (iv) Tax and sectorial charges; (v) Weighted Average Cost of Capital – WACC; and (vi) the energy acquisition costs. Other costs might be defined in real cases.

3.3.5 Economic assessment

The ESCO is the company responsible for implementing, administration, operation, and maintenance of the facilities. Therefore, to participate in a public auction an economic assessment should be previously carried out. Firstly, the initial investment should be considered and then, a long-term study considering buy and sell energy prices, power prices, operation and maintenance costs, administrative expenses, electrical losses, among others should be done. In case of µUPSH as DG being part of SCEE, the compensated energy and avoided consumption should be priced in this analysis. Some economic decision criteria are presented in the following paragraphs.

The Net Present Value – NPV is an important financial tool that can be calculated by a discounted cash flow considering several inputs, such as initial investments, management costs, facilities life span, operating time, Minimum Attractiveness Return Rate – MARR, electricity tariffs, taxes and, eventually, credits from state programs or subsidies, among others (ZHOU et al., 2009).

Since that, several authors such as Aquila et al. (2020); Ayodele et al. (2019); Krishan and Suhag (2019); and Li, Lu, and Wu (2013), have claimed that NPV is the most adequate method for economic analyses of any enterprise, being the most used economic tool by researcher.

The NPV's goal is to calculate the current value of future sum of income and expenses, discounted by a desirable discount rate, the MARR, as presented in Equation 3.3. According to EPE, an adequate MARR for long term studies is around of 8% per year, nevertheless, each investor can choose a different one based on their risk aversion. A positive NPV means economic viability of the project, NPV equal zero means that all investments are recovered in the project life span, but with no profits, whereas a negative NPV means economic unviability (DE DOILE et al., 2020; EPE, 2020a).

$$NPV = \sum_{i=1}^{n} \frac{Cf_i}{(1+r)^i} - I_0 \qquad i \in 1 \leq \mathbf{N} \leq n \qquad (3.3)$$

where I_0 is the initial investment; n is the project life span; Cf is the cash flow in each period i; and r is the MARR stablished to the project. Cf for each period i is given by Equation 3.4 for an UPSH,

$$Cf = C_{SE} - C_{PE} - C_{O\&M} - C_{Adm} \qquad (3.4)$$

where C_{SE} is the sold energy income; C_{PE} is the purchased energy cost; $C_{O\&M}$ is the operation and maintenance cost; and C_{Adm} is the administration cost where taxes, fees, and other administrative expenses are included.

The Internal Return Rate – IRR is a discount rate that makes the NPV null. In other words, the IRR is a discount rate that makes the discounted cash flow during the project life span equal to initial investment. IRR is an indicator to be compared with a MARR stablished by an investor. IRR greater than the MARR means that the project is economic viable with a positive NPV and profits greater than expected by the investor. In opposite, IRR lower than MARR means unviable project with negative NPV. The IRR can be calculated by Equation 3.5 (DOYLE et al., 2021).

$$\sum_{i=1}^{n} \frac{Cf_i}{(1+IRR)^i} = I_0 \qquad i \in 1 \leq \mathbf{N} \leq n \qquad (3.5)$$

NPV and IRR criteria are based on a perfect and efficient markets, certainty of project life, and no capital rationing, ensuring profitability. However, most of these assumptions are not true in practice, which does not guarantee liquidity. The Discounted Payback Period – DPP, on the other hand, meets most of the characteristics of an ideal decision rule including liquidity and profitability. The DPP, given by Equation 3.6, is the period of the project life in which the NPV of cash flows is equal to zero. In other words, it is the moment when the project begins to be profitable (BHANDARI, 1989).

$$\sum_{i=0}^{DPP} \frac{Cf_i}{(1+r)^i} = I_0 \qquad i \in 0 \leq \mathbf{Q} \leq DPP \qquad (3.6)$$

Note that i is no longer an integer and can assume a fraction of a year. Equations 3.5 and 3.6 have not easy analytical solutions, however, there are several software as Excel® spreadsheets to numerically solve them for an actual case.

3.3.6 Economic assessment tools

Optimization is a useful tool when there are no limits to the UPSH underground reservoir, and a deterministic study is enough to dimension the energy storage plant. Optimization tools can be used to find the optimal financial return provided by the plant, Equation 3.7, or to find the optimal of other variables of interest.

$$\begin{aligned} &\max_{t\in Q^+}\{NPV(r,Cf_i,I_0)+IRR(Cf_i,I_0)-DPP(r,Cf_i,I_0)\} \\ Subject\ to:\ &q(r,Cf_i,I_0)\leq 0 \\ &h(r,Cf_i,I_0)=0 \end{aligned} \tag{3.7}$$

The OF is to maximize the NPV, Equation 3.3, and IRR, Equation 3.5, and minimize the DPP, Equation 3.6, at the same time. Note that there is a trade-off between the three variables. The higher the NPV, the lower the IRR. The higher the IRR, the higher the DPP. Therefore, to achieve the goal is necessary to minimise I_0 and/or maximise Cf_i variables. Constraint equations, $q(r,Cf_i,I_0)$ and $h(r,Cf_i,I_0)$, will depend on available resources, initial budget, energy prices, among other variables to be defined by the designer.

As most economic indicators are based on assumptions that are not true in practice, stochastic analyses present themselves as important tools for economic and financial analyses. Here, the input probabilities are known and presented as PDF. Results also will be probability functions, based on that decision makers can take the best option for the project.

By MCS the probability of NPV greater than zero, IRR greater than MARR, and DPP lower than a desired time can be estimated. MCS allows, among other things, to add constraints and correlations on stochastic variables. For instance, it is possible to use a constraint on solar radiation, which is present only during daytime, or a correlation between consumption at peak time and electricity tariffs. Stochastic input parameters could be as presented in Table 3.5, (DE DOILE et al., 2023b).

Table 3.5 – PDF for some input parameters.

Parameter	PDF	Description
I_0 – Initial investment	Weibull	Initial investments depend mainly on the price of material and the price of work force, both of which vary according to the location of installation. Typically, these prices have a small variation below the average and a large variation above the average, being well represented by a Weibull PDF.
Solar PV production	Beta	Solar radiation is well represented by a positively skewed Beta function, where the minimum value occurs at sunrise and sunset and the maximum value in the middle of this period.
Consumption	Gamma	The Gamma PDF well represents consumption, which is not very elastic for values below the average and quite elastic for values above the average.

Tariffs	Logistic	Tariff growth is well represented by a Logistics function, where the downward and upward variations are similar.
MARR	Normal	As MARR is an expectation based on the inflation rate, the Normal PDF is the one that best represents it.

The outputs will be probabilities, as exemplified in Figure 3.2, which presents the results for a photovoltaic solar power plant. The NPV has a 75.55% probability of being positive, which means that less than 25% of the simulated cases are economically unviable. The project is a good economic option when looking only at this indicator.

However, when looking at the IRR results, the conclusion may change. A 12% annual return rate is an acceptable rate in Brazil for entrepreneurs in general. The result shows a 50.24% probability of an IRR greater than 12%, following a beta curve where results lower than 12% are more frequent than those higher than 12%. This is not a good result for conservative investors.

The expected payback period for the simulated project was 10 years and the probability found was 34.75%. A probability lower than 50% is generally considered unfeasible in economic analyses, however, the results follow a lognormal curve where small DPBs are more frequent than larger ones. If the other indicators were good, the project could be considered viable. Nevertheless, this does not happen in this example where two indicators are not that good, this being a high-risk project.

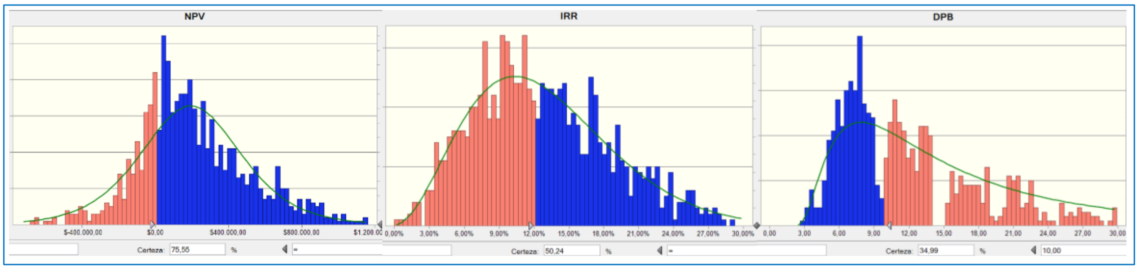


Figure 3.2 – Examples of MCS outputs. NPV, IRR, and DPB for a solar photovoltaic power plant.

3.4 Project execution

Normally, the executive project, environmental studies and licensing, public permissions and the construction itself are carried out by an Engineering, Procurement and Construction company – EPC, under the owner supervision.

3.4.1 Executive project

The executive project, based on basic design explained in previous subsections, is a set of technical information necessary and sufficient to carry out the enterprise, containing in a clear, precise and complete manner all the indications and construction details for the perfect installation, assembly and execution of the services and works.

It is worth highlighting that the executive project is not a new project, but rather an extension and detailing of what was previously produced in the preliminary design. The project detail at this stage is much higher than the previous stages, as the executive project serves as an instruction manual for those on the construction site (WINCH, 2009).

3.4.2 Environmental licencing and public permissions

There are several environmental bodies where licensing can be applied depending on the location of the project. However, they all follow, at least, the main standard established by IBAMA, the national environmental agency (IBAMA, 2024).

After choosing the competent environmental body, the EPC will request the Preliminary License – LP by filing the EIA/RIMA. The EIA must consider all technological and project location alternatives, comparing them with the hypothesis of non-execution of the project, as well as limiting the geographic area to be affected directly and indirectly, identifying and evaluating environmental impacts generated in the implementation and operation phases of the activity. The minimal technical activities to be carried out in an EIA are:

1) The environmental diagnosis of the project's complete influence area, describing and analysing environmental resources and their interactions, as they exist, to characterize the environmental situation of the area, before implementing the project, considering:

a) **the physical environment** – the subsoil, water, air and climate, highlighting mineral resources, topography, soil types and capacities, water bodies, the hydrological regime, sea currents, atmospheric currents.

b) **the biological environment and natural ecosystems** – fauna and flora, highlighting species that are indicators of environmental quality, of scientific and economic value, rare and threatened with extinction and areas of permanent preservation.

c) **the socioeconomic environment** – the use and occupation of land, water uses and socioeconomics, highlighting the community's archaeological, historical and cultural sites and monuments, the dependency relationships between local society, environmental resources and potential use of these resources in the future.

2) Analysis of the environmental impacts of the project and its alternatives over the three environments described above, through identification, prediction of the

magnitude and interpretation of the importance of the likely relevant impacts, discriminating: positive and negative impacts (beneficial and adverse); direct and indirect; immediate, medium, and long-term; temporary and permanent; its degree of reversibility; its cumulative and synergistic properties; the distribution of social charges and benefits.

3) Measures definition to mitigate negative impacts, including control equipment and waste treatment systems, evaluating the efficiency of each of them.

4) Preparation of the follow-up and monitoring program for positive and negative impacts, indicating the factors and parameters to be considered.

5) The decommission plan as provided for in ANM Resolution nº 68 (ANM, 2021).

All technical studies and results produced in the EIA must be summarized in the RIMA, in colloquial language accessible to the lay public, which will be printed and distributed to interested parties.

Small projects with little potential for environmental impacts are allowed to present a Simplified Environmental Report – RAS. According to Conama Resolution nº 279, the RAS should contain at least:

1) Project description: objectives and justifications; technological and locational alternatives, considering the hypothesis of non-implementation, specifying the area of influence.

2) Environmental diagnosis and prognosis: description of the probable environmental and socioeconomic impacts, considering the project, its alternatives, the time horizons of incidence of the impacts and indicating the methods, techniques and criteria for their identification, quantification and interpretation.

Characterization of the future environmental quality of the area of influence.

3) Mitigating and compensatory measures: identify the impacts that cannot be avoided; recommendation regarding the most favourable alternative; monitoring, follow-up and control program (CONAMA, 2001).

The LP certifies that the proposed project is environmentally viable and lists a series of activities that must be carried out before and during project implementation to prevent, mitigate and/or compensate for environmental impacts. The minimum requirements for the Basic Environmental Project – PBA are also presented in the LP.

With the LP issued, the EPC company must apply for the Installation License – LI and an authorization, a public permission, from the city hall to begin the works. Each municipality has its own procedure for requesting this authorization and will require documents such as the LP, the Note of Technical Responsibility – ART signed by an engineer, tax status of the owner and of the EPC company, among others.

The PBA, required to apply for the LI, is a document that contains the management programs for the socio-environmental issues of an enterprise, which aim to eliminate, mitigate and/or compensate for negative impacts and maximize the positive impacts expected with the implementation of the project. In such a design, all environmental issues listed in the LP must be addressed, resolved or justified, if they have not already been done (BONO et al., 2023).

The LI approves the PBA, presents the environmental guidelines to be adopted during the implementation of the project, the mitigating and compensatory measures to be adopted, as well as the conditions for issuing the Operating License – LO.

All environmental licenses have a validity period that depends on the potential impact of each activity. The LI must be applied for before the LP expires, otherwise the entire process will have to be restarted. All work, assembly and commissioning must be completed before the LI expires. In case of justified delay, the validity of the LI may be extended. The LO must be renewed before each expiration date, when actions to mitigate environmental impacts, decommissioning, among other activities, will be reviewed.

3.4.3 Construction and assembly

After the emission of all necessary licenses, the construction itself begins with soil preparation, earthworks and excavations for underground reservoir, when planned. The shaft sizing to the lower reservoir and the powerhouse is of great importance, as this is where the excavation can be optimized. The penstock, the balancing chimney (surge tank), the electrical conductors and the entry of personnel, material, and equipment will be through this shaft. Large projects may have separate axes for smaller groups of items or even for each of those items.

Several studies have presented variables relations for the penstock optimal design, since Blair that proposed a relation in terms of installed power, P, and waterhead, H, in 1945. Such relations are empirical relations developed from correlated statistical data of existing installations. Some authors have proposed improvements in the Blair formula as explained by Singhal and Arun. The last published formula is presented in Equation 3.8 (BLAIR, 1945; SINGHAL; ARUN, 2015).

$$D_P = \frac{0.52P^{0.43}}{H^{0.6}} \tag{3.8}$$

where D_P is the optimal diameter for the penstock in meters; P is the nominal installed power in kW; and H is the waterhead in meters.

Another main definer of the shaft area is the lift area which depends on the size of the hydro and electrical machines, typically about twice the area of the penstock.

3.4.4 Commissioning

The operation scheme should be planned by conclusion of excavations, civil construction, equipment assembly, and connections. Several control schemes, as voltage control, frequency control, and speed control will depend on the objective of installation. Power plants from 30 MW must follow the grid code issued by the National Electrical System Operator – ONS, whereas small installation can have their own operation and control schemes (ONS, 2024a).

Before connecting to the distribution or transmission grid, the entrepreneur must apply for the LO, also issued by the same competent environmental body that have issued the LP and the LI. After that, commissioning tests can be requested from ONS or DISCO in case of small projects connected as DG. The ONS will issue the Test Release Term – TLT allowing the start of electrical tests. Test operation will be allowed during light load periods, mainly during weekends. These tests allow the ONS, together with the local ESCO operator, to adjust and define the final operation scheme.

After approval of the tests and issuance of the LO, the ONS will issue the Preliminary Release Term – TLP, if there are any pending issue that do not prevent the safe operation of the facilities, or the Definitive Release Term – TLD, otherwise. Both documents will allow the commercial operation of the ESS facilities and the receipt of the corresponding revenues by the ESCO.

3.5 Decommissioning

In recent decades there has been a growing concern about the closure of industrial activities, the disposal of unusable waste, and the recovery of the environment degraded by industrial activities, driven mainly by environmental guidelines and policies. As there is no regulation for UPSH in Brazil, the regulation for mines closure will be used by similarity in this work.

According to Clark and Clark (2005), governments' understanding of the need to combine economic development with environmental preservation emerged in the 1970s in some developed countries. The main concern of mining codes in most countries until 1980s was to regulate methods of exploiting mineral resources, determining administrative procedures, rights and duties of miners. At that time, the competent bodies were not explicitly concerned with environmental aspects of mining projects, such as the gradual closure of mining fronts or the recovery of degraded areas after the depletion of mineral reserves.

Mining is an ancient activity that, in Brazil, began a few years after the arrival of Portuguese. There was no regulation for the activity, therefore they followed European standards. The first regulations in Brazil were issued after the establishment of the Republic at the end of the 19^{th} century. However, environmental concerns only arose in the 1980s through the Law nº 6,938, that established the National Environmental Policy – PNMA, in 1981, and the National Constitution issued in 1988 (BRASIL, 1981, 1988).

Although concerns about mine closures began in the 1970s in developed countries, in Brazil, the first regulatory acts in this regard were only published in the 2000s. Before that, many mining facilities were abandoned without any process of decommissioning and rehabilitation of degraded areas, due to the high costs of this process, as well as due to the lack of regulation for deactivation phase of the projects (TONIDANDEL; PARIZZI; LIMA, 2012).

The first act related to the decommissioning of mines was the Ordinance nº 237, issued by National Department of Mineral Production – DNPM in 2001. This ordinance provided for 22 Mining Regulatory Standards – NRMs, including NRM nº 20 and NRM nº 21, which provides rules for the closure of mines and rehabilitation of impacted areas, respectively. These rules remain valid even after the extinction of the DNPM and the creation of the National Mining Agency – ANM in 2017. However, items 20.4 and 20.5 of NRM 20 which provided for the definitive closure of mines were revoked by ANM Resolution nº 68 in 2021. The resolution 68 created the Mine Closure Plan – PFM to replace the NRM 20.4 and 20.5 (ANM, 2021; DNPM, 2001).

The PFM is defined as a set of procedures for decommissioning the mine area after mining activity, involving the demobilization of temporary structures supporting mining and processing operations, the physical and chemical stabilization of permanent structures and their monitoring, as well as the qualification of the area for new mineral exploitation or other future use. The obligations set forth in the PFM that should be applied by similarity to UPSH includes:

1) the characterization of the project area, presenting data related to civil, geotechnical, hydraulic structures, electrical installations, equipment, among others, and the expected useful life of the project;

2) the physical-financial schedule of the program, integrating pre-closure, closure and post-closure actions;
3) the planned monitoring and maintenance actions in the area;
4) the assessment of risks arising from the closure of the project and ways to mitigate any damage resulting from the activity;
5) the demobilization plan for the facilities and equipment that make up the project's infrastructure;
6) the project for decommissioning civil structures;
7) the physical and chemical stabilization plan for the remaining structures;
8) measures to prevent unauthorized access to the project's facilities;
9) maintenance and monitoring actions for the remaining structures after the project's closure; and
10) guidelines for adapting the area to its future use.

According to NRM nº 21, the rehabilitation project for degraded areas, as well as the PFM, must be submitted to the competent body together of environmental studies. Such a project should include at least the following items:

1) identification and analysis of direct or indirect environmental impacts on the physical, biotic and anthropic environments;
2) aspects of landscape and topographic conformation, observing:
    a) stability;
    b) erosion control;
    c) drainage;
    d) landscape and topographic suitability; and
    e) revegetation.
3) monitoring and follow-up program;
4) updated plan showing the current topographic situation of the areas to be rehabilitated;
5) suitability and future use of the area; and
6) physical and financial schedule of the rehabilitation plan.

As the decommissioning project must be presented during the environmental licensing process, it will be part of obligations provided on LO. Such a project must be reviewed and renewed periodically, as the socio-environmental neighbourhood of the facilities is dynamic and it changes every year, as well as the environmental legislation.

Chapter 4 – Case study 1: Proposal for an μUPSH at Unifei's campus

There are several definitions for a microgrid; however, three patterns are present in all of them: a microgrid is an intentional island formed in an electrical distribution system; it may operate in island or grid connected mode; and must have at least one generation plant, one energy storage facility, and loads. Based on this context, the campus of Unifei can be seen as a microgrid, as it has clear electrical boundary, a single grid connection, own solar PV generation, and several kinds of loads, as laboratories, classrooms, and many other activities, as illustrated in Figure 4.1 (ARAGON et al., 2022; DE DOILE et al., 2023a; KROPOSKI et al., 2008; REY et al., 2017).

A self-sufficient microgrid should operate islanded for an indefinite period, however, in some cases, it is sufficient to operate islanded for a few hours. In this context, this work proposes the second alternative: zero grid consumption during peak time, when the tariff is high, even if extra grid consumption is necessary during off-peak time.

Figure 4.1 – Unifei campus schematic.

4.1 Prospecting

As can be seen in Figure 4.1, Unifei campus has an artificial lake. Considering the lake area in its normal level, approximately 12,000 m², and two meters of variable level (the useful volume), the lake has more than 24,000 m^3 of useful water, Figure 4.2.

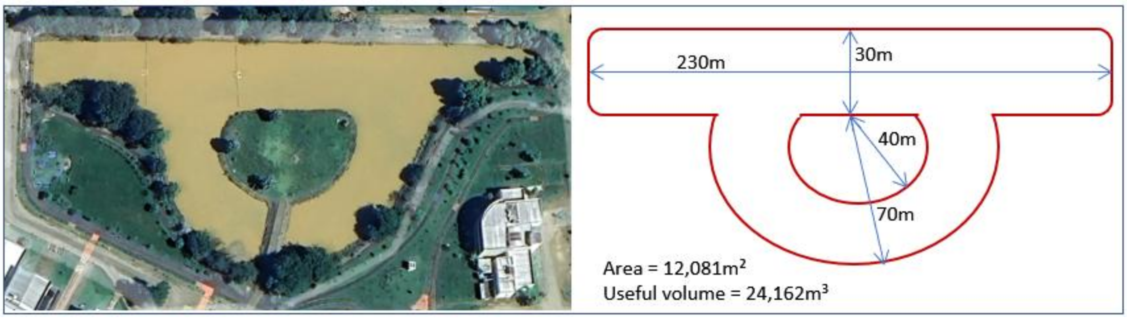


Figure 4.2 – Unifei lake. Considering 2 m level variation, the lake presents more than 24,000 m³ of useful water.

At this stage, only the installed power magnitude order needs to be known. Unifei's contracted demand is 1,100 kW since November of 2022, which means the need for an installed power of less than 5 MW, making the Unifei plant classified as µUPSH. However, the lake potential (the energy availability) must be defined. The water flow rate, *Q*, is given by (4.1) (SALLES; BONATTO; RIBEIRO, 2021).

$$Q(t) = Vt^{-1} \tag{4.1}$$

where *V* is the available volume of water in cubic meters and *t* is the time in seconds.

Thus, the energy available can be calculated by (4.2) (BROCKSCHINK; GURNEY; SEELY, 2001).

$$E = \int_0^T \eta g \rho H Q(t) dt \tag{4.2}$$

where η is the dimensionless overall plant yield; *g* is the gravitational acceleration; ρ is the water specific weight; and *H* is the waterhead.

Making *T* = 1 hour, the energy *E*, in Watts-hour, becomes equal to the power *P*, in Watts, that can be calculated by varying the waterhead, *H*, as the other variables are known in this case study: Q = 24,162 m^3/3,600 s = 6.71 m^3/s per hour, given by (4.1); ρ = 1,000 kg/m^3; g = 9.81 m/s^2; and η = 80%, as stated by Energy Research Company – EPE in the Reversible Hydropower Technical Report (EPE, 2021).

The minimum waterhead, *H*, is equal to the lake level variation, 2 m. Therefore, the minimum installed power, *P*, could be 105 kW for an hourly system. The minimum excavation volume will be equal to the useful volume, 24,000 m^3, that will be the lower reservoir volume. The soil survey will define the shape of the lower reservoir, which will be, at least, a cube with sides equal to 28.85 m.

The required waterhead will define the penstock length and powerhouse location. There is a direct relationship between the penstock length (volume of excavation) and the installed power. The installed power and penstock length will be defined in next sections.

As a µUPSH, the environmental license should be requested from the municipality, in the Environment Municipal Secretariat, following the procedures described in its webpage (PM ITAJUBA, 2024).

The technical designs and grid connection must follow the distribution procedures and distribution company's requirements, in this case, the Cemig's Distributed Generation Handbook (CEMIG, 2024).

As Unifei is a non-profit public institution, the sale of energy is not the institution's objective. Therefore, considering that the current regulations allow the insertion of ESS in the DG, the commercial status of Unifei's µUPSH should be Distributed Generation – DG included in the Electrical Energy Compensation System – SCEE.

4.2 Design

Unifei has a contracted demand from the distribution company of 1,100 kW, that is: the university management is sure that the demand will not exceed that peak value, as a penalty may be charged if happen. On the other hand, the historical peak of demand was 860 kW which, considering a safety margin of 20%, would not exceed the contracted demand.

Historical daily average load curves before the entry on operation of Solar PV power plant are presented in Figure 4.3 for a year (A), first scholar semester from March to June (B), second scholar semester from August to November (C), and non-scholar months December, January, February, and July (D). The highest consumption is in the second scholar semester afternoon, while the lowest is in the non-scholar period early morning.

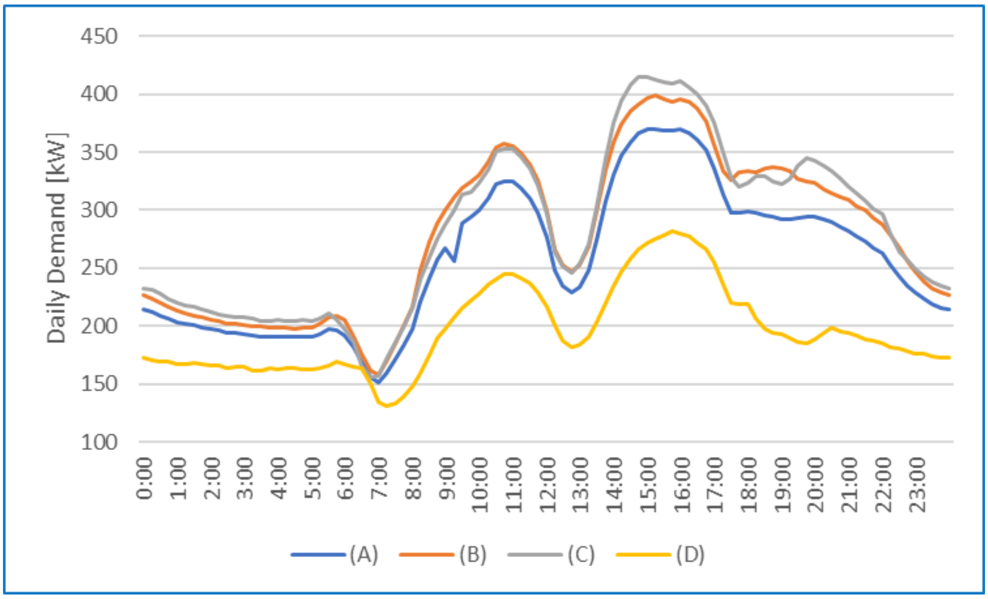


Figure 4.3 – Unifei average electrical consumption before the entry on operation of Solar PV power-plant. (A) a yearlong in blue, (B) from March to June in orange, (C) from August to November in grey, and (D) other months in yellow colour.

Daily average of solar PV production in 2023 is shown in Figure 4.4. (A) maximum generation that occurs during the summer, (B) average of the maximum generation, (C) average and (D) minimum generation, during the winter.

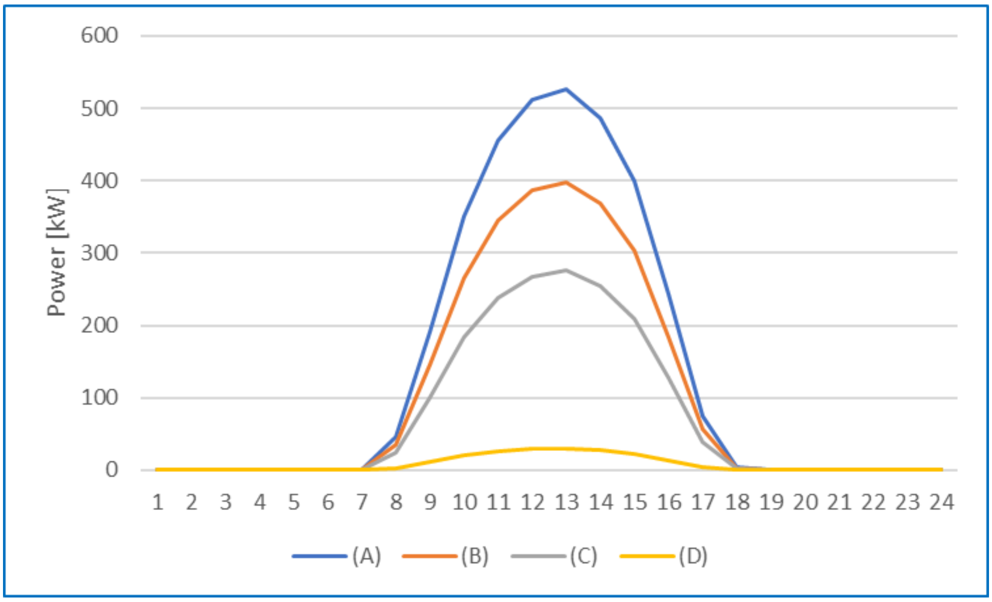


Figure 4.4 – Unifei Solar PV production in 2023. (A) maximum production in blue colour (B) maximum average in orange, (C) average in grey, and (D) minimal production in yellow.

Two alternatives were considered when dimensioning the photovoltaic solar plant: (i) compensating for all consumption on the Unifei campus and (ii) compensating for peak time consumption. In the first case, photovoltaic solar production should be greater than campus consumption. The second, where generation should be equal to consumption during peak time between 5pm and 10pm, has been implemented in the Unifei's campus. However, the new regulation establishes that compensation must be at the same tariff post that the energy surplus was injected into the grid. If compensation occurs at the peak time, the tariff difference is discounted, frustrating the first objective. The solution for such an issue, beyond the installation of other generation sources, is the installation of an ESS.

The first approach for µUPSH is to identify the energy deficit and generation surplus available. The maximum generation surplus will occur in the summer non-scholar months, Figure 4.5, where generation comes from Figure 4.4 (A) and consumption from Figure 4.3 (D). Conversely, the maximum energy deficit will occur in the second scholar semester raining days, Figure 4.3 (C).

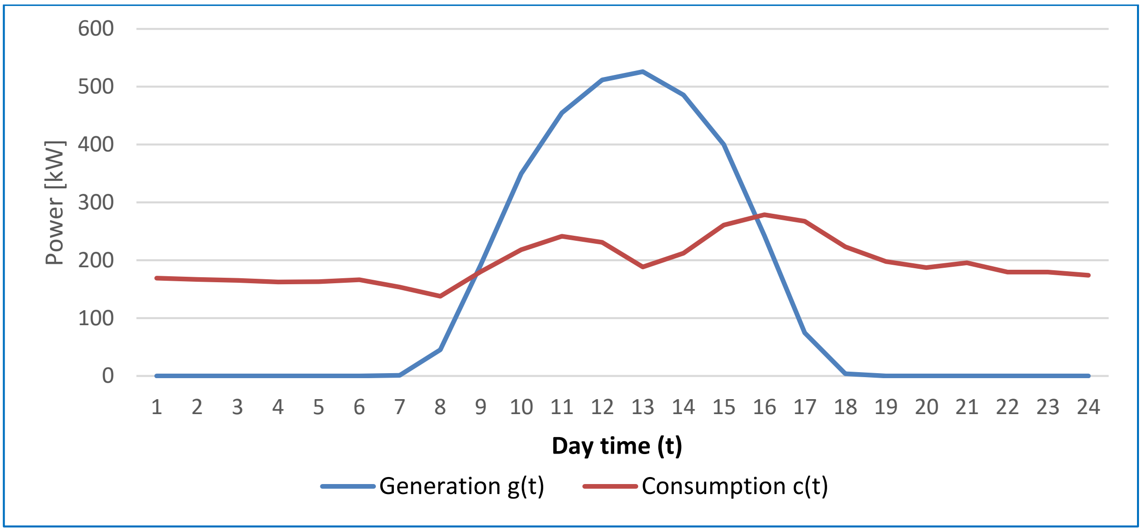


Figure 4.5 – Unifei Solar PV production in blue and consumption in red. Surplus generation between 8:30am and 4pm should be used to avoid consumption during peak time from 5pm to 10pm.

The energy surplus, *S*, is given by the positive values of the integral of the difference between generation, $g(t)$, and consumption, $c(t)$, (4.3). The deficit will be represented by the negative values of this same integral. The deficit during peak time, D_{PT}, is given by (4.4).

$$S = \int_{t=1}^{24} [g(t) - c(t)]dt, \quad g(t) > c(t) \tag{4.3}$$

$$D_{PT} = \int_{t=17}^{21} [g(t) - c(t)]dt \tag{4.4}$$

In this case study, S = 1,388 kWh and D_{PT} = 1,689 kWh (maximum consumption in the 5 hours of peak time on a cloudy day with solar PV generation equal zero), which means that the generation installed on the Unifei campus is not enough to meet peak time without additional grid consumption. Conversely, considering a 1,700 kWh µUPSH (312 kWh comes from the grid during out-off-peak time) to operate in flat mode during 5 hours on peak time, the waterhead calculated through (4.2), is of 32.4 m. Considering an elevation of one meter in the perimeter of the lake, the new useful volume will be 36,243 m³. Firstly, this volume of material removed to build the underground reservoir is sufficient to raise the perimeter of the lake. The new water head calculated will be 21.5 m, as the new water flow through penstock is 10.07 m³/s per hour or 2.01 m³/s in 5 hours of peak time. The nominal power in this case should be 1,700/5, or 340 kW, and must be checked with the maximum peak power.

It is not the objective of this study, however the solution to reducing the need for energy storage is to increase generation, especially with a complementary source like wind power, as photovoltaic solar energy is not capable of producing at peak times.

4.2.1 Adjustments of design

The next step is to adjust the project using statistical and financial tools and long-term data. The variation in generation, from zero to maximum observed, and consumption, from minimum to maximum measured, were used as input to find the deficit to be covered by the µUPSH. Both inputs, generation and consumption, were considered following a BetaPERT distribution. Such a distribution is continuous and describes a situation in which the minimum, maximum and most likely values to occur are known. Maximum and minimum values have less probability, while intermediate values are considered more often in the simulation. Results for 10,000 runs (scenarios) are shown in Figure 4.6.

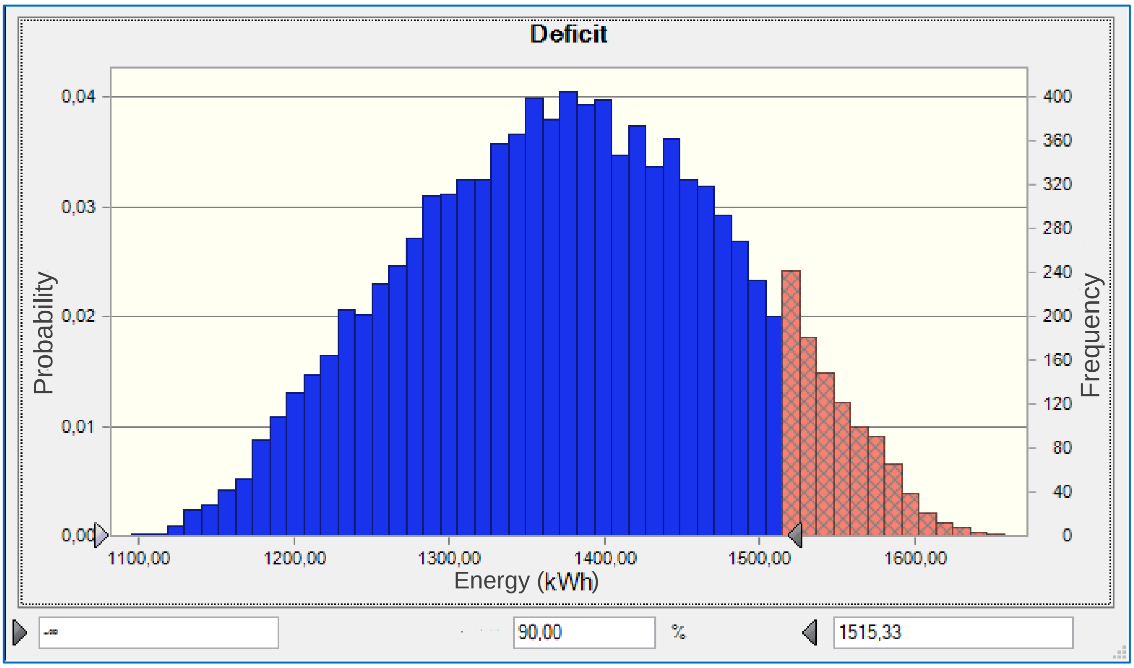


Figure 4.6 – Deficit probability. Result shows the difference between the consumption and generation during peak hours, from 5pm to 10pm.

The most common deficit value is of 1,380 kWh occurring in around 50% of cases. 80% of scenarios presents deficit less than 1,470 kWh, while a value of 1,515 kWh covers around 90% of scenarios and 1600 kWh, 99.5% of scenarios. Decision makers could choose any of these scenarios based on how much they would be willing to pay for peak time consumption. A number that covers 90% of scenarios is usually chosen. In this case study, a µUPSH capacity of 1,500 kWh will be considered to cover approximately 90% of power deficit cases. Assuming that the soil survey confirms the possibility of excavations of about 50 m depth (penstock of about 20 m plus lower reservoir's height, that is at least a cube of 33 m side), the waterhead could be at least 19 m in this case study to cover around 90% of scenarios. However, the peak power will define the final waterhead.

The rated power of µUPSH will be defined by the maximum demand on peak time, which is 395 kW, according to historical data. The µUPSH rated power should be 500 kW, considering a safety margin and a long-term demand growth of 1% per year. When operating at maximum power, 500 kW, the plant will be limited to its capacity of 1,500 kWh and then limited to three hours of operation. Being the water flow 3.35 m^3/s, the calculated waterhead will be 19.13 m, confirming the value estimated before (SIOSHANSI, 2013).

The set of turbine-generator, reversible to motor-pump, should be Kaplan turbine coupled to an induction motor. Kaplan is the most efficient turbine for medium waterhead while the squirrel-cage induction motor is suitable for grid follow plants. The machine operating as motor or as generator will be synchronized to the grid, not requiring complex and accurate frequency and voltage control in this operation mode (SHADHU KHAN; CHATTERJEE, 1999).

4.3 Business plan

Unifei µUPSH, connected as DG, will be used primarily for self-consumption meeting peak demand, to avoid or, at least, reduce the campus consumption during peak time, when tariffs are high.

An economic assessment must be carried out in this phase. Firstly, the initial investment should be considered and then, a long-term study considering operation and maintenance costs, the compensated energy, avoided consumption, and electrical losses must be priced in this analysis.

The Net Present Value – NPV, (3.3), and the Internal Return Rate – IRR, (3.5), of the difference between Unifei's energy bill before µUPSH entry into operation, (4.3), and after µUPSH, (4.4), was carried out for a series of 30 years.

$$U_B = D * T_D + (C_{OP} - G_{OP} + S_{OP}) * T_{OP} + (C_{IN} - G_{IN} + S_{IN}) * T_{IN} + (C_{PK} - G_{PK} + S_{PK}) * T_{PK} \quad (4.3)$$

where U_B is the Unifei's energy bill before µUPSH entry into operation ($U_{Bi} = C_{fi}$ in 3.3 and 3.5; $1 \leq i \leq 30$); D is the contracted demand; T is the tariff; C is the consumption; G

is the generation; S is the surplus; and subindexes D means demand; OP, out-of-peak time tariff; IN, intermediate time tariff; and PK, peak time tariff. Note that, for each consumption parcel, if $C > G$, $S = 0$ and U_B will be positive; if $C = G$, $S = 0$ and $U_B = 0$; finally, if $C < G$, $S = G - C$ and $U_B = 0$ again.

$$U_A = D * T_D + (C_{OP} + C_{ES} - G_{OP} + S_{OP}) * T_{OP} + (C_{IN} - G_{IN} + S_{IN} - ES_{IN}) * T_{IN} + (C_{PK} - G_{PK} + S_{PK} - ES_{PK}) * T_{PK} \tag{4.4}$$

where U_A is the Unifei's energy bill after µUPSH entry into operation, $U_{Ai} = C_{fi}$ in (3.3) and (3.5) for $1 \leq i \leq 30$; C_{ES} is the µUPSH's consumption from the grid when the surplus is not enough; and ES is the stored energy by µUPSH and then consumed. Note that the last two parcels in (4.4) will be nonzero only when the deficit exceeds the installed capacity of µUPSH. In other words, when the instantaneous demand is greater than 500 kW or the daily energy deficit is greater than 1,500 kWh.

The initial investment, I_0 in (3.3) and (3.5), in a PSH stated by EPE is from 1,000 up to 3,500 USD/kW (EPE, 2021). Saltuk (2023) state that the average initial costs are 2,200 USD, while Topalovi, Haas, and Sayer (2024) in a European study point 528 Euros per kW of installed power. In this case study a BetaPERT distribution, varying from 500 up to 3,500 USD, with the most frequent value of 2,000 USD/kW, was considered, as costs dropped last year and the forecast for the coming years is that they will continue to fall (MANNING, 2024).

The annual inflation was considered varying from 1.5% up to 10%, with the most frequent value equal to 4%, based on historical data given by IBGE (IBGE, 2024). Solar PV generation varies from 150 up to 3,500 kWh per day, with the most frequent value equal to 2,000 kWh, while consumption varies from 4,800 up to 7,000 kWh per day, with the most frequent value equal to 5,900 kWh, both of then based on Unifei's data. Results are presented in Figure 4.7.

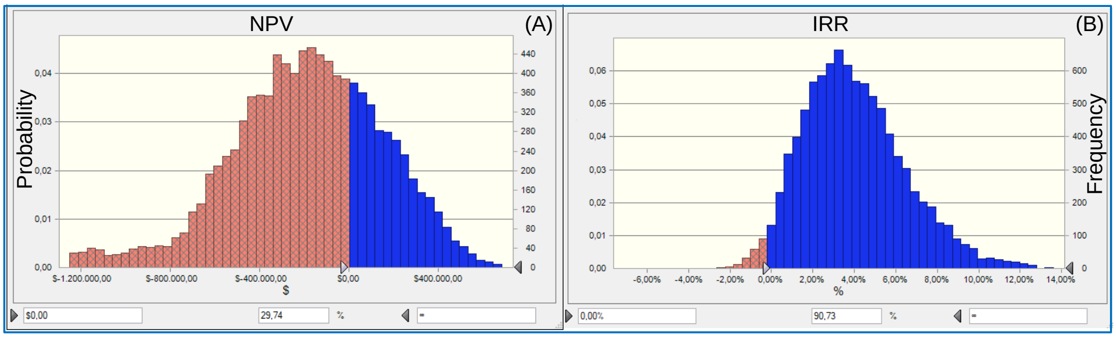


Figure 4.7 – NPV and IRR probability for the Unifei's µUPSH after 10,000 MCS runs.

An NPV of zero means that all investment and costs are recovered in the analysed period. No profits are made in such a case. The higher the positive NPV, the greater the investor's profits. The result presents around a 30% probability of a positive NPV, Figure 4.7 (A). This result does not encourage a private investor, however, as previously stated, Unifei is a non-profit public institution. Therefore, a 30% probability of positive NPV is a good result for research and development.

Conversely, a positive IRR means that the recovered investment will be monetary adjusted, while negative values mean money lost. The result in Figure 4.7 (B) shows a high probability of a positive IRR, however very little probability of an IRR greater than the inflation rate. IRRs not exceeding the inflation rate are not attractive to private investors.

The technical and economic feasibility of a µUPSH prototype on the Unifei's campus of Itajubá was demonstrated in this phase of the case study. Advanced civil construction studies, sizing of hydraulic and electrical machines, and control and electrical stability should be carried out in the future. This prototype will allow advances in research related to the topic, for instance, the use of other energy sources, power plant dimensioning, control and protection, grid stability, and many others, in addition to saving the University's energy bills.

4.4 Project execution

Once the design phase is complete, the environmental licensing and public licensing processes can begin, as predicted in subsection 3.4.2. This phase is normally carried out by an EPC company, through a turnkey contract, with the owner or contractor only responsible for supervision.

Unifei's µUPSH can be classified as of little potential for environmental impacts. Therefore, the environmental studies to be presented to municipality of Itajubá can be summarized in a RAS, with the follow minimal contents:

a) The influence area is restricted to the University's campus. There is no locational alternative, as the project considers the use of the existing lake. Battery banks is a technical alternative; however, the environmental impact may be worse when considered the production and disposal of batteries.

b) There will be no socioeconomic impacts; nevertheless, aquatic life in the lake will be affected. A monitoring program with some interventions to guarantee the aquatic life must be included in the RAS.

c) Lake monitoring and control programs must be implemented after the enter in operation of plant, as this impact cannot be avoided.

After obtaining the proper permits, the Preliminary License – LP and the Installation License – LI or, in some cases at the discretion of the environmental body, the unified Preliminary and Installation Licence – LPI, the construction itself can begin.

The first phase of construction, in this case, will be the soil preparation and excavation of the lower reservoir. The shaft section must be sufficient to accommodate the penstock, electrical conductors, ventilation, and personnel access. The material removed during the excavation should be used to raise the lake dam by at least one meter.

Penstock optimal diameter calculated by (3.8) is of 0,98 m, leading to a shaft section of around 3 m² to accommodate all facilities, including the lift. An additional emergency exit must be installed in the powerhouse, as provided for in NRMs nº 07 and nº 14. Such an exit must have a slope of less than 20° with the ground, to dispense with the use of a ladder, leading the access to a distance of 60 to 140 m from the main shaft, depending on the height of the powerhouse. The general aspects of facilities are shown in Figure 4.8.

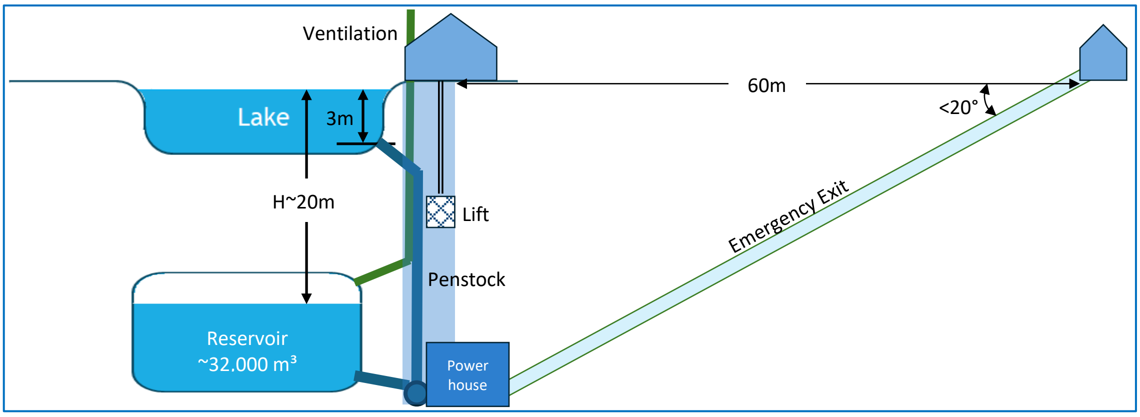


Figure 4.8 – Schematic of Unifei's µUPSH (Dimensions in the figure are not proportional.)

Due to the lack of specific regulation, µUPHS will be equated to Distributed Generation – DG and, in this way, connected to the distribution grid as a grid-follow installation, that is: voltage and frequency will be controlled by the distribution grid. Local control will only be responsible for dispatching (power control).

Considering that the main objective of the installation is to reduce grid consumption during peak hours, the plant will be dispatched for five hours per day, between 5pm and

10pm. The dispatch control will read the current at the Common Coupling Point – CCP and dispatch the plant by controlling the rotor speed, with the aim of making such a current equal to zero.

Even though it is outside the peak time of 10pm to midnight, the µUPSH will be in standby mode, as consumption on campus is still high. From midnight to 5pm, the plant will be able to pump water from the lower reservoir to the upper reservoir. The amount of water to be pumped at each time interval will depend on the weather forecast for the following day. If a clear day is forecast with a high probability of generation surplus, an amount of water equivalent to this generation surplus will be pumped using that surplus of energy. The difference, when there is one, is pumped in advance between midnight and 6am, the period of lowest consumption on campus. If the weather forecast does not come true, the difference necessary to empty the lower reservoir will be pumped out before 5pm. On some days there may be a surplus of energy greater than necessary to empty the lower reservoir. On these days, surplus energy is injected into the distribution grid and compensated through the SCEE. The flowchart of proposed control is presented in Figure 4.9.

As from 5pm solar PV production is reduced, a specific study could be carried out to connect the µUPHS to the grid through the solar power plant ac-dc-ac converter. More robust and functional controls can be implemented through such a converter.

More robust, precise and functional controls might be implemented through a dedicated ac-dc-ac converter. In this case, the converter adjusts the frequency to vary the power maintaining the torque of the electrical machine in generator mode. When in motor mode a squirrel cage machine cannot have consumption control if it is connected directly to the grid. However, when connected through a dedicated ac-dc-ac converter, its power can be controlled, making it a variable load. This arrangement can be used to modulate the consumption of the motor pump set during the period of surplus solar photovoltaic generation and also put less stress on the network with an equal distribution of pump consumption over time.

After completion of the works, the EPC should start the open circuit tests and, in parallel, request the Operating Licence – LO from the competent environmental authority and an authorization for energized tests from the local DISCO, CEMIG. During the tests, the DISCO will check the impacts on the distribution grid. If all the tests are well done and approved by the DISCO, the installation is ready to enter into operation.

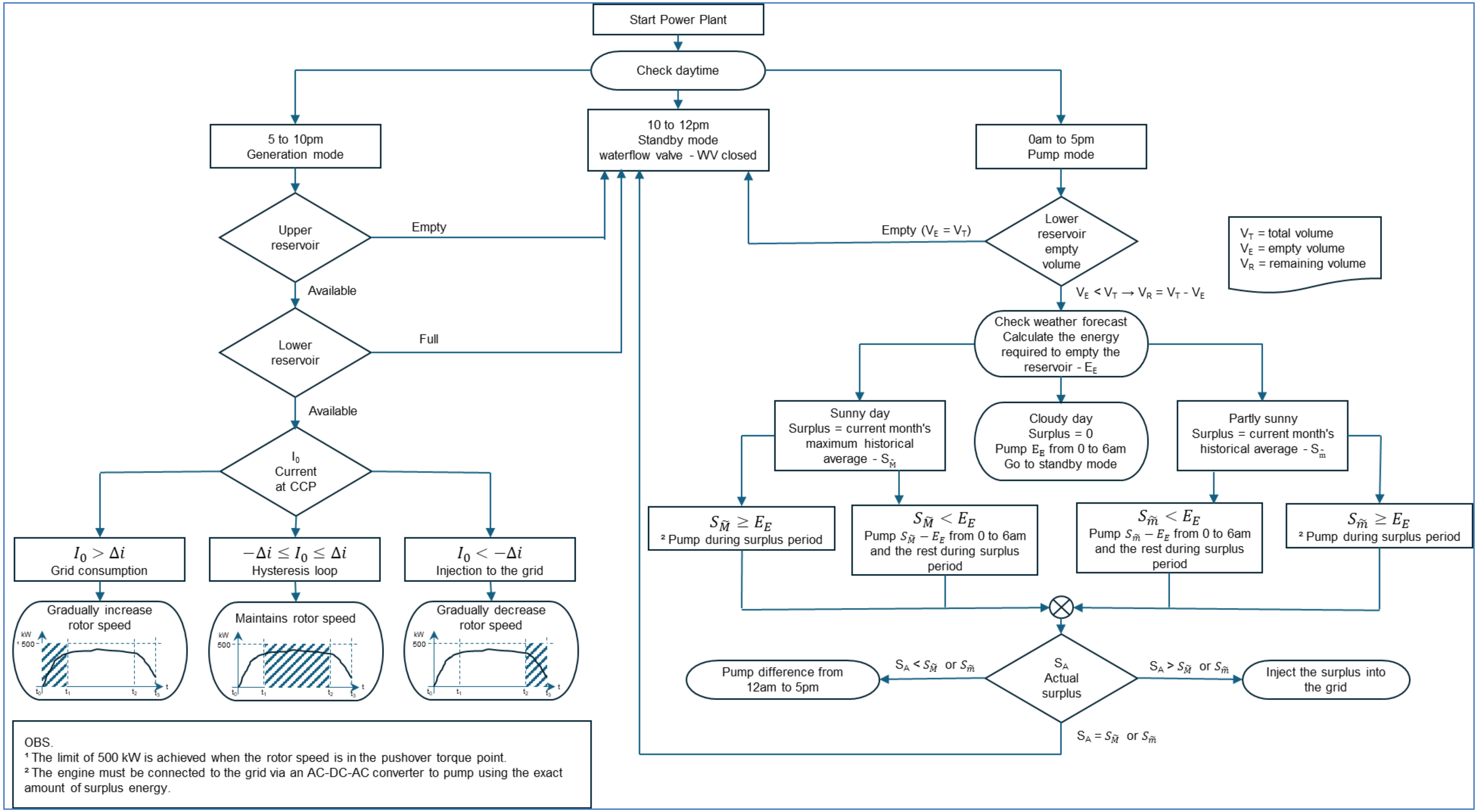


Figure 4.9 – µUPSH's control flowchart.

The maintenance program will basically be preventive maintenance. Machinery and electrical equipment should be constantly monitored. Accessible areas should be regularly cleaned to avoid accidents. A µUPSH stopping for general maintenance should be scheduled during the July school break, when electricity consumption and solar photovoltaic generation are lower. During such a shutdown, the turbine and generator should be disassembled, inspected, cleaned and lubricated. Eventually, some damaged parts should be replaced. A complete set of tests should be carried out once more before reconnecting the installation to the distribution grid.

4.5 Decommissioning

Even though the facility has a very long useful life, around 50 years, the preliminary decommissioning project must be presented during the environmental licensing process, reviewed and updated periodically. Such a project must contain, at least:

1) the characterization of the project area;
2) the planned monitoring and maintenance actions in the area;
3) the risk assessment of the project and ways to mitigate any damage;
4) the demobilization plan for the facilities;
5) the project for decommissioning civil structures;
6) guidelines for adapting the area to its future use; and
7) monitoring and follow-up program.

Since the installation will be entirely on campus, the characteristics of the area may not undergo major changes during the project's lifetime. The lake water should be monitored for animal life, as well as preventing eventually chemical pollution. After decommissioning the lake should return to its previous conditions.

At the end of their useful life, all facilities should be destinated for recycling, except for civil structures that may be used for other university activities. The underground reservoir, shafts, and all excavated areas must be filled with sand or other material to prevent the soil from sinking. After that, the soil stability must be periodically monitored.

Chapter 5 – Case study 2: Proposal for an UPSH at Lake Mundaú

Lake Mundaú, with a volume of more than 100 million cubic meters of water, is one of several large lakes in Brazil. It is located on side of Maceió city, the capital of Alagoas state, in the Northeastern region. This lake is close to many of the wind farms installed in that region and, also, close to someone deactivated deep mines. Nevertheless, these deep mines cannot be considered in this case study, as they are under legal demand due to environmental issues, and there is no data available.

The objective of the facility proposed in this case study is to reduce wind and solar power curtailment and constrained-off through energy time shifting and peak shaving to decongest the transmission system, respectively. Consequently, the UPSH will provide a deferral of investment in new transmission lines. Additionally, other services can be provided, such as voltage and frequency support, black start, integration of new wind and solar energy, among others.

5.1 Prospecting

Firstly, to carry out the prospecting phase, the so-called Hydroelectric Inventory Studies – EIH in the hydroelectricity regulation, registration with ANEEL is mandatory. Such a registration is mainly to avoid duplicate studies of the same hydroelectric potential.

The geological characteristics of Lake Mundaú area are presented in Table 5.1. As can be seen, the soil is suitable for deep excavations of up to 2,350 m. Kramer et al (2020) stated that waterhead should be as high as possible to minimize the volume of the underground reservoir and therefore the costs. However, the highest waterhead considered feasible by the pump-turbine manufacturers is about 1,400 m. Therefore, to avoid the salt layer, between 1 and 1.5 thousand meters, this project will be limited to 1,000 m depth (MARIANO, 2021).

Table 5.1 – Geological characteristics of Lake Mundaú region.

<table>
<tr><th>Geological era</th><th>Formation</th><th>Group</th><th>Main rocks</th><th>Depth [m]</th></tr>
<tr><td rowspan="3">Cenozoic</td><td rowspan="3">Algodoais</td><td>Barreiras</td><td>Sandstones, claystones, and conglomerates</td><td>0 up to 165</td></tr>
<tr><td>Marituba</td><td>Sandstones and claystones</td><td>165 up to 335</td></tr>
<tr><td>Muribeca</td><td>Limestone intercalated with shale and sandstone</td><td>365 up to 670</td></tr>
<tr><td>Mesozoic</td><td colspan="2">Poção</td><td>Conglomerates formed by pebbles and boulders of igneous and metamorphic rocks in a fine sandy matrix</td><td>670 up to 725</td></tr>
</table>

Cretaceous	Maceió	Sandstones with clasts of dispersed igneous and metamorphic rocks, followed by siltstones, shales, and rocks with a high halite content intercalated between thin levels of shales and limestones.	725 up to 2,000 Evaporite layer (salt deposit) between 1,010 and 1,480 m
	Coqueiro Seco	Sandstones interbedded with shales, siltstones, and thin layers of limestone.	2000 up to 2350

Figure 5.1 shows the area of the lake. The surface area of the lake at normal level is about 24 km² with an average of 4.5 m depth, resulting in a volume of 0.108 km³ or 108 million cubic meters of water. Considering only 0.5 m of level variation, the useful volume of water is $12x10^6$ m³, and the hourly water flow rate is of 3,333 m³/s ($12x10^6$m³/ $3.6x10^3$s), given by (4.1). Thus, with a waterhead of 1,000 m, the power availability, calculated by (4.2), will be of 26.16 GW, more than twice of Itaipu power. From another point of view, water availability is not a limiting factor for this project.

Figure 5.1 – Lake Mundaú. Considering 0.5 m level variation, the lake presents more than 12,000,000 m³ of useful water.

Even though they are synonyms, the terms curtailment and constrained-off have different meanings in Brazilian regulations. Curtailment is not yet regulated and occurs when generation is greater than demand, forcing the operator to shut down some plants. In other hand, the constrained-off is regulated by REN nº 1,073 and occurs when there is some restriction on the grid that requires the interruption of the plants dispatch. The cost of energy not dispatched due to constrained-off will be covered by consumers and paid via system charges (ANEEL, 2023d).

According to Souto Jr. (2024), the annual average of curtailment in wind energy corresponds to 5.25% of generation, with solar energy approaching this level in the firsts months of 2024. Adding 8% on average of turbinable discharge in hydropower already noticed by ONS, the annual average of the power surplus is around 7 GW, being 1 GW from wind and solar photovoltaic curtailment.

According to the National Energy Plan – PNE 2050 wind and solar energy will grow between 4 and 5 times by 2050, reaching around 220 GW of installed capacity, being 80% of this amount located at Northeastern region. Considering the same growth, the wind and solar curtailment will be between 4 and 5 GW in average by 2050 (EPE, 2020b).

Considering that there are several lakes and dams in the Northeastern region and, to avoid transmission congestion, this case study will be limited to 500 MW of installed power and 1 GWh of energy capacity. The remaining demand can be met by other projects, similar to this one, using other of several available water bodies in the region.

An accurate load flow study should be carried out to define grid connection point and, eventually transmission reinforcements, as well as some stability essays, such as electromechanical stability and dynamic stability. The Messias 500 kV substation, located 30 km from Lake Mundaú, will be considered as the provisional connection point in this case study.

A 500 MW UPSH may be considered of great environmental risk leading to the need of Environmental Impact Study – EIA and the corresponding Environmental Impact Report – RIMA for licencing. According to current legislation, such licensing should be requested from the state environmental agency, the Alagoas State Environmental Institute – IMA, since the affected area, the lake area and the transmission line corridor, is in more than one municipality. However, Ibama may invoke this licensing process due to the likelihood of major environmental impact (BRASIL, 2011; IMA-AL, 2024).

The technical designs and grid connection must follow the Grid Code, provided by ONS, whereas excavations for shafts, power-house, and underground reservoirs must follow the mining regulation provided by ANM (ANM, 2025; ONS, 2024a).

This facility size is classified as UPSH and must be granted through a public auction, according to current legislation, the Law 9,074/1995. The main services should be contracted at the auction and other possible services should be left at the entrepreneur risk, making this project a mix of public service and Independent Energy Producer – PIE (BRASIL, 1995a).

Interested entrepreneurs should register this study with ANEEL and prepare an updated Technical and Economic Feasibility Study – EVTE, the Design phase in this case study. After this, the previous environmental license – LP should be requested from the IMA and wait for the facility tender.

5.2 Design

This phase of the project, the EVTE in the hydropower regulation, must also be registered with ANEEL and now await the issuance of an Authorization Order. With the Order in hand, the first step is to dimension the demand for energy storage services. The main UPSH objective is to avoid wind power curtailment; therefore, the last year wind production is presented in Figure 5.2 to show the average of power curtailment.

In the Figure 5.2 is plotted the monthly average of Capacity Factor – FC, the average maximum generation, and the average minimum generation. FC is the ratio between the actual generation capacity and the nominal installed power. As can be seen by the curves, most of the time the difference between FC and minimum average is greater than the difference between maximum average and the FC, evidencing the curtailment, that varies from 100 up to 950 MW. The UPSH project proposed in this study case can meet part of this curtailment.

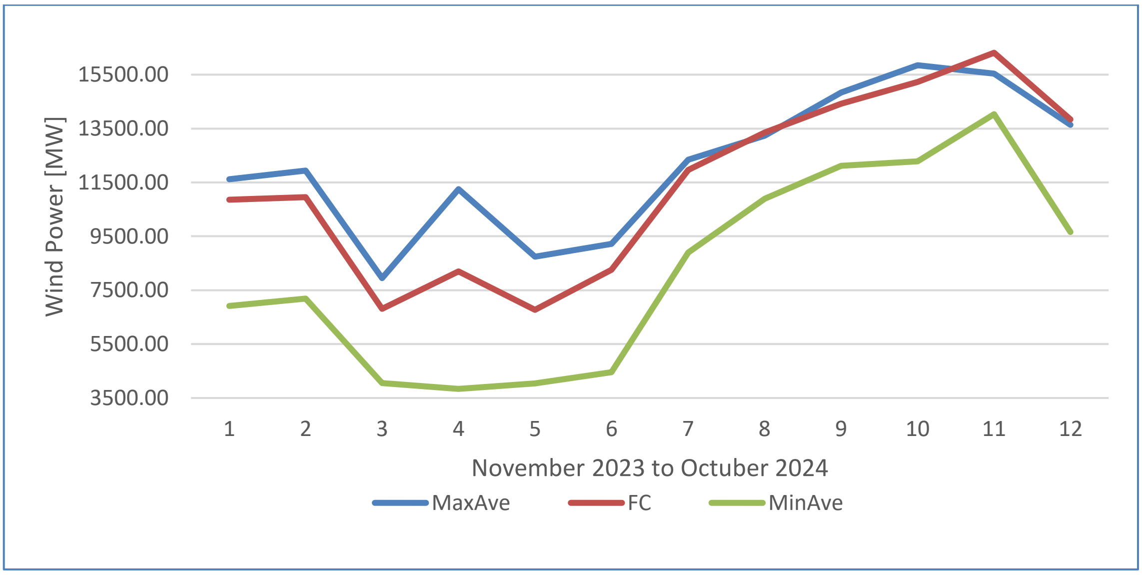


Figure 5.2 – Capacity factor and maximum and minimum daily averages of wind production in Northeastern region from November 2023 up to October 2024.

According to data from the National Electrical System Operator – ONS, 91.2% of wind capacity is installed in the Northeastern region, while 58% of photovoltaic solar is in this same region, totalling 81.9% of intermittent renewable energy installed in there.

Such data, together with total curtailment data, allows us to infer that around 800 MW on average were restricted last year in the Northeastern region (ONS, 2024b).

Another important task to be done by the UPSH is to reduce the daily power ramp, that varies from 2.3 up to 9.8 GW as presented in Figure 5.3. The daily power ramp in September and October of 2024 presents the greatest power ramp achieving almost 10 GW, whereas the smallest ramp is of 2.3 GW in January of 2024.

As shown in these two datasets, the need for energy storage is much greater than the proposed UPSH here. Therefore, the 500 MW of installed capacity and 1 GWh of energy proposed will be maintained, even though it is not enough to meet the need and having water resources, since generation is dispersed in the region and would need new transmission lines. Other projects like this should be developed for other grid connection points, taking advantage of other existing lakes.

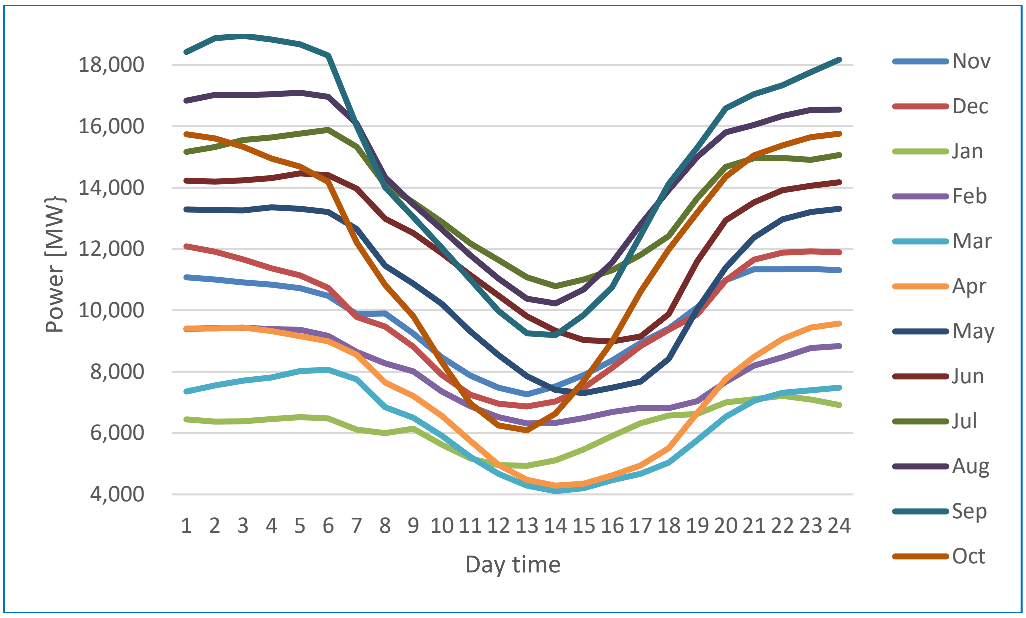


Figure 5.3 – Daily variation of wind production in Northeastern region from November 2023 up to October 2024. The power ramp achieves almost 10 GW in September and October.

The next step is to define the underground reservoir volume, given by (5.1), which is (2.1) for Q coming from (2.2), and penstock diameter, given by (3.8). The maximum water flow, considering a waterhead of 1,000 m and the maximum power of 500 MW, will be of 63.69 m^3/s, calculated in (5.2). Since the UPSH should operate at least 2 hours at full power, the water flow must be multiplied by 7,200 seconds to obtain the reservoir volume of 458,568 m^3, resulting in a cube with sides of 77 m approximately.

$$V = \frac{PT}{\eta g H} \tag{5.1}$$

where V is the reservoir volume in m³; P is the nominal power in kW; T is the total time of the nominal capacity in s (7,200 s in this case study); η is the dimensionless overall yield of the plant; g is the gravitational acceleration in m/s²; and H is the waterhead in m.

$$P = \eta g Q H \ \rightarrow 500x10^3 = 0.8 * 9.81 * 10^3 * Q$$
$$Q = \frac{500}{7.85} = 63.69 \ {m^3}/{s} \tag{5.2}$$

To avoid large underground drillings and consequent subsidence of the soil, the diameter limit of underground reservoir must be smaller than 30 m, according to Mariano (2021). Therefore, this project will be divided into 5 underground reservoirs with approximately 100,000 m³ each. The same division must be applied to the penstock, making the final project 5 UPSHs of 100 MW, 200 MWh, as shown in Figure 5.4. The diameter of the 5 penstocks, calculated by (5.2), was rounded to 2.5 m.

$$D_P = \frac{0.52P^{0.43}}{H^{0.6}} = \frac{0.52 * (100x10^3)^{0.43}}{(10^3)^{0.6}} = 2.24m \tag{5.2}$$

Each penstock should be connected to 10 turbine generator sets, reversible to motor pump, of 10 MW, as the size of the machines is limited by the shaft section. Special Francis pump turbines must be designed for this project, due to the high stress on moving parts, such as axes, blades and vanes, operating under a 1,000 m waterhead. The motor generator should operate as a grid former to provide various services, in which case the synchronous machine is the most suitable.

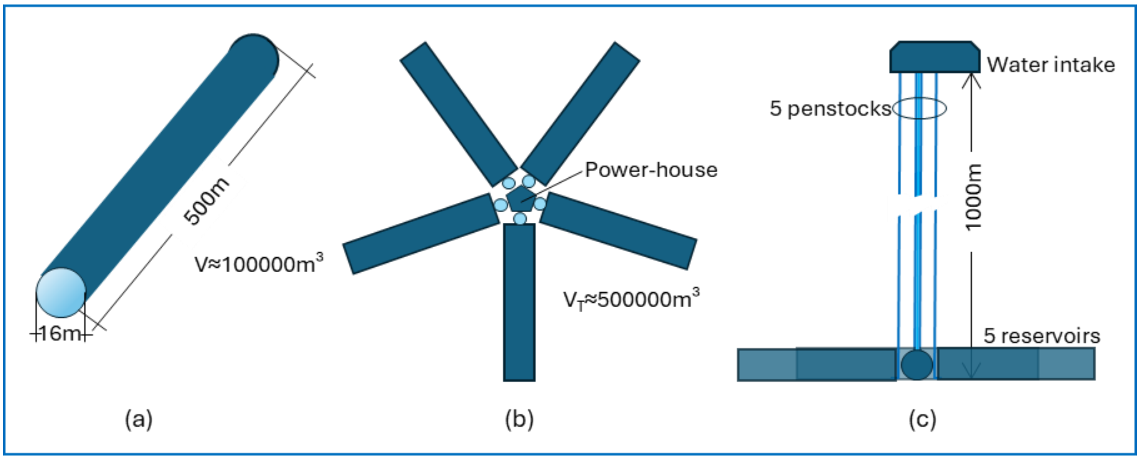


Figure 5.4 – Proposed arrangement of underground reservoirs. a) single reservoir dimensions, b) top view, and c) side view.

5.3 Business plan

This facility should follow the proposed business model in 3.3.4. The revenue stacking will be composed by three instalments: (i) an Energy Storage Service Annual Revenue – RASA to reimburse the initial investment, (ii) an energy price to remunerate the services requested by the ONS (the grid operator), and (iii) a parcel from other services sold by the entrepreneur in the ACL (the free market).

Manageable activities such as administration, operation and maintenance should be remunerated by the last two instalments. This is where the entrepreneur can maximize his profits. The first parcel should only provide the guarantee of the return on the initial investment.

The RASA and the energy price will be defined in a public auction, where the RASA ceiling is previously defined, and bidders offer discounts on it. The reserve price of energy, the highest price that the consumer can pay, is not known to the bidders, as well as the total amount to be sold in the ACR. The most economical proposal for consumers will be the winner.

5.3.1 RASA ceiling definition

To calculate the maximum RASA to be taken to auction, the initial investment must be known and then, a long-term cash-flow should be carried out. At this stage, only the expected inflation rate should be considered, as the capital remuneration comes from other revenues in this business model. According to Teixeira and Viana (2023), the long-term inflation rate will be about 4.5% per year. However, the same author stated that a long-term economic forecast is subject to notable errors and is full of uncertainty. Therefore, the probability of having larger and smaller values will be considered in later stochastic analyses.

The initial investment in a PSH stated by EPE is from 1,150 up to 2,875 USD/kW. Saltuk (2023) state that the average initial costs are 2,200 USD/kW, while Topalovi, Haas, and Sayer (2024) in a recent European study point 528 Euros per kW of installed power. Nevertheless, the best initial investment approach for this case study is the one presented in a Dutch study for a 1,400 m deep UPSH of about 1,400 €/kW of installed power. Such a facility has an installed power of 1.4 GW and a capacity of 8.4 GWh, being the converted to US dollar investment of around 1500 USD/kW or 250 USD/kWh. The capital investment ratio in the underground reservoir is around 40% of the total investment, bringing the initial investment for this case study to 1,100 USD/kW (EPE, 2024; KRAMER et al., 2020).

Hydropower are normally designed for an operating lifetime of about 50 years, and their lifespan can reach more than 100 years with proper operation and maintenance. A lifetime of 50 years was considered in this case study and results for the maximum RASA are in Table 5.2 (VORLET; DE CESARE, 2024).

Table 5.2 – RASA ceiling and data used for calculation.

Investment	Inflation rate	Lifetime	Depreciation	RASA ceiling
550,000,000 USD	4.5%/year	50 years	2% per year	31,400,000 USD

5.3.2 Reserve price definition

There are four types of auctions in terms of reserve price: (i) simple bidding without a reserve price, (ii) bidding with an announced reserve price, (iii) bidding with a secret reserve price, and (iv) bidding with a secret reserve price, but with the possibility of ex post negotiation if the winner has a bid above the reserve price. Forgoing a reserve price can lead to purchasing the energy at a very high price. However, in a competitive market where there are several potential bidders, such a risk is quite low, making a reserve price unnecessary. Even so, auctioneers often have a reference price to check if bids are too high in relation to it. (BUGARIN; PORTUGAL, 2022).

In this case study, a reference price will be calculated to be used in the economic assessment. Such a reference price must remunerate the invested capital and cover all expenses, such as energy acquisition, administration, operation and maintenance, taxes and sector charges.

Six inputs are necessary for this calculation: (i) the initial investment used to consider the capital remuneration only; (ii) the amount of energy dispatched, considered in this case study equal to 60% of total capacity (30% could be sold in the ACL and 10% of operational reserve); (iii) the operation and maintenance costs estimated by EPE in the Ten-Year Energy Expansion Plan – PDE 2034 of 15.33 USD/kWh per year; (iv) Tax and sectorial charges of about 39% on net profit, as stated in the PDE 2034; (v) Weighted Average Cost of Capital – WACC of 8% calculated by EPE in the PDE 2034; and (vi) the energy acquisition costs of 10.91 USD/MWh, that is the first quartile of the annual average of the Difference Settlement Price – PLD, the electricity spot price in Brazil published by CCEE (CCEE, 2024d; EPE, 2024).

The reference price of 175 USD/MWh was obtained using the Net Present Value - NPV tool performed in an Excel® spreadsheet. This reference price is slightly above the third quartile of the annual PLD average.

5.3.3 Economic assessment

The RASA ceiling plus the reference price times the energy sold is enough to cover all investments and costs, with a small profit. However, a sensitivity study should be carried out using stochastic tools to verify the economic viability of the proposed facility.

The Probability Density Functions – PDFs of the inputs to be used in the stochastic analyses are presented in Table 5.3, with NPV and Internal Rate Return – IRR being the outputs.

Table 5.3 – Inputs for stochastic analyses.

Input variable	Minimum	Most likely	Maximum	PDF
Investment [USD]	275,000,000	550,000,000	1,450,000,000	BetaPERT
RASA [USD/year]	15,700,000	31,400,000	82,000,000	BetaPERT
Dispatch [MWh/year]	36,500	219,000	365,000	BetaPERT
Energy price to buy [USD/MWh]	2	10.91	155	Triangular
Energy price to sell [USD/MWh]	32.15	154.13	175	Triangular
O&M [USD/kW/year]	7.67	15.33	30.66	Lognormal
WACC [%]	4	8	12	Normal
Plant yield [%]	65	80	95	Normal
Other revenues [USD/year]	1,000,000	25,000,000	50,000,000	BetaPERT

The most likely investment is the one used to calculate the RASA ceiling and half of it was considered the minimum. The maximum is the one provided for in the PDE 2034. The BetaPERT PDF chosen for this variable is positively skewed, where most values are close to the most probably and fewer values are close to the maximum.

RASA follows the same variation as investments, with the RASA ceiling being the most likely and minimum and maximum proportional to respective investments. It is also represented by a BetaPERT PDF.

The maximum dispatch was considered to be 100% of the plant capacity, 60% as the most likely and 10% as the minimum dispatch. The BetaPERT PDF, in this case, is negatively skewed, where most values are close to the maximum.

A triangular PDF was chosen for the variation in energy prices, representing a linear growth from the minimum to the most likely value and then falling, also linearly, to the maximum value. All values come from historical prices provided by CCEE, except the maximum sale price, which is the reference price calculated in this case study.

The most likely O&M costs are from PDE 2034 and double and half of it were considered the maximum and minimum, respectively. This variable follows a Lognormal PDF with one standard deviation to the left, where the smaller values are, and two standard deviations to the right where the higher values are.

The most likely WACC, including the inflation rate, is the one provided in the PDE 2034, and the maximum is the average rate used by the mayor part of private investors in the electricity market. This variable follows a normal PDF with a mean of 8% and a standard deviation of 1.2%.

Losses in generation mode and pumping mode of a PSH were stratified in a recent study resulting in a plant yield of around 80%, the same value found by EPE. A variation of plus or minus 15% was considered, as the machinery technology is in constant improvement to achieve high yields, as well as some projects may use machines from decommissioned plants. A normal PDF was considered with a mean of 80% and standard deviation of 5% (BRANDÃO; CASTRO; HUNT, 2021; EPE, 2021).

Other revenues were estimated in this case study. The most likely value of USD 25 million per year occurs when the entrepreneur is able to sell 30% of the energy destined for the ACL at the reserve price. Other services were considered only in the calculation of the maximum value. The minimum value represents a situation where no energy was sold, and few additional services were provided. In this case, a slightly negative-biased BetaPERT PDF was used.

A Monte Carlo Simulation – MCS with ten thousand runs was performed, using the 9 variable inputs from Table 5.3 and monitoring the NPV and IRR outputs. The results are presented in Figure 5.5.

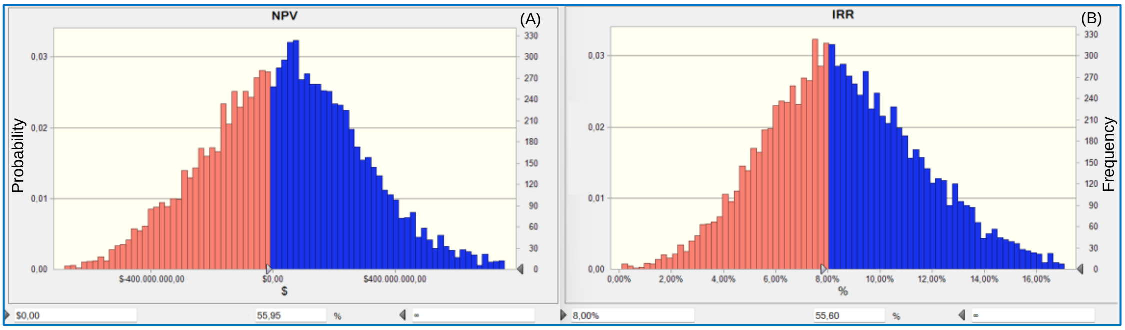


Figure 5.5 – NPV and IRR probability for the Mundaú UPSH after 10,000 MCS runs.

An NPV of zero means that all investment and costs are recovered in the analysed period. No profits are made in such a case. The higher the positive NPV, the greater the investor's profits. The results in Figure 5.5 (A) show a feasible project with more than 55% of simulated scenarios presenting positive NPVs.

On the other hand, a positive IRR means that the investment recovered will be adjusted monetarily, while negative values mean money lost. The result in Figure 5.5 (B) shows only positive values and a high probability of an IRR of about 8%, with returns higher than 15% being possible.

A sensitivity analysis was performed using the extremes of each variable: maximum, most likely, and minimum, Figure 5.6. The results show that the initial investment is the most sensitive variable, ranging from almost unfeasible for the maximum investment to almost 100% viable for the minimum investment. This variable is market dependent and needs a strong market to reduce the prices of services and materials.

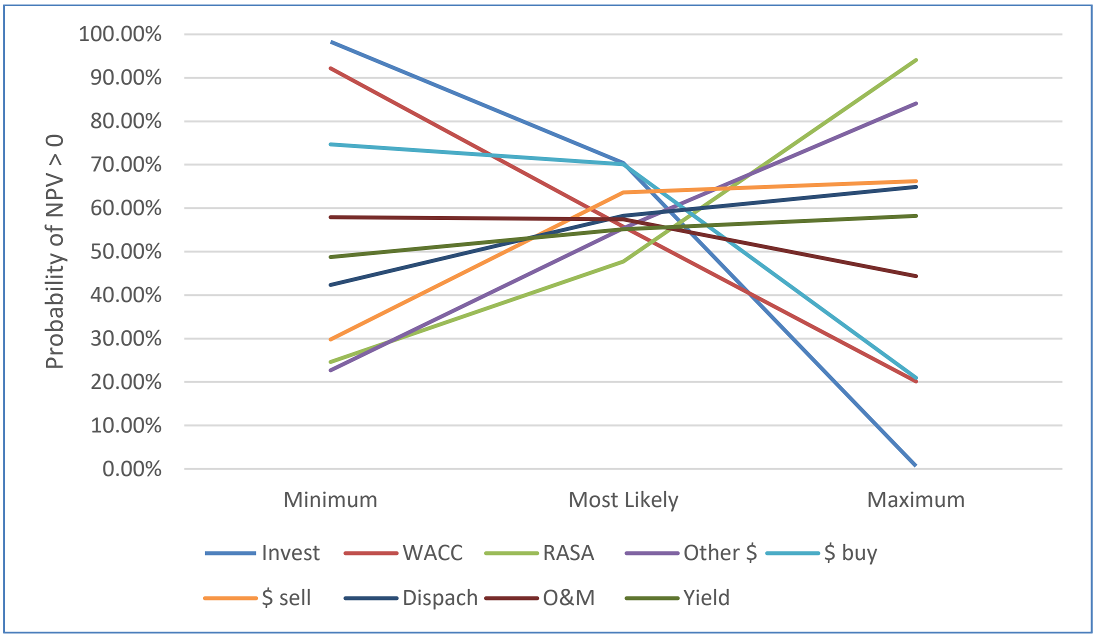


Figure 5.6 – Sensitivity analysis for all 9 variables used in the economic assessment.

The three subsequent most sensitive variables: return rate, with a variation of 72 percentage points, RASA, with a variation of 69 points, and other revenues, with a variation of 61 points, are manageable by the entrepreneur. However, the NPV results for RASA and return rate are inversely proportional, with the latter being the result of the former. A higher RASA means higher returns, but a higher desired return rate for the same RASA may make the venture unviable.

Energy prices vary the NPV result by around 50%, with the difference between them being more relevant than their absolute values. Conversely, the NPV result is less sensitive to variations in plant dispatch, plant efficiency and O&M costs.

The results demonstrate that an UPSH at Lake Mundaú cam be technical and economic feasible. Advanced technical and economic studies could be carried out by the sectoral planning, taking advantage of its tools, more accurate data, and know-how to define other UPSH in the Brazilian electrical sector, taking advantage of the abundance of water availability in the country.

5.4 Project execution

Unlike small projects, an UPSH must request the LP before the assignment of the company responsible for its construction. Normally, the same entrepreneur responsible for the design and economic assessment phases, the EVTE, requires the LP to the competent environmental body. The EVTE approved by ANEEL together the issued LP constitute a valuable asset to negotiate with bidders before the project auction.

The EIA/RIMA must include an environmental diagnosis of the lake area and its neighbourhoods, describing and analysing environmental resources and the interactions among them and with local communities to characterize the environmental situation of the area before implementing the project. Such an analyses should contain:

1) the physical environment – the subsoil, water, air and climate, highlighting mineral resources, topography, soil types and capacities, water bodies, the hydrological regime, sea currents, and atmospheric currents.
2) the biological environment and natural ecosystems – fauna and flora, highlighting species that are indicators of environmental quality, of scientific and economic value, rare and threatened with extinction and areas of permanent preservation.
3) the socioeconomic environment – the use and occupation of the land, water uses and socioeconomics, highlighting the community's archaeological, historical and cultural sites and monuments, the dependency relationships between local society, environmental resources and potential use of these resources in the future.

The second phase of the EIA consists in analysing the impacts of the project over the three environments described above, through identification, prediction of the magnitude and interpretation of the importance of the likely relevant impacts, discriminating: beneficial and adverse impacts; direct and indirect; immediate, medium, and long-term; temporary and permanent; their degree of reversibility; their cumulative and synergistic properties; the distribution of social charges and benefits.

The study also requires definitions to mitigate negative impacts, including control equipment and waste treatment systems; a monitoring program for positive and negative impacts, indicating the factors and parameters to be considered, especially for lake monitoring; and the decommissioning plan.

The published LP should be included in the administrative process at ANEEL, that will issue the Aptitude for Tender Registration Order – DRA. This document attest that the designed enterprise is read to be tendered.

The entrepreneur assigned through the public auction will then hire an EPC company to execute the entire project, from public permits to commissioning.

Firstly, the EPC will prepare the Basic Environmental Project – PBA, which must contain the management programs for the socio-environmental issues presented in the EIA and explained in the LP, which aim to eliminate, mitigate and/or compensate for the negative impacts and maximize the positive impacts expected with the implementation of the venture. In this PBA, all environmental issues presented in the EIA or listed in the LP must be addressed, resolved or justified, if they have not already been done.

After obtaining the LI and government authorizations to install construction sites and begin the works, the construction itself can start. The first phase of construction is the soil preparation and excavation for penstocks, shafts, and lower reservoirs. There will be at least 3 shafts in addition to the 5 penstocks: one main entrance, from where people, materials, and machinery should enter; one emergency exit for people only; and one ventilation shaft.

The largest indivisible part is the Francis turbine rotor, which is the determining part for the dimensioning of the main shaft, Figure 5.7.

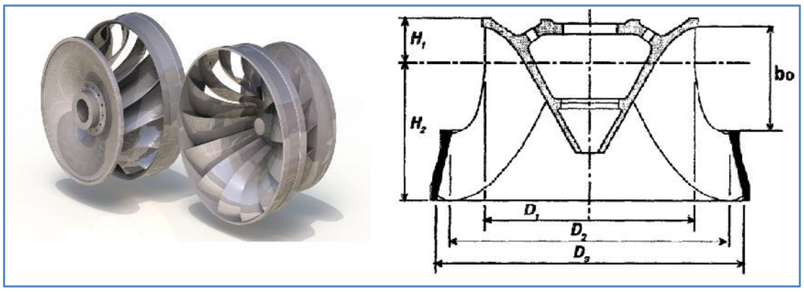


Figure 5.7 – Main dimensions of a Francis rotor.

The outer diameter, D3, is the measurement required for sizing the shaft and can be calculated by the equations 5.3 and 5.4 (BERGAMO, 2018; apud VIDAL BARRENA, 2018).

$$D_3 = 1000\sqrt{\frac{4Q}{\pi C_3}} \quad (5.3)$$

$$C_3 = \sqrt{\frac{gK_cH}{50}} \quad (5.4)$$

where D_3 is the draft tube diameter (Francis rotor outer diameter) in m; Q is water flow in m^3/s; C_3 is the output water speed in m/s; g is the gravitational acceleration in m/s^2; K_C is a dimensionless constant that depends on the turbine speed, varying from 0.04 for slow Francis turbines to 0.25 for ultrafast Francis turbines; and H is the waterhead in m.

The Francis rotor diameter in this case study will be about one meter and will need to be sized in a specific study, as it is not a conventional turbine. A comprehensive study must be carried out to size the machinery in an actual project, as this power plant is outside the conventional range. The technical and economic study will determine whether a special reversible Francis turbine or a Pelton turbine and a separate water pump is better.

The operating scheme should be planned after the completion of excavations, civil construction, equipment assembly and connections. Since this is a large UPSH, equivalent to a large hydropower – UHE in terms of regulations, it must follow the grid code issued by the National Electrical System Operator – ONS. The ONS, together with the Energy Storage Company – ESCO operator, will define the operating scheme.

Before connecting to the transmission grid, the ESCO must apply for the Environmental Operating Licence – LO, also issued by the same competent environmental body that have issued the LP and the LI. All environmental issues presented in LP and LI must have been resolved or at least addressed and justified to obtain the LO. The LO will approve the long-term environmental monitoring plan.

After that, commissioning tests can be requested from ONS, that will issue the TLT allowing the start of electrical testing. Test operation will be allowed during light load periods, mainly during weekends. These tests allow the ONS, together with the local ESCO operator, to adjust and validate the final operation scheme.

After approval of the tests and issuance of the LO, the ONS will issue the TLP or the TLD, depending on whether or not there are pending issues that do not impede the safe operation of the facilities. Such a document will allow the commercial operation of the UPSH facilities and the receipt of the corresponding revenues by the ESCO.

4.2 Decommissioning

The regulations for the closure of underground mines, as provided by the National Mining Agency – ANM, will be used for similarity in this work due to the lack of specific regulations for this case in the electricity sector regulation.

Even though the UPSH has a very long lifespan of about 100 years, the preliminary decommissioning project and the rehabilitation project for degraded areas must be presented during the environmental licensing process, reviewed and updated periodically, as provide for in the Mine Closure Plan – PFM. Such projects must contain, at least:

1) The characterization of the project area;
2) the physical-financial schedule of the program, integrating pre-closure, closure and post-closure monitoring actions;
3) the planned monitoring and maintenance actions in the affected area;
4) the risk assessment of the closure project and ways to mitigate any damage resulting from that project;
5) the demobilization plan for the facilities;
6) the project for decommissioning civil structures, explaining possible reuse for other activities;
7) the physical and chemical stabilization plan for the remaining structures;
8) measures to prevent unauthorized access to the remaining project's facilities;
9) maintenance and monitoring actions for the remaining structures after the project's closure;
10) guidelines for adapting the area to its future use; and
11) monitoring and follow-up programs (ANM, 2021).

Since the installation will be in an urban lake, the characteristics of the area will be constantly changing during the project's lifetime. An integrated monitoring plan must be drawn up in agreement with all stakeholders in the lake area.

Except for reusable civil structures, all facilities should be recycled, such as machinery, pipes, cables, etc. The underground reservoirs, shafts, and all excavated areas must be filled to prevent soil subsidence. After that, the soil stability must be periodically monitored.

Chapter 6 – Final considerations

The main objective of this Thesis is to attract the attention of the academic community, decision-makers, sector planners, entrepreneurs and governments to study, understand and develop the technology of Underground Pumped Storage Hydropower – UPSH, since this technology has great potential worldwide, especially in Brazil where there is an abundance of water bodies and several abandoned deep mines.

To achieve this main objective, some steps were taken. Firstly, a Systematic Literature Review – SRL was carried out to understand the state of the art of the subject in the world and confirm the uniqueness of the theme in Brazil. There are a few published articles about UPSH in the world, however no one dedicated to Brazil or written by Brazilian researchers, which demonstrates a gap in this research field, whose filling begins with the works derived from this Thesis.

Since there was no regulation for Energy Storage Systems – ESS in force in Brazil until 2025, a survey was carried out on the legislation and regulations applied to hydroelectric power and mining that could be used due to the similarity with UPSH. The findings can be grouped into two segments: (i) laws; and (ii) standards, both divided into three subgroups: (i) hydroelectric; (ii) mining; and (iii) environment. 14 laws were found (2 for hydroelectric, 1 for mining, and 11 for environment) and 25 standards (4 for hydroelectric, 10 for mining, and 11 for environment).

The history of Pumped Storage Hydropower – PSH, ancestor of UPHS, was researched, as well as the history of UPSH together with an evaluation of the main equipment of an UPSH. Research and development of PSH began a few years after the development of hydropower, whereas UPSH is a recent research field driven by environmental barriers to PSH, the need for reuse of deactivated underground mines, and the lack of suitable relief for PSH in some countries.

The turbine and generator set are the central machinery of a hydroelectric power plant. Turbines can be split into three types: (i) impulse machines, such as the Pelton turbine, which are non-reversible for pumping; (ii) reaction machines, such as the Kaplan turbine, which is a reversible turbine suitable for medium head applications; and (iii) mixed machines, such as the Francis turbine, the most widely used reversible turbine in the world, suitable for almost all projects.

Generators are divided into two groups, synchronous and asynchronous machines. The former is suitable for large grid-forming plants and the latter for medium to small plants operating as grid followers. Both can be converted into motors that power water pumps, and the asynchronous machines can be connected via an ac-dc-ac converter to the grid, then being grid formers providing other services to the electrical system.

The main contribution of this Thesis is in chapter 3, where **an integrated framework for the general evaluation of UPSH** is presented. Such a framework can be split into five phases: (i) prospecting, (ii) design, (iii) business plan, (iv) project execution, and (v) decommissioning.

In the prospecting phase the resources availability is assessed, as water availability, soil survey, energy storage demand, among other. The power plant classification in the current regulations for hydropower, according to its nominal capacity, is also done at this phase. Based on this classification, the competent environmental licensing agency, the method of commercialization of energy and services, as well as the procedures to be adopted for connection to the grid and operation of the facility are defined.

The refined sizing of turbines, generators, underground reservoirs, penstocks, and other facilities is carried out during the design phase. When the boundaries are well known, the deterministic approach can be used at this stage. On the other hand, when there is interdependence among limits, a stochastic approach is more appropriate.

The third phase depends on the business model. Therefore, after analysing the three current business model in the Brazilian electrical sector, a specific business model for ESS is proposed in this Thesis. This model is perhaps the main technical contribution of this Thesis. The model includes new types of revenue, a revenue stacking system to remunerate all services provided by the ESS and a systematic for combinatorial auction. These new features should be implemented in the Brazilian electrical sector regulatory framework through specific economic regulations for the ESS.

Knowing all revenue instalments and the revenue stack weights, a stochastic economic analysis can be carried out. This analysis is performed through Monte Carlo Simulation – MCS using economic tools as Net Present Value – NPV, Internal Rate Return – IRR, and Discounted Payback – DPP.

The execution phase is when the actual project comes to fruition. Environmental permits and public permission must be issued at this stage. Then, construction and assembly must be carried out and finally the facility is commissioned, tested and put into operation. An operation and maintenance plan must be agreed with the public operator, the National Electrical System Operator – ONS or the Distribution Company – DISCO, depending on the size of the energy storage plant.

Lately there has been a growing concern about the closure of industrial activities, the disposal of unusable waste, and the recovery of the environment degraded by deactivated industrial activities. Thus, the final phase of the framework for UPSH assessment is a proposal to use by similarity the regulation for underground mining, as there is no regulation for ESS in Brazil yet.

The conclusion of this Thesis consists of two case studies. The first is a proposal for a 500 kW μUPSH with 1.5 MWh of capacity on the Unifei's campus of Itajubá, taking advantage of an existing lake. The installation was designed to meet peak demand, where tariffs are higher, connected as a Distributed Generation – DG participating in the Electrical Energy Compensation System – SCEE. Despite a low probability of NPV greater than zero and IRR greater than the inflation rate, the viability of a prototype for studies was attested.

The proposal for new regulation, revenue stacking and combinatorial auction was tested in the second case study. The proposal for a 1,000 m depth, 500 MW, 1 GWh ultra-deep UPSH was evaluated, and its technical and economic feasibility was confirmed.

The general conclusion is that UPSH technology is technically and economically viable and lacks adequate legislation and regulation to provide legal security to entrepreneurs interested in the technology. Further studies are needed to consolidate the regulatory proposal presented in this Thesis, as well as for comparisons with other technologies.

BIBLIOGRAPHY

ADEYANJU, Olatunji M.; SIANO, Pierluigi; CANHA, Luciane N. *Dedicated Microgrid Planning and Operation Approach for Distribution Network Support with Pumped-Hydro Storage*. **IEEE Transactions on Industrial Informatics**, n. 2, 2022. DOI: 10.1109/TII.2022.3216299.

ALLEN, A. E. *Potential for conventional and underground pumped-storage*. **IEEE Transactions on Power Apparatus and Systems**, v. 96, n. 3, p. 993–998, 1977. DOI: 10.1109/T-PAS.1977.32413.

ANA. **Base Hidrográfica Ottocodificada - BHO**. 2023. Available at: https://dadosabertos.ana.gov.br/datasets/2f54775d2229431bad6a41daf3ed04d8_0/explore. Accessed on: Jul. 28th, 2023.

ANDRADE, T.; KELMAN, R.; CUNHA, T. M.; ALBUQUERQUE, L. R.; CALILI, R. F. *An Integer Programming Model for the Selection of Pumped-Hydro Storage Projects*. **Water Resources Research**, v. 58, n. 1, 2022. DOI: 10.1029/2020WR028625.

ANEEL. **Normative Resolution nº 875**. **ANEEL**Digital Library., , 2020. Available at: https://www2.aneel.gov.br/cedoc/atren2020875.pdf. Accessed on: Jan. 18th, 2024.

ANEEL. **Normative Resolution nº 957**. 2021a. Available at: https://www2.aneel.gov.br/cedoc/ren2021957.pdf. Accessed on: Ago. 20th, 2024.

ANEEL. **PRODIST - Distribution Procedures**. **ANEEL**Digital Library., , 2021. b. Available at: https://www2.aneel.gov.br/cedoc/aren2021956_2_2.pdf. Accessed on: Jan. 23th, 2024.

ANEEL. **Normative Resolution nº 1,000**. **ANEEL**Digital Library., , 2021. c. Available at: https://www2.aneel.gov.br/cedoc/ren20211000.html. Accessed on: Jan. 29th, 2024.

ANEEL. **Normative Resolution nº 1,030**. **ANEEL**Digital Library., , 2022. a. Available at: https://www2.aneel.gov.br/cedoc/ren20221030.pdf. Accessed on: Jan. 31th, 2024.

ANEEL. **PRORET - Tariff Regulation Procedures**. 2022b. Available at: https://www.gov.br/aneel/pt-br/centrais-de-conteudos/procedimentos-regulatorios/proret. Accessed on: Out. 18th, 2024.

ANEEL. **Normative Resolution nº 1,080**. 2023a. Available at: https://www2.aneel.gov.br/cedoc/ren20231080.pdf. Accessed on: Ago. 20th, 2024.

ANEEL. **Normative Resolution nº 1,059**. 2023b. Available at: https://www2.aneel.gov.br/cedoc/ren20231059.html. Accessed on: Nov. 7th, 2024.

ANEEL. **Normative Resolution nº 1,071**. 2023c. Available at: https://www2.aneel.gov.br/cedoc/ren20231071.pdf. Accessed on: Jan. 17th, 2025.

ANEEL. **Normative Resolution nº 1,073**. **ANEEL**Digital Library., , 2023. d. Available at: https://www2.aneel.gov.br/cedoc/ren20231071.pdf. Accessed on: Fev. 7th, 2024.

ANEEL. **SIGA - ANEEL's Information System of Generation**. 2025a. Available at: https://www.gov.br/aneel/pt-br/centrais-de-conteudos/relatorios-e-indicadores/geracao. Accessed on: Jan. 7th, 2025.

ANEEL. **ANEEL's Virtual Library**. 2025b. Available at: https://biblioteca.aneel.gov.br/. Accessed on: Dez. 26th, 2023.

ANM. **ANM Resolution nº 68**. 2021. Available at: https://anmlegis.datalegis.net/action/UrlPublicasAction.php?acao=abrirAtoPublico&num_ato=00000068&sgl_tipo=RES&sgl_orgao=ANM/MME&vlr_ano=2021&seq_ato=000&cod_tipo=&des_item=&des_item_fim=&num_linha=&cod_modulo=351&cod_menu=6710. Accessed on: Ago. 16th, 2024.

ANM. **ANM Mining Registry**. 2024. Available at: https://dados.gov.br/dados/conjuntos-dados/sistema-de-cadastro-mineiro. Accessed on: Jan. 26th, 2024.

ANM. **ANM Legis**. 2025. Available at: https://anmlegis.datalegis.net/action/ActionDatalegis.php?acao=apresentacao&cod_modulo=351&cod_menu=8014. Accessed on: Dez. 27th, 2023.

AQUILA, Giancarlo; SOUZA ROCHA, Luiz Célio; ROTELA JUNIOR, Paulo; SAAB JUNIOR, Joseph Youssif; DE SÁ BRASIL LIMA, João; BALESTRASSI, Pedro Paulo. *Economic planning of wind farms from a NBI-RSM-DEA multiobjective programming*. **Renewable Energy**, v. 158, p. 628–641, 2020. DOI:

10.1016/j.renene.2020.05.179.

ARAGON, Carlos Alfaro; GUZMAN, Ramon; DE VICUNA, Luis Garcia; MIRET, Jaume; CASTILLA, Miguel. *Constrained Predictive Control Based on a Large-Signal Model for a Three-Phase Inverter Connected to a Microgrid*. **IEEE Transactions on Industrial Electronics**, v. 69, n. 7, p. 6497–6507, 2022. DOI: 10.1109/TIE.2021.3097608.

AREE, Pichai. *Analytical determination of speed-torque and speed-current curves of single-cage induction motor under supply voltage and frequency variations*. **COMPEL - The International Journal for Computation and Mathematics in Electrical and Electronic Engineering**, v. 37, n. 6, p. 2279–2298, 2018. DOI: 10.1108/COMPEL-09-2017-0404.

AYODELE, Esan; MISRA, Sanjay; DAMASEVICIUS, Robertas; MASKELIUNAS, Rytis. *Hybrid microgrid for microfinance institutions in rural areas – A field demonstration in West Africa*. **Sustainable Energy Technologies and Assessments**, v. 35, n. February, p. 89–97, 2019. DOI: 10.1016/j.seta.2019.06.009.

BARBOUR, Edward; WILSON, I. A. Gran.; RADCLIFFE, Jonathan; DING, Yulong; LI, Yongliang. *A review of pumped hydro energy storage development in significant international electricity markets*. **Renewable and Sustainable Energy Reviews**, v. 61, p. 421–432, 2016. DOI: 10.1016/j.rser.2016.04.019.

BARIN, Alexandre; CANHA, Luciane Neves; DA ROSA ABAIDE, Alzenira; MAGNAGO, Karine Faverzani. *Selection of storage energy technologies in a power quality scenario—the AHP and the fuzzy logic*. *In*: 2009 35TH ANNUAL CONFERENCE OF IEEE INDUSTRIAL ELECTRONICS 2009, : IEEE, 2009. p. 3615–3620.

BERGAMO, Paula da Rosa. *Especificações de turbinas hidráulicas*. p. 72, 2018. Available at: http://repositorio.utfpr.edu.br/jspui/bitstream/1/14941/1/PB_COELT_2018_2_17.pdf.

BHANDARI, Shyam B. *Discounted Payback Period - Some Extensions*. n. May 1989, 1989.

BLAIR, J. S. *Controlling pipe line surges by means of air vessels*. **Proceedings of the Institution of Mechanical Engineers**, v. 153, n. 1, p. 1–14, 1945.

BLALOCK, T. J.; WOODWORTH, C. A. *25-Hz at Niagara Falls [history]*. **IEEE Power and Energy Magazine**, v. 6, n. 1, p. 84–89, 2008. DOI: 10.1109/MPAE.2008.4412948.

BOLDEA, Ion. **Electric Generators Handbook - Vol 2**. Second ed. Boca Raton, FL: CRC Press- Taylor & Francis Group, 2018.

BONO, Mariana dos Santos; LONGARAY, André Andrade; ADAMATTI, Diana Francisca; SIQUEIRA, Tirzah Moreira; MACHADO, Catia Maria dos Santos; MUNHOZ, Paulo Roberto da Silva. *Proposta de modelo multicritério de apoio à decisão para avaliação do Projeto Básico Ambiental de pequenas centrais hidrelétricas*. **Revista de Gestão e Secretariado (Management and Administrative Professional Review)**, v. 14, n. 9, p. 15878–15893, 2023. DOI: 10.7769/gesec.v14i9.2587.

BOSTIC, Maud. **Handbook of Electrical Generators**. Dehli: White Word Publications, 2014.

BRANDÃO, ROBERTO; CASTRO, Nivalde; HUNT, J. D. **A Viabilidade das Usinas Reversíveis no Sistema Interligado Nacional**. GESEL/UFRJ, , 2021.

BRASIL. **National Law nº 6,938**. 1981. Available at: https://www.planalto.gov.br/ccivil_03/leis/L6938compilada.htm. Accessed on: Ago. 15th, 2024.

BRASIL. **Constitution of the Federative Republic of Brazil**. 1988. Available at: https://www.planalto.gov.br/ccivil_03/constituicao/constituicao.htm. Accessed on: Ago. 15th, 2024.

BRASIL. **National Law nº 9,074**. 1995a. Available at: https://www.planalto.gov.br/ccivil_03/leis/L9074compilada.htm. Accessed on: Jan. 31th, 2024.

BRASIL. **National Law nº 8,987**. 1995b. Available at: https://www.planalto.gov.br/ccivil_03/leis/l8987cons.htm. Accessed on: Jan. 17th, 2025.

BRASIL. **National Law nº 9,433 - The Water Resources Law**. 1997. Available at: https://www.planalto.gov.br/ccivil_03/leis/l9433.htm. Accessed on: Ago. 19th, 2024.

BRASIL. **National Law nº 10,848**. 2004. Available at: https://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/lei/l10.848.htm. Accessed on: Jan. 17th, 2025.

BRASIL. **National Complementary Law nº 140**. 2011. Available at: https://www.planalto.gov.br/ccivil_03/leis/LCP/Lcp140.htm. Accessed on: Jan. 16th, 2024.

BRASIL. **National Law nº 12,783**. 2013. Available at: https://www.planalto.gov.br/ccivil_03/_ato2011-2014/2013/lei/l12783.htm. Accessed on: Jan. 21th, 2025.

BRASIL. **National Decree nº 8,437**. 2015. Available at: https://www.planalto.gov.br/ccivil_03/_ato2015-2018/2015/decreto/d8437.htm. Accessed on: Jan. 16th, 2024.

BRASIL. **National Decree nº 10,935**. 2022a. Available at: http://www.planalto.gov.br/ccivil_03/_Ato2019-2022/2022/Decreto/D10935.htm#art12. Accessed on: Jan. 18th, 2024.

BRASIL. **National Law nº 14,300**. 2022b. Available at: https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2022/lei/l14300.htm. Accessed on: Jan. 29th, 2024.

BRASIL. **Portal da Legislação**. 2025. Available at: https://www4.planalto.gov.br/legislacao. Accessed on: Jan. 3th, 2024.

BRASIL, Agência. **Afundamento do solo de mina em Maceió**. 2023. Available at: https://agenciabrasil.ebc.com.br/geral/noticia/2023-12/afundamento-do-solo-de-mina-em-maceio-ja-passa-de-2-m-de-profundidade. Accessed on: Dez. 26th, 2023.

BREEZE, Paul. **Hydropower**. San Diego: Elsevier Science & Technology, 2018. DOI: 10.1016/C2016-0-03622-7.

BROCKSCHINK, Steven R.; GURNEY, James H.; SEELY, Douglas B. *Hydroelectric Power Generation*. *In*: GRIGSBY, Leonard L. (org.). **Electric Power Generation, Transmission, and Distribution**. Second ed. Boca Raton, FL: CRC Press Boca Raton, 2001. p. 44–55.

BUGARIN, Maurício S.; PORTUGAL, Adriana C. **Licitações com preço de reserva secreto e negociação: Uma análise de teoria dos leilões para o caso de valores privados**. v. 52 DOI: 10.1590/1980-53575242mbap.

CCEE. **Electrical Energy Marketing Rules**. 2024a. Available at: https://www.ccee.org.br/web/guest/mercado/regras-de-comercializacao. Accessed on: Ago. 20th, 2024.

CCEE. **Electrical Energy Marketing Procedures**. 2024b. Available at: https://www.ccee.org.br/web/guest/mercado/procedimentos-de-comercializacao. Accessed on: Ago. 20th, 2024.

CCEE. **Electrical Energy Auction Procedures**. 2024c. Available at: https://capacita.ccee.org.br/home/teams/categories. Accessed on: Out. 23th, 2024.

CCEE. **Electricity Prices Panel**. 2024d. Available at: https://www.ccee.org.br/web/guest/precos/painel-precos. Accessed on: Nov. 17th, 2024.

CECAV, ICMBio. **Statistical Yearbook of Brazilian Speliological Heritage**. 2022. Available at: https://www.gov.br/icmbio/pt-br/assuntos/centros-de-pesquisa/cecav/anuario-estatistico-do-patrimonio-espeleologico-brasileiro/.

CEMIG. **Cemig's Distributed Generation Handbook**. **Cemig**Cemig's Data Library., , 2024. Available at: https://www.cemig.com.br/manual-de-geracao-distribuida/. Accessed on: Jan. 23th, 2024.

CHIBA, S.; WAKI, M. *Innovative power generator using dielectric elastomers (creating the foundations of an environmentally sustainable society)*. **Sustainable Chemistry and Pharmacy**, v. 15, n. May 2019, p. 100205, 2020. DOI: 10.1016/j.scp.2019.100205. Available at: https://doi.org/10.1016/j.scp.2019.100205.

CLARK, A. L.; CLARK, J. C. *An International Overview of Legal Frameworks for Mine Closure*. **Environmental Law Alliance Worldwide: Eugene, OR, USA**, 2005.

COLAS, Elisa; KUKLA, Peter A.; AMANN, Florian; BACK, Stefan. *Geological and mining factors influencing further use of abandoned coal mines – A multi-disciplinary workflow towards sustainable underground storage*. **Journal of Energy Storage**, v. 108, n. June 2024, p. 115101, 2025. DOI: 10.1016/j.est.2024.115101. Available at: https://doi.org/10.1016/j.est.2024.115101.

CONAMA. **CONAMA Resolution nº 001**. 1986. Available at: https://conama.mma.gov.br/?option=com_sisconama&task=arquivo.download&id=745. Accessed on:

Ago. 24th, 2024.

CONAMA. **CONAMA Resolution nº 006**. 1987. Available at: https://conama.mma.gov.br/?option=com_sisconama&task=arquivo.download&id=57. Accessed on: Jan. 18th, 2024.

CONAMA. **CONAMA Resolution nº 237**. 1997. Available at: https://conama.mma.gov.br/?option=com_sisconama&task=arquivo.download&id=237. Accessed on: Jan. 18th, 2024.

CONAMA. **CONAMA Resolution nº 279**. 2001. Available at: https://www.icmbio.gov.br/cepsul/images/stories/legislacao/Resolucao/2001/res_conama_279_2001_licenciamentoambientalsimplificadoparaempreendimentoseletricos.pdf. Accessed on: Jan. 18th, 2024.

CRAMTON, Peter; SHOHAM, Yoav; STEINBERG, Richard. *An overview of combinatorial auctions*. **ACM SIGecom Exchanges**, v. 7, n. 1, p. 3–14, 2007. DOI: 10.1145/1345037.1345039.

DA COSTA, A. M.; AMARAL, C. S.; POIATE, E.; PEREIRA, A. M. B.; MARTHA, L. F.; GATTASS, M.; ROEHL, D. *Underground storage of natural gas and CO2 in salt caverns in deep and ultra-deep water offshore Brazil*. *In*: ISRM CONGRESS 2011, : ISRM, 2011. p. ISRM-12CONGRESS.

DE ASSIS BRASIL WEBER, Natália; HUNT, Julian David; ZAKERI, Behnam; SMITH SCHNEIDER, Paulo; ASFOR PARENTE, Fernando Sérgio; DELAVALD MARQUES, Augusto; OLÍMPIO PEREIRA JUNIOR, Amaro. *Seasonal pumped hydropower storage role in responding to climate change impacts on the Brazilian electrical sector*. **Journal of Energy Storage**, v. 87, n. February, 2024. DOI: 10.1016/j.est.2024.111249.

DE DOILE, Gabriel N. D.; BALESTRASSI, Pedro P.; ZAMBRONI DE SOUZA, Antonio C.; GARCIA, Reinaldo C. *Assessment of a 1.0 Gwh Ultra-Deep Underground Pumped Storage Hydropower and Contributions for Economic Regulation, Revenue Stack, and Combinatorial Auction*. **e-Prime - Advances in Electrical Engineering, Electronics and Energy - Preprint Article**, 2025. Available at: https://ssrn.com/abstract=5088145 or http://dx.doi.org/10.2139/ssrn.5088145.

DE DOILE, Gabriel N. D.; ROTELLA JUNIOR, Paulo; ROCHA, Luiz Celio; BOLIS, Ivan; JANDA, Karel; COELHO JUNIOR, Luiz Moreira. *Hybrid wind-photovoltaic generation with Energy Storage Systems: A Systematic Literature Review and contributions to techno-economic regulation*. **Energies**, 2021.

DE DOILE, Gabriel Nasser Doyle. *Rede Elétrica Chinesa aos Olhos de um Brasileiro*. *In*: (Cigre-Brasil, Org.)XIV SYMPOSIUM OF SPECIALISTS IN ELECTRIC OPERATIONAL AND EXPANSION PLANNING 2018, Recife - PE. Recife - PE p. 1–11.

DE DOILE, Gabriel Nasser Doyle; BALESTRASSI, Pedro Paulo; CASTILLA, Miguel; ZAMBRONI DE SOUZA, Antonio Carlos; MIRET, Jaume. *An Experimental Approach for Secondary Consensus Control Tuning for Inverter-Based Islanded Microgrids*. **Energies**, v. 16, n. 1, 2023. a. DOI: 10.3390/en16010517.

DE DOILE, Gabriel Nasser Doyle; BALESTRASSI, Pedro Paulo; ZAMBRONI DE SOUZA, Antonio Carlos. *Assessment of an Underground Pumped Storage Hydropower for Unifei's Campus of Itajubá*. *In*: 59TH INTERNATIONAL UNIVERSITIES POWER ENGINEERING CONFERENCE (UPEC), 2024 2024, Cardiff, UK. Cardiff, UK: IEEE Xplore, 2024. p. 6.

DE DOILE, Gabriel Nasser Doyle; BONATTO, Benedito Donizete; ZAMBRONI DE SOUZA, Antonio Carlos; DA COSTA, Vinicius Braga Ferreira. *Review on Energy Storage Through Pumped Hydro Systems Using Underground Lower Reservoir*. *In*: ANAIS DO XIII CONGRESSO BRASILEIRO DE PLANEJAMENTO ENERGÉTICO 2022, Itajubá - MG. Itajubá - MG p. 89–95.

DE DOILE, Gabriel Nasser Doyle; ROTELA, Paulo; CARNEIRO, Priscila Franca Gonzaga; PERUCHI, Rogerio Santana. *Economic Feasibility of Photovoltaic Micro-Plants Connected to the Brazilian Distribution Grid Facing the Regulation Changes Proposed*. *In*: 2020 55TH INTERNATIONAL UNIVERSITIES POWER ENGINEERING CONFERENCE (UPEC) 2020, : IEEE, 2020. p. 1–6. DOI: 10.1109/UPEC49904.2020.9209842.

DE DOILE, Gabriel Nasser Doyle; ROTELLA JUNIOR, Paulo; ROCHA, Luiz Célio Souza; JANDA, Karel; PERUCHI, Rogério; AQUILA, Giancarlo; BALESTRASSI, Pedro Paulo. *Impacts of economic regulation on photovoltaic distributed generation with battery energy storage systems*. **Journal of Energy Storage**, v. 72, n. July, 2023. b. DOI: 10.1016/j.est.2023.108382.

DE DOYLE, Gabriel Nasser Doile; ROTELLA JUNIOR, Paulo; ROCHA, Luiz Célio Souza; CARNEIRO, Priscila França Gonzaga; PERUCHI, Rogério Santana; JANDA, Karel; AQUILA, Giancarlo. *Impact of regulatory changes on economic feasibility of distributed generation solar units in Brazil*. **Sustainable Energy Technologies and Assessments**, v. 48, n. October, 2021. DOI: 10.1016/j.seta.2021.101660.

DE SOUZA NOEL SIMAS BARBOSA, Larissa; OROZCO, Javier Farfan; BOGDANOV, Dmitrii; VAINIKKA, Pasi; BREYER, Christian. *Hydropower and Power-to-gas Storage Options: The Brazilian Energy System Case*. **Energy Procedia**, v. 99, n. March, p. 89–107, 2016. DOI: 10.1016/j.egypro.2016.10.101. Available at: http://dx.doi.org/10.1016/j.egypro.2016.10.101.

DELAIGLE, Aurore; HALL, Peter. *Defining probability density for a distribution of random functions*. **Annals of Statistics**, v. 38, n. 2, p. 1171–1193, 2010. DOI: 10.1214/09-AOS741.

DIAS, Williams; ROEHL, Deane; MEJIA, Cristian; SOTOMAYOR, Paul. *Cavern integrity for underground hydrogen storage in the Brazilian pre-salt fields*. **International Journal of Hydrogen Energy**, 2023.

DNPM. **DNPM Ordinance nº 237**. 2001. Available at: https://anmlegis.datalegis.net/action/UrlPublicasAction.php?acao=abrirAtoPublico&num_ato=00000237&sgl_tipo=POR&sgl_orgao=DNPM/MME&vlr_ano=2001&seq_ato=000&cod_tipo=&des_item=&des_item_fim=&num_linha=&cod_modulo=351&cod_menu=6710. Accessed on: Ago. 15th, 2024.

DOYLE DE DOILE, Gabriel Nasser. *Connection of Wind Power Plants at Brazilian Integrated Power Grid*. *In*: 15TH WIND INTEGRATION WORKSHOP 2016, Viena. Viena

EMAE. **EMAE Pumping Plants**. 2023. Available at: http://emae.com.br/elevatorias/. Accessed on: Maio 14th, 2023.

EPE. **PDE 2030 - Ten-year Energy Expansion Plan**. **Energy Research Company**EPE's Publications., , 2020. a.

EPE. **National Energy Plan – PNE 2050**. 2020b. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-227/topico-563/Relatorio Final do PNE 2050.pdf. Accessed on: Nov. 8th, 2024.

EPE. **Usinas Hidrelétricas Reversíveis (UHR): Desafios para inserção em mercados de energia elétrica**. EPE's Publications., , 2021. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-561/EPE-DEE-NT-013_2021-r0.pdf.

EPE. **Ten-Year Energy Expansion Plan - PDE 2034**. 2024. Available at: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2034. Accessed on: Nov. 17th, 2024.

FIGUEIREDO, Erli F. *Rotating Electrical Machines BT - Springer Handbook of Power Systems*. *In*: PAPAILIOU, Konstantin O. (org.). Singapore: Springer Singapore, 2021. p. 367–441. DOI: 10.1007/978-981-32-9938-2_6. Available at: https://doi.org/10.1007/978-981-32-9938-2_6.

GALVÃO, Maria Cristiane Barbosa; RICARTE, Ivan Luiz Marques. *Revisão Sistemática Da Literatura: Conceituação, Produção E Publicação*. **Logeion: Filosofia da Informação**, v. 6, n. 1, p. 57–73, 2019. DOI: 10.21728/logeion.2019v6n1.p57-73.

GETH, F.; BRIJS, T.; KATHAN, J.; DRIESEN, J.; BELMANS, R. *An overview of large-scale stationary electricity storage plants in Europe: Current status and new developments*. **Renewable and Sustainable Energy Reviews**, v. 52, p. 1212–1227, 2015. DOI: 10.1016/j.rser.2015.07.145.

GHOSH, Arunabh. *Multiple makings at China's first hydroelectric power station at Shilongba, 1908–1912*. **History and Technology**, v. 38, n. 2–3, p. 167–185, 2022. DOI: 10.1080/07341512.2022.2112295. Available at: https://doi.org/10.1080/07341512.2022.2112295.

GOLDEMBERG, José. *The evolution of the energy and carbon intensities of developing countries*. **Energy Policy**, v. 137, n. October 2019, 2020. DOI: 10.1016/j.enpol.2019.111060.

GUIMARÃES, Alberto de Almeida Bossi; BASTOS, Adriano Silva; VIANA, Edna Maria de Faria; MENDES, Victor Flores; MARTINEZ, Carlos Barreira. *Implementation of pumped hydro/photovoltaic systems in mining-degraded areas: a case study in Quadrilátero Ferrífero, Minas Gerais, Brazil*. **International Journal of Renewable Energy Development**, v. 13, n. 4, p. 639–653, 2024. DOI: 10.61435/ijred.2024.60005.

HAPPOLDT, H. K.; HARTMANN, O. J.; WIEDEMANN, E. *The Present State of Pumped Storage in Europe*. **IEEE Transactions on Power Apparatus and Systems**, v. 82, n. 68, p. 618–631, 1963. DOI: 10.1109/TPAS.1963.291376.

HERNANDEZ, Hugo. *Multivariate Probability Theory: Determination of Probability Density Functions*. **ForsChem Research Reports**, v. 2, n. 13, p. 1–20, 2017. DOI: 10.13140/RG.2.2.28214.60481. Available at: www.forschem.org.

HJALMARSSON, Johannes; THOMAS, Karin; BOSTRÖM, Cecilia. *Service stacking using energy storage systems for grid applications – A review*. **Journal of Energy Storage**, v. 60, n. March 2022, 2023. DOI: 10.1016/j.est.2023.106639.

HUNT, Julian David et al. *Underground Gravity Energy Storage: A Solution for Long-Term Energy Storage*. **SSRN Electronic Journal**, 2023. DOI: 10.2139/ssrn.4184471.

HUNT, Julian David; FREITAS, Marcos Aurélio Vasconcelos De; PEREIRA JUNIOR, Amaro Olímpio. *A review of seasonal pumped-storage combined with dams in cascade in Brazil*. **Renewable and Sustainable Energy Reviews**, v. 70, n. October 2016, p. 385–398, 2017. DOI: 10.1016/j.rser.2016.11.255. Available at: http://dx.doi.org/10.1016/j.rser.2016.11.255.

HUNT, Julian David; FREITAS, Marcos Aurélio Vasconcelos; PEREIRA JUNIOR, Amaro Olímipio. *Enhanced-Pumped-Storage: Combining pumped-storage in a yearly storage cycle with dams in cascade in Brazil*. **Energy**, v. 78, p. 513–523, 2014. DOI: 10.1016/j.energy.2014.10.038.

HUNT, Julian David; ZAKERI, Behnam; LOPES, Rafael; BARBOSA, Paulo Sérgio Franco; NASCIMENTO, Andreas; CASTRO, Nivalde José De; BRANDÃO, Roberto; SCHNEIDER, Paulo Smith; WADA, Yoshihide. *Existing and new arrangements of pumped-hydro storage plants*. **Renewable and Sustainable Energy Reviews**, v. 129, n. May, 2020. DOI: 10.1016/j.rser.2020.109914.

IBAMA. **IBAMA Ordinance nº 924**. 2021. Available at: https://www.in.gov.br/en/web/dou/-/portaria-n-924-de-22-de-abril-de-2021-402816039. Accessed on: Jan. 18th, 2024.

IBAMA. **National Environmental Library**. 2024. Available at: https://www.ibama.gov.br/sophia/. Accessed on: Jul. 16th, 2024.

IBAMA. **IBAMA Legislation**. 2025. Available at: https://www.ibama.gov.br/legislacao. Accessed on: Jan. 3th, 2024.

IBGE. **IBGE - Brazilian Institute of Geography and Statistics**. 2024. Available at: https://www.ibge.gov.br/explica/inflacao.php. Accessed on: Jul. 4th, 2024.

ICMBIO. **Brasil ultrapassa a marca de 20 mil cavernas conhecidas**. 2021.

IEA. **Share of renewable energy in power generation, 2030**. 2025. Available at: https://www.iea.org/data-and-statistics/data-tools/renewable-energy-progress-tracker. Accessed on: Jan. 7th, 2025.

IMA-AL. **Alagoas State Environmental Institute**. 2024. Available at: https://www2.ima.al.gov.br/. Accessed on: Nov. 13th, 2024.

IRIA, José; SOARES, Filipe. *An energy-as-a-service business model for aggregators of prosumers*. **Applied Energy**, v. 347, n. March, 2023. DOI: 10.1016/j.apenergy.2023.121487.

ITAJUBA. **Municipal Law nº 3,353**. 2019.

ITAJUBA. **Municipal Environmental Licencing Procedures of Itajubá**. 2024.

KITCHENHAM, Barbara. *Procedures for Performing Systematic Literature Reviews*. **Joint Technical Report, Keele University TR/SE-0401 and NICTA TR-0400011T.1**, v. 33, p. 33, 2004.

KITSIKOUDIS, Vasileios; ARCHAMBEAU, Pierre; DEWALS, Benjamin; PUJADES, Estanislao; ORBAN, Philippe; DASSARGUES, Alain; PIROTTON, Michel; ERPICUM, Sebastien. *Underground pumped-storage hydropower (UPSH) at the martelange mine (belgium): Underground reservoir hydraulics*. **Energies**, v. 13, n. 14, 2020. DOI: 10.3390/en13143512.

KRAMER, Gert Jan; ARTS, Twan; URAI, Janos L.; VRIJLING, Han; HUYNEN, Jan M. H. *Risk mitigation and investability of a U-PHS project in the Netherlands*. **Energies**, v. 13, n. 19, 2020. DOI: 10.3390/en13195072.

KREBS, Antônio S. J.; AMBONI, Tiago M.; ROMANO NETO, Roberto; ZANUZ, Marcio; GOMES, Cleber J. B.; AMARAL, José E. *Monitoramento das bocas de minas abandonadas com drenagens ácidas, na área correspondente à Bacia Carbonífera de Santa Catarina*. **XVI Congresso Brasileiro de Águas Subterrâneas e XVII Encontro Nacional de Perfuradores de Poços**, n. 48, p. 1–16, 2010. Available at: https://rigeo.cprm.gov.br/bitstream/doc/933/1/evento_PAP003018.pdf8.pdf.

KRISHAN, Om; SUHAG, Sathans. *Techno-economic analysis of a hybrid renewable energy system for an energy poor rural community*. **Journal of Energy Storage**, v. 23, n. April, p. 305–319, 2019. DOI: 10.1016/j.est.2019.04.002.

KROPOSKI, Benjamin; LASSETER, Robert; ISE, Toshifumi; MOROZUMI, Satoshi; PAPATHANASSIOU, Stavros; HATZIARGYRIOU, Nikos. *Making microgrids work*. **IEEE power and energy magazine**, v. 6, n. 3, p. 40–53, 2008.

KUSAKANA, Kanzumba. *Using PV with borehole pumped hydro storage systems for small farming activities in South Africa*. **2017 IEEE Innovative Smart Grid Technologies - Asia: Smart Grid for Smart Community, ISGT-Asia 2017**, p. 1–6, 2018. DOI: 10.1109/ISGT-Asia.2017.8378384.

KUSAKANA, Kanzumba. *Hydro aeropower for sustainable electricity cost reduction in South African farming applications*. **Energy Reports**, v. 5, p. 1645–1650, 2019. DOI: 10.1016/j.egyr.2019.11.023.

LI, Cun-bin; LU, Gong-shu; WU, Si. *The investment risk analysis of wind power project in China*. **Renewable Energy**, v. 50, n. 2013, p. 481–487, 2013. DOI: 10.1016/j.renene.2012.07.007.

LIU, Yaqiong; SUN, Shudong; WANG, Xi Vincent; WANG, Lihui. *An iterative combinatorial auction mechanism for multi-agent parallel machine scheduling*. **International Journal of Production Research**, v. 60, n. 1, p. 361–380, 2022. DOI: 10.1080/00207543.2021.1950938. Available at: https://doi.org/10.1080/00207543.2021.1950938.

MAIA DA COSTA, Alvaro et al. *Potential of storing gas with high CO2 content in salt caverns built in ultra-deep water in Brazil*. **Greenhouse Gases: Science and Technology**, v. 9, n. 1, p. 79–94, 2019.

MANNING, Melissa. **Top Ten Cleantech Trends in 2024**. S&P Global.

MARIANO, Yuri. **Aspectos geotécnicos dos afundamentos em Maceió**. 2021. Available at: https://www.geoportalufjf.com/post-unico/aspectos-geotécnicos-dos-afundamentos-em-maceió. Accessed on: Nov. 5th, 2024.

MARTINS, Felipe Nascimento; SOUSA, Gilberto Costa Drumond. *Controle Fuzzy Do Gerador De Indução Trifásico Para Micro Centrais Hidrelétricas*. **Eletrônica de Potência**, v. 12, n. 2, p. 137–146, 2007. DOI: 10.18618/rep.2007.2.137146.

MATOS, Catarina R.; CARNEIRO, Júlio F.; SILVA, Patrícia P. *Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification*. **Journal of Energy Storage**, v. 21, n. December 2018, p. 241–258, 2019. DOI: 10.1016/j.est.2018.11.023. Available at: https://doi.org/10.1016/j.est.2018.11.023.

MELFI, Adolpho J.; MISI, Aroldo; CAMPOS, Diogenes A.; CORDANI, Umberto G. **Recursos Minerais no Brasil: Problemas e Dasafios**. Rio de janeiro: Academia Brasileira de Ciências, 2016.

MENÉNDEZ, Javier; FERNÁNDEZ-ORO, Jesús Manuel; LOREDO, Jorge. *Economic feasibility of underground pumped storage hydropower plants providing ancillary services*. **Applied Sciences (Switzerland)**, v. 10, n. 11, 2020. DOI: 10.3390/app10113947.

MENÉNDEZ, Javier; ORDÓÑEZ, Almudena; ÁLVAREZ, Rodrigo; LOREDO, Jorge. *Energy from closed mines: Underground energy storage and geothermal applications*. **Renewable and Sustainable Energy Reviews**, v. 108, n. March, p. 498–512, 2019. DOI: 10.1016/j.rser.2019.04.007.

MENSAH, Johnson Herlich Roslee; SANTOS, Ivan Felipe Silva Dos; RAIMUNDO, Danielle Rodrigues; COSTA DE OLIVEIRA BOTAN, Maria Cláudia; BARROS, Regina Mambeli; TIAGO FILHO, Geraldo Lucio. *Energy and economic study of using Pumped Hydropower Storage with renewable resources to recover the Furnas reservoir*. **Renewable Energy**, v. 199, n. September, p. 320–334, 2022. DOI: 10.1016/j.renene.2022.09.003.

MINAS GERAIS. **MG State Decree nº 18,466**. 1977. Available at: https://www.almg.gov.br/legislacao-mineira/DEC/18466/1977/#texto. Accessed on: Ago. 28th, 2024.

MINAS GERAIS. **MG State Law nº 21,972**. 2016. Available at: https://www.almg.gov.br/legislacao-mineira/texto/LEI/21972/2016/?cons=1. Accessed on: Ago. 28th, 2024.

MINAS GERAIS. **MG State Decree nº 47,383**. 2018. Available at: https://www.almg.gov.br/legislacao-mineira/DEC/47383/2018/. Accessed on: Ago. 28th, 2024.

MMA. **National Environmental Licensing Portal**. 2024. Available at: https://pnla.mma.gov.br/.

MORIOKA, Sandra Naomi; BOLIS, Ivan; CARVALHO, Marly Monteiro De. *From an ideal dream towards reality analysis: Proposing Sustainable Value Exchange Matrix (SVEM) from systematic literature review on sustainable business models and face validation*. **Journal of Cleaner Production**, v. 178, p. 76–88, 2018. DOI: 10.1016/j.jclepro.2017.12.078.

NIKOLAOS, Papadakis C.; MARIOS, Fafalakis; DIMITRIS, Katsaprakakis. *A Review of Pumped Hydro Storage Systems*. 2023.

ONS. **Hydroelectric Reservoirs**. 2023. Available at: https://www.ons.org.br/paginas/energia-agora/reservatorios. Accessed on: Jun. 19th, 2023.

ONS. **Grid Procedures**. 2024a. Available at: https://www.ons.org.br/paginas/sobre-o-ons/procedimentos-de-rede/o-que-sao. Accessed on: Jan. 18th, 2024.

ONS. **History of Wind and Solar Photovoltaic Generation**. 2024b. Available at: https://www.ons.org.br/paginas/resultados-da-operacao/historico-da-operacao/dados-de-geração-eólica-e-solar.

PEARRE, Nathaniel; SWAN, Lukas. *Reimagining renewable electricity grid management with dispatchable generation to stabilize energy storage*. **Energy**, v. 203, p. 117917, 2020. DOI: 10.1016/j.energy.2020.117917.

PECZKIS, Grzeggorz. *Practical possibilities of pumped-storage power plants implementation in liquidated underground mines*. v. 101, n. 4, p. 213–225, 2021.

PICKARD, William F. *The history, present state, and future prospects of underground pumped hydro for massive energy storage*. **Proceedings of the IEEE**, v. 100, n. 2, p. 473–483, 2012. DOI: 10.1109/JPROC.2011.2126030.

PM ITAJUBA. **Itajubá Environment Municipal Secretariat**. **PM Itajuba**Environmental Licenses., , 2024. Available at: https://www.itajuba.mg.gov.br/detalhe-da-unidade/nome/licenciamento-ambiental/395. Accessed on: Jan. 23th, 2024.

RABI, Ayah Marwan; RADULOVIC, Jovana; BUICK, James M. *Comprehensive review of compressed air energy storage (CAES) technologies*. **Thermo**, v. 3, n. 1, p. 104–126, 2023.

RAYCHAUDHURI, Samik. *Introduction to monte carlo simulation*. *In*: PROCEEDINGS - WINTER SIMULATION CONFERENCE 2008, Broomfield, CO, USA. Broomfield, CO, USA: IEEE, 2008. p. 91–100. DOI: 10.1109/WSC.2008.4736059.

REHMAN, Shafiqur; AL-HADHRAMI, Luai M.; ALAM, Md Mahbub. *Pumped hydro energy storage system: A technological review*. **Renewable and Sustainable Energy Reviews**, v. 44, p. 586–598, 2015. DOI: 10.1016/j.rser.2014.12.040.

REY, Juan M.; MARTI, Pau; VELASCO, Manel; MIRET, Jaume; CASTILLA, Miguel. *Secondary Switched Control with no Communications for Islanded Microgrids*. **IEEE Transactions on Industrial Electronics**, v. 64, n. 11, p. 8534–8545, 2017. DOI: 10.1109/TIE.2017.2703669.

ROTELLA JUNIOR, Paulo; ROCHA, Luiz Célio Souza; MORIOKA, Sandra Naomi; BOLIS, Ivan; CHICCO, Gianfranco; MAZZA, Andrea; JANDA, Karel. *Economic Analysis of the Investments in Battery Energy Storage Systems: Review and Current Perspectives*. **Energies**, v. 14, n. 9, p. 2503, 2021. DOI: 10.3390/en14092503.

SAES, Alexandre Mac Chione. *Modernizing electric utilities in Brazil: National vs. foreign capital, 1889-1930*. **Business History Review**, v. 87, n. 2, p. 229–253, 2013. DOI: 10.1017/S0007680513000445.

SALLES, Mateus Gomes de Siqueira; BONATTO, Benedito Donizeti; RIBEIRO, Paulo. *Análise Econômica-Tarifária da instalação de sistema de energia solar fotovoltaica com ou sem armazenamento no campus da UNIFEI-Itajubá*. *In*: XIV CBQEE - CONFERENCIA BRASILEIRA SOBRE QUALIDADE DA ENERGIA ELÉTRICA 2021, Online from Foz do Iguaçu, PR. Online from Foz do Iguaçu, PR p. 1–8. DOI: 10.17648/cbqee-2021-130562.

SALTUK, Muhammed Fatih. *Prefeasibility analysis of the pumped hydro storage (PHS) system in Türkiye : A case study on a hybrid system*. **Energy Storage and Conversion**, v. 1, n. 1, p. 1–18, 2023.

DOI: 10.59400/esc.v1i1.215.

SANGAL, Saurabh; GARG, Arpit; KUMAR, Dinesh. *Review of Optimal Selection of Turbines for Hydroelectric Projects*. **Review of Optimal Selection of Turbines for Hydroelectric Projects**, v. 3, n. 3, p. 424–430, 2013.

SCHMITT, G. E. *Pumped storage installation in Texas*. **Electrical Engineering**, v. 69, n. 7, p. 588, 1950. DOI: 10.1109/EE.1950.6433949.

SCHULZ, R. R.; WALL, A. *Pumped storage hydro and sewage plants may go underground.* **ENGNG. NEWS REC.**, v. 194, n. 21, May 22, 1975, p. 12, 1975. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0016448850&partnerID=40&md5=85c46c64ee215d37e8221b49957a8f35.

SHADHU KHAN, P. K.; CHATTERJEE, J. K. *Three-phase induction generators: A discussion on performance*. **Electric Machines and Power Systems**, v. 27, n. 8, p. 813–832, 1999. DOI: 10.1080/073135699268867.

SHARLIN, Harold I. *From Faraday to the dynamo*. **Scientific American**, v. 204, n. 5, p. 107–119, 1961.

SHIRINDA, K.; KUSAKANA, K.; KOKO, S. P. *Techno-economic analysis of a standalone solar PV with groundwater pumped-hydro-storage system*. *In*: PROCEEDINGS OF THE 27TH INTERNATIONAL CONFERENCE ON THE DOMESTIC USE OF ENERGY, DUE 2019 2019, Wellington, South Africa. Wellington, South Africa: cape peninsula university of technology, 2019. p. 90–95.

SHIRINDA, Khanyisa; KUSAKANA, Kanzumba; KOKO, Sandile P. *Optimal Power Dispatch of a Grid-Connected Photovoltaic with Groundwater Pumped-Hydro Storage System Supplying a Farmhouse*. *In*: 2020 8TH INTERNATIONAL CONFERENCE ON SMART GRID AND CLEAN ENERGY TECHNOLOGIES, ICSGCE 2020 2020, Kuching, Malaysia. Kuching, Malaysia p. 5–9. DOI: 10.1109/ICSGCE49177.2020.9275604.

SHIRINDA, Khanyisa; KUSAKANA, Kanzumba; KOKO, Sandile Philip. *A Survey of Groundwater Pumping Technologies for Electricity Generation Through Hydropower*. *In*: 2018 OPEN INNOVATIONS CONFERENCE, OI 2018 2018, Johannesburg, South Africa. Johannesburg, South Africa: IEEE, 2018. p. 96–101. DOI: 10.1109/OI.2018.8535632.

SINGHAL, M. K.; ARUN, Kumar. *Optimum Design of Penstock for Hydro Projects*. **International Journal of Energy and Power Engineering**, v. 4, n. 4, p. 216, 2015. DOI: 10.11648/j.ijepe.20150404.14.

SIOSHANSI, F. **Energy Efficiency: Towards the End of Demand Growth**. Waltham, MA, USA: Elsevier Science, 2013. Available at: https://books.google.com.br/books?id=Mv-JeNm-zVIC.

SNISB. **National Information System on Dam Safety**. 2023. Available at: https://www.snisb.gov.br/portal-snisb/inicio. Accessed on: Jun. 12th, 2023.

SOUTO JR, Levi. **O custo que poucos falam. Parte 2: Curtailment**. 2024. Available at: https://brasilenergia.com.br/energia/o-custo-que-poucos-falam-parte-2-curtailment. Accessed on: Nov. 7th, 2024.

SUISSE ADMINISTRATION. **Where is electricity produced in Switzerland?** 2021.

TEIXEIRA, Aloisio; VIANNA, Salvador Werneck. **Cenários macroeconômicos no horizonte 2022/2030**. DOI: 10.7476/9788581100159.0003.

TONIDANDEL, Rodrigo De Paula; PARIZZI, Maria Giovana; LIMA, Hernani Mota De. *Aspectos Legais E Ambientais Sobre Fechamento De Mina, Com Ênfase No Estado De Minas Gerais*. **Geonomos**, v. 20, n. 1, p. 32–40, 2012. DOI: 10.18285/geonomos.v20i1.24.

TOPALOVI, Zejneba; HAAS, Reinhard; SAYER, Marlene. *Economic benefits of PHS and Li-ion storage . Study cases : Austria and Bosnia and Herzegovina*. **Applied Energy**, v. 362, n. March, 2024. DOI: 10.1016/j.apenergy.2024.122988.

TRANFIELD, David; DENYER, David; SMART, Palminder. *Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review*. **British Journal of Management**, v. 14, n. 3, p. 207–222, 2003. DOI: 10.1111/1467-8551.00375.

UDDIN, Nasim. *Geotechnical issues in the creation of underground reservoirs for massive energy* *storage*. **Proceedings of the IEEE**, v. 100, n. 2, p. 484–492, 2012. DOI: 10.1109/JPROC.2011.2161969.

VAHIDINASAB, Vahid; HABIBI, Mahdi. *Electric energy storage systems integration in energy markets and balancing services*. *In*: **Energy Storage in Energy Markets**. : Elsevier Inc., 2021. p. 287–316. DOI: 10.1016/b978-0-12-820095-7.00019-4.

VASSILEVA, Magdalena; AL-HALBOUNI, Djamil; MOTAGH, Mahdi; WALTER, Thomas R.; DAHM, Torsten; WETZEL, Hans Ulrich. *A decade-long silent ground subsidence hazard culminating in a metropolitan disaster in Maceió, Brazil*. **Scientific Reports**, v. 11, n. 1, p. 1–13, 2021. DOI: 10.1038/s41598-021-87033-0.

VIDAL BARRENA, Victor. **Análisis del dimensionamiento de una turbina hidráulica, por redes neuronales para una minicentral**. **Paradigmas**, 2018. DOI: 10.31381/paradigmas.v2i1.1512.

VILANOVA, Mateus Ricardo Nogueira; FLORES, Alessandro Thiessen; BALESTIERI, José Antônio Perrella. *Pumped hydro storage plants: a review*. **Journal of the Brazilian Society of Mechanical Sciences and Engineering**, v. 42, n. 8, p. 1–14, 2020. DOI: 10.1007/s40430-020-02505-0.

VISSER, Martijn; JAN VAN ECK, Nees; WALTMAN, Ludo. *Large-scale comparison of bibliographic data sources: Web of Science, Scopus, Dimensions, and CrossRef*. **17th International Conference on Scientometrics and Informetrics, ISSI 2019 - Proceedings**, v. 2, p. 2358–2369, 2019.

VORLET, S. L.; DE CESARE, G. *A comprehensive review on geomembrane systems application in hydropower*. **Renewable and Sustainable Energy Reviews**, v. 189, n. PA, p. 113951, 2024. DOI: 10.1016/j.rser.2023.113951. Available at: https://doi.org/10.1016/j.rser.2023.113951.

WILSON, F. M. *Pumping for power in the Colorado rockies*. **Electrical Engineering**, v. 67, n. 10, p. 980, 1948. DOI: 10.1109/EE.1948.6444385.

WINCH, Graham M. **Managing construction projects**. : John Wiley & Sons, 2009.

WINDE, Frank; KAISER, Friederike; ERASMUS, Ewald. *Exploring the use of deep level gold mines in South Africa for underground pumped hydroelectric energy storage schemes*. **Renewable and Sustainable Energy Reviews**, v. 78, n. April, p. 668–682, 2017. DOI: 10.1016/j.rser.2017.04.116.

YANG, Ke; FU, Qiang; YUAN, Liang; LIU, Qinjie; HE, Xiang; LIU, Feiyue. *Research on development demand and potential of pumped storage power plants combined with abandoned mines in China*. **Journal of Energy Storage**, v. 63, n. November 2022, p. 106977, 2023. DOI: 10.1016/j.est.2023.106977. Available at: https://doi.org/10.1016/j.est.2023.106977.

YANG, Yuqing; BREMNER, Stephen; MENICTAS, Chris; KAY, Merlinde. *Battery energy storage system size determination in renewable energy systems: A review*. **Renewable and Sustainable Energy Reviews**, v. 91, p. 109–125, 2018. DOI: https://doi.org/10.1016/j.rser.2018.03.047. Available at: https://www.sciencedirect.com/science/article/pii/S1364032118301436.

ZAMBON, Renato C.; BARROS, Mario T. L.; YEH, William W. G. *Storage, Productivity, and Resilience in the Brazilian Hydropower System*. *In*: WORLD ENVIRONMENTAL AND WATER RESOURCES CONGRESS 2019 2019, Reston, VA. Reston, VA: American Society of Civil Engineers, 2019. p. 98–106. DOI: 10.1061/9780784482339.011.

ZHOU, Xinping; YANG, Jiakuan; WANG, Fen; XIAO, Bo. *Economic analysis of power generation from floating solar chimney power plant*. **Renewable and Sustainable Energy Reviews**, v. 13, n. 4, p. 736–749, 2009. DOI: 10.1016/j.rser.2008.02.011.