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Analysis of environmental risks and impacts of an energy storage system: An applied case study of a photovoltaic plant in the Northeast of Brazil

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Abstract *— Batteries have been increasingly used as energy storage tools associated with the generation of solar and wind energy, contributing to the reduction of negative environmental impacts. However, as much as there is a reduction in impacts, when compared to other forms of energy generation, it is still relevant to analyze the environmental risks and impacts that may be linked to Energy Storage Systems (ESS). This study presents an analysis of environmental risks and impacts related to ESSs, based on lithium-ion (Li-ion) batteries, of a photovoltaic plant located in the Northeast of Brazil. The applied methodology involved two techniques: the Bow Tie method, for the analysis of environmental risks, and the Interaction Matrix method, for the analysis of environmental impacts. Within the scope of the Bow Tie method, diagrams of the situations relevant to this study were generated, identifying causes and consequences, as well as prevention and mitigation actions for each risk. The main environmental risks found were of fire and/or explosions and environmental contamination. In the event that these risks occur, the environmental impacts associated with the physical, biotic and anthropic environments, as well as with the phases of the Li-ion ESSs (operation and decommissioning), were also identified through the Interaction Matrix, which confirmed the importance of applying preventive and appropriate measures for the listed risks, in order to, as much as possible, avoid a wide range of impacts on the environment. Through this study, it was possible to highlight both the importance of the appropriate care for the protection of the environment and for the safety of the plant's employees and the surrounding community.*

I. INTRODUCTION

Electrochemical energy storage systems, batteries and supercapacitors are increasingly presented as potential storage tools with several applications in the Brazilian energy sector. They can be used both in residential and industrial establishments, providing different services, including for compensation of the variability of wind and solar generation. Therefore, such equipment fosters the renewable energy market, reducing some negative environmental impacts such as greenhouse gas emissions, e.g. The application of technologies aimed at storing energy through batteries, in several countries, occurs, in principle, because they prove to be economically and environmentally effective; characteristics which are strongly related to the purpose of the circular economy [1; 2].

Li-ion batteries are among the most widely used technologies in the world for energy storage. The advantages of Li-ion batteries, including having a high electrochemical potential and low maintenance, contribute to large-scale production of stationary storage systems using this type of technology. Although Li-ion batteries are more costly when compared to other "battery" type energy storage devices, they offer the capacity to store renewable energy at a competitive normalized cost of storage in many applications [3].

A typical Li-ion battery is composed of a graphite negative electrode and a lithium metal oxide positive electrode ($LiCoO_2$, $LiMnO_2$, $LiNiO_2$). The electrolyte is formed by a solution of lithium hexafluorophosphate salt ($LiPF_6$) dissolved in an organic solvent. Additionally, at the cathode and at the anode, collector interfaces made of aluminum and copper, respectively, are used [4].

Lithium-iron phosphate (LFP, $LiFePO_4$) is another commercially available cathodic material. The LFP battery offers good electrochemical performance with low resistance. This is possible with the nanoscale phosphate cathode material. Its main benefits are high rated current, long service life, as well as good thermal stability and increased safety and tolerance in heavy use. Furthermore, it is more tolerant under full load conditions and less stressed than other Li-ion systems, if kept at high voltage for a prolonged time [5; 6].

The electroactive materials of the electrodes are fixed on collector metallic strips made of aluminum for the cathode and of copper for the anode. The organic compound polyvinylidene fluoride (PVDF) or the copolymer polyvinylidene fluoride hexafluoropropylene fluoride (PVDF-HFP) are used as fixative and binding material for the particles of the active materials. The positive and negative electrodes are electrically insulated by a polyethylene or polypropylene microporous separator film in batteries that employ a liquid electrolyte; a polymer gel electrolyte layer in lithium-polymer batteries or solid electrolyte in solid-state batteries [7].

Also used as electrolytes are lithium salt solutions, such as lithium perchlorate ($LiClO_4$), lithium tetrafluoroborate ($LiBF_4$) and lithium hexafluoroarsenate ($LiAsF_6$), dissolved in organic solvents, such as propylene carbonate (PC), ethylene carbonate (EC), di-methyl carbonate (DMC), ethyl-methyl carbonate (EMC) among others, or a mixture of these organic solvents [7].

Currently, several Li-ion battery technologies are available on the market, containing different chemical compositions and employing various combinations of anodic and cathodic materials. Each chemical compound has its own electrical and economic characteristics.

It is important to highlight that in order to develop a more sustainable and competitive battery industry, it is essential to use responsibly sourced materials (using hazardous substances as strictly necessary), recycled materials (as much as possible), a minimal use of labels and batteries that have greater durability and performance, as well as having collection and recycling targets [8].

Thus, achieving a circular economy with a neutral climate impact requires the full mobilization of the industrial battery sector. In this context, the European Union (EU), e.g., has been adopting the circular economy as an economic model, in which the value of products and materials are maintained as long as possible in the economy through a reduction on the generation of waste and on the use of resources, as well as the constant valorization process for the reuse of a product until the end of its useful life. The transition is being implemented gradually and constitutes an indispensable element of the new EU industrial strategy, making Europe less dependent on primary raw materials [9].

Worldwide, the annual level of raw material extraction tripled between 1970 and 2017, and continues to rise, posing a huge global risk. About half of greenhouse gas emissions and more than 90% of biodiversity loss and pressure on water resources comes from the extraction resources and their transformation into materials, fuels and food. The industrial process remains highly linear and depends on the extraction of new raw materials, which are later traded and transformed into goods and, finally, disposed as waste or emissions. In the EU, industry has initiated the change, but it is still responsible for 20% of the EU's greenhouse gas emissions. [10].

Hence, the continuous decarbonization of the energy system is essential to achieve the climate targets established for 2030 and 2050. Renewable energy sources will play a fundamental role, and the smart integration of renewable energies, energy efficiency and other sustainable solutions in all sectors will contribute to achieving this decarbonisation at the lowest possible cost [9].

In this scenario, the growth in photovoltaic energy generation in the world has been noticeable, both for economic and environmental reasons, and thus the battery market has also taken on considerably large proportions. Thus, in order to develop technological knowledge of the behavior of photovoltaic plants in interconnected systems and to support future commercial generation projects, Petrobras, together with Lactec and other partner institutions (Federal University of Minas Gerais – UFMG and Federal University of Rio de Janeiro – UFRJ), started a Research and Development project (P&D 0553-0046/2016 by the National Electric Energy Agency – ANEEL) called “Technical and commercial arrangements for the inclusion of energy storage systems in the Brazilian energy sector”. The project consisted in building a pilot energy storage plant connected directly to the electricity distribution network, with the purpose of testing the capacity of energy storage plants (by Li-ion batteries) to mitigate power intermittence, improving the frequency and voltage stability of electrical networks connected to photovoltaic plants.

One of the steps of that project was to identify and analyze possible environmental risks and impacts related to the operation and decommissioning of the Li-ion-battery Energy Storage System (ESS) of a photovoltaic plant. Thus, the objective of this study is to present the analyzes that were projected for the operation and decommissioning phases of this ESS, in order to contribute with information on the possible environmental risks and impacts that can be generated by this type of ESS.

II. CASE STUDY AREA

The case study was carried out at the Alto do Rodrigues Photovoltaic Plant (UFV-AR) located in an area of 4.16 ha (Fig. 1) of the Vale do Açu Thermoelectric Plant (UTE-VLA), owned by Petrobras, also called Termoaçu.

This plant is located in the municipality of Alto do Rodrigues, in the state of Rio Grande do Norte, Brazil, and has a nominal power of 1.1 MWp. The ESS (1 MW/0.49 MWh) is internally connected to the UFV-AR, which has been connected to the electricity distribution network of Rio Grande do Norte State Energy Company (COSERN) since 2014. The ESS has been in operation since November 2021.

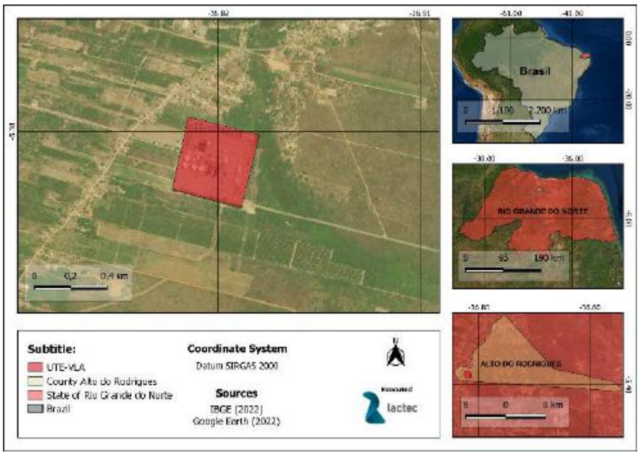

Fig.1: UFV-AR inserted in the land of UTE-VLA.

III. METHODOLOGY

We sought to analyze the regulations aimed at batteries and photovoltaic solar energy as a whole. In the international scenario, the project had as reference the policies established by the European Union, which is currently one of the most renowned and a pioneer on these matters, i.e., the European Ecological Pact, in order to explore more deeply the concepts of circular economy and decarbonization of the world energy system. The Brazilian legislation at the federal and state level was also consulted and referenced, also mentioning the main normative resolutions of ANEEL on the subject of this case study.

The Emergency Response Plan (ERP) of the UTE-VLA of Petrobras was also used as a basis, through which it was possible to verify the existence of protective and mitigating measures in case of accidents such as fires, explosions, among others. A brief socio-environmental characterization of the area in which the photovoltaic plant, together with its ESS, is located was also carried out, compiling the main physical, biotic and socioeconomic characteristics.

The characterization of the ESS of this case study was also performed, including all the components connected to the batteries and also their structures, from the container, in which the module is stored, to its electrocenter.

The environmental risk and impact analysis methodology applied in this case study essentially involved two techniques: 1) Bow Tie Method and; 2) Interaction Matrix Method, respectively. Both were employed in order to provide a systemic view of the activities involved in the processes that were assessed (operation and decommissioning of the ESS).

The Bow Tie method was used for the analysis of events of possible risk caused by another event called imminent danger. The central part of the “tie” divides the analyzed scenario between pre and post-event, allowing the verification of causes and their consequences. This methodology became popular in the 90's, when applied by the Shell group [11; 12]. For this study, the free version of the BowTie XP software was used to generate diagrams of both pre- and post-event scenarios in both phases of the ESS (operation and decommissioning).

As for the Interaction Matrix method, it was adopted within the scope of environmental impact assessment in order to identify possible interactions between the components of a project and the elements of the environment (impacts on the physical, biotic and anthropic environments) [13]. In this study, Excel software was used to generate the impact interaction matrix.

From the generation of Bow-Tie and Interaction Matrix diagrams, it was possible to visualize and understand the situations analyzed here, and the results were presented and discussed for each of the methods applied in this study.

IV. RESULTS AND DISCUSSION

4.1 Socio-environmental Characterization of the Surrounding Area

Regarding the socio-environmental characterization of the area where the UFV-AR is located, there is a predominance of herbaceous caatinga (with plants up to one meter, such as bromeliads and grasses) and arboreal (plants of up to two meters, such as leguminous plants), and there are also areas with exposed soil with drought-adapted deciduous species. The fauna of this region is characterized by some species of lizards, amphisbaenids, snakes and turtles. Local biodiversity is adapted to the semi-arid climate [14].

Regarding the hydrography, the UFV-AR is located around 1.9 km from the Piranhas River, which belongs to the Piancó-Piranhas-Açu river basin, which has a drainage area equivalent to 43,681.50 km ^{2}, covering 47 municipalities in Rio Grande do Norte. It should be noted that in the surroundings of the plant, there are no surface water bodies [15].

With regard to socioeconomic aspects, according to the last demographic census [16], the municipality of Alto do Rodrigues had a population of 12,305 people. Currently, it is estimated at 14,923 inhabitants. Land use for the agricultural sector represents 50% of municipal land use, mainly for agricultural activities. Forest areas represent the second most expressive land occupation, with emphasis on the savannah biome [17].

Next to the Petrobras plant (about 100 m) there is a village called São José, which is home to approximately 1,000 people.

4.2 Application of the *Bow Tie* Method for Analysis of Environmental Risks Related to the Operation and Decommissioning of the ESS

A total of two Bow Tie diagrams were generated for this case study, through the BowTie XP software, in view of two possible environmental events/risks that were previously selected, based on the bibliographic research that was carried out for this type of battery technology, and associated with the operation and decommissioning of the UFV-AR ESS, namely: Fire and/or Explosion (Fig. 2, with pre and post-event information) within the scope of the ESS operation and; Environmental Contamination (Fig. 3, with pre-event information and Fig. 4, with post-event information) within the scope of the ESS decommissioning. Both diagrams provided a more representative and understandable analysis of the hazards involving the operation and decommissioning of the ESS, listing the possible causes of the identified events, the prevention barriers, the mitigation barriers and the possible consequences linked to the occurrence of these events/risks. In both diagrams, the perspectives of three different environments (physical, biotic and anthropic) were covered.

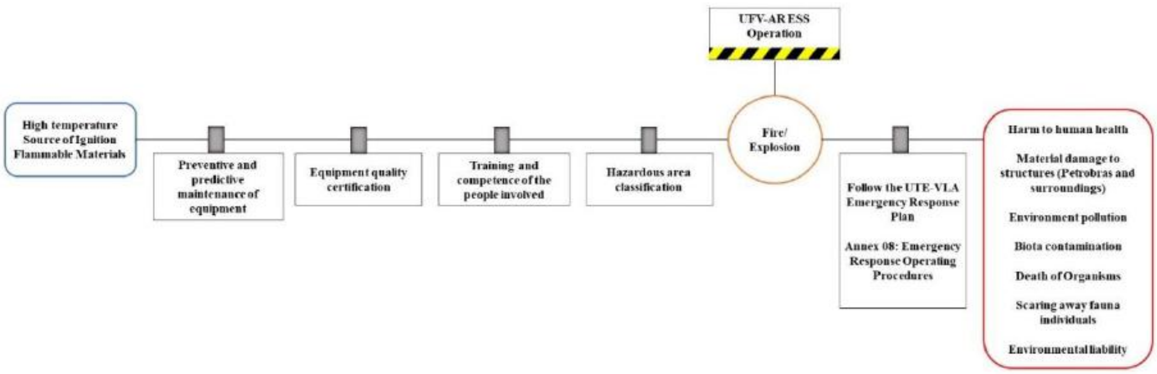

Fig. 2: Bow Tie Diagram (Pre and Post-Event Scenarios) - UFV-AR ESS Operation

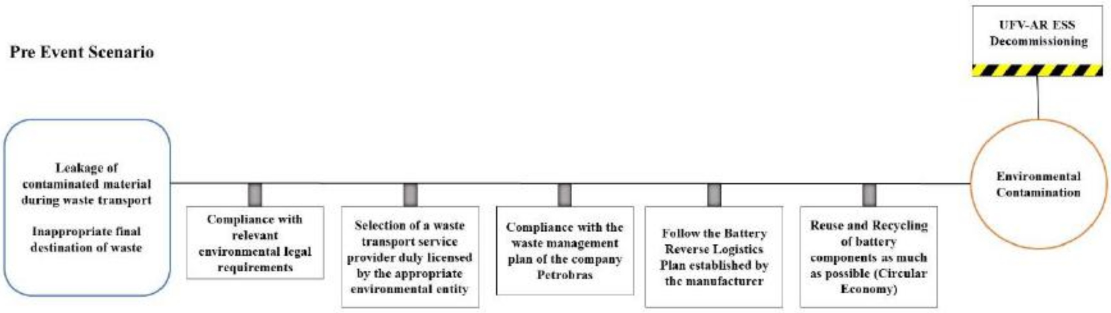

Fig. 3: Bow Tie Diagram (Pre-Event Scenario) - UFV-AR ESS Decommissioning

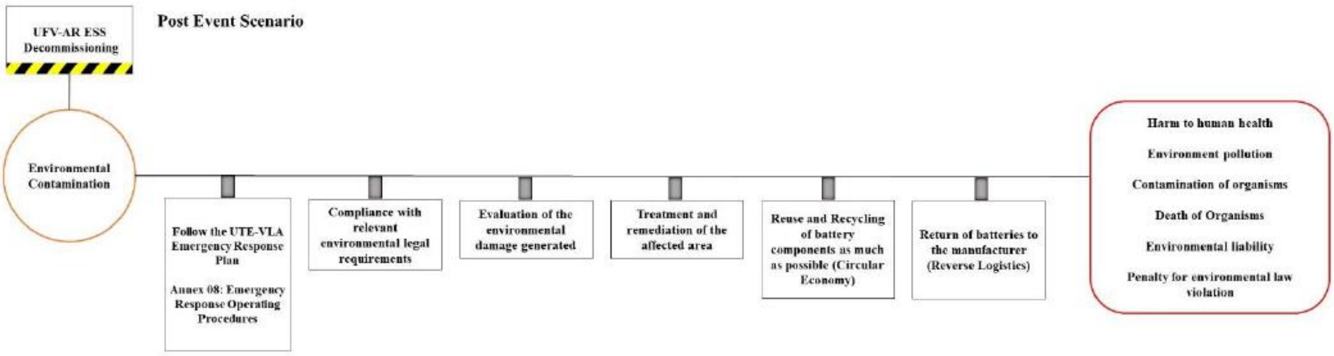

Fig. 4: Bow Tie Diagram (Post-Event Scenario) - UFV-AR ESS Decommissioning

Finally, the perspectives for each environment are detailed below, in order to provide more technical support compared to what was listed in the Bow Tie diagrams (Fig. 2, Fig. 3 and Fig. 4). Such perspectives were also based on the bibliographic research carried out for this study, as well as on the ERP of Petrobras' UTE-VLA.

4.2.1 Physical Environment

Energy storage systems have evolved over time, as is the case with Li-ion batteries. There are three known categories of failures related to Li-ion batteries: mechanical, electrical and thermal failures, which are associated with potential hazards such as gas release, fire and explosion. Battery plant fires share similarities with plastic fires, including thermal radiation, convective gas flow, and release of toxic chemicals. Still in relation to possible fires, the main damage envisaged is to the lives of the people involved and to property, especially when there is spread and the flames reach other structures [18].

Risks involve the relationship between impact and probability of occurrence. Also, working or living near an energy storage system is less dangerous than driving a vehicle 10 hours a week, smoking, or working in areas such as construction and agriculture [19]. In order for these facilities to continue providing safety to all, mitigation and control barriers must be designed in order to minimize and mitigate possible impacts. As technology evolves, these tools and their developers must increasingly seek to make work environments safer.

Li-ion batteries are designed to work within the so-called operational window, that is, in predetermined ranges of values within operational parameters (e.g. voltage and temperature). Hazardous situations are not to be expected when the battery system is operating within its operating windows.

The evolution of a hazardous situation in a Li-ion cell is typically characterized by an increase in cell temperature. When the thermal threshold is exceeded, the rate of heat dissipation may be less than the rate of heat generation. This will cause a thermal avalanche that could lead to solvent evaporation, pressure build-up and local fire. When the thermal avalanche from a single cell propagates to the next, inside a module or battery set, the so-called uncontrolled thermal propagation occurs, which can lead to serious consequences such as additional pressure increase, casing rupture, hot, corrosive and toxic gas venting, fire and, in specific circumstances, explosion. In principle, the greater the amount of chemicals and energy stored in a system, the greater the consequences [20].

However, safety systems are designed to ensure minimum safety conditions during battery life [20]. For stationary applications, the safety of battery systems is not regulated. However, there are international standards that can be used. Safety assessment in industrial applications (including stationary applications) is primarily based on the international standard IEC 62619:2017. This standard refers to overload conditions and is specific to lithium-ion batteries [20].

When considering the reuse (second use) of batteries, questions arise about the safety level of batteries at the end of their first life and how to ensure the safety of the systems used, especially in case of unkown history of use. In fact, the safety of batteries at the end of first use still needs further research. In addition, reused batteries will be subjected to different operating conditions and therefore will have to be tested according to standards appropriate to the new application. A new work proposal was established by IEC TC 21 (Secondary cells and batteries) for IEC 63330 ED1 “Requirements for reuse of secondary batteries”. The scope of the document specifies the procedure for assessing the performance and safety of used batteries and battery systems for reuse purposes [20].

For recycling an ESS, information on how to access and remove critical and hazardous components must be available. The type of information depends on the product, the components to be removed (e.g. solid, liquid and/or gas) and the techniques available for recycling. Some removal operations are automated; others require manual disassembly, access and manipulation. To optimize recycling operations and prevent damage to components, a disassembly procedure, including information on battery chemistry (hazardous, valuable, rare), is necessary. Also, it is important to note that disassembly must be carried out in discharged units [20].

Facilities used for the purpose of storing batteries (repair, reuse, remanufacturing, recycling or disposal) must comply with local fire and building codes of practice and rules regarding the storage of hazardous materials. Monitoring and controlling the temperature and possibly the humidity of the storage rooms is critical, as well as recording information about the battery, such as charging or discharging, and the open circuit voltage at the start and end of storage [20].

Another situation that should offer an adequate level of safety is the transport of batteries. For example, in Europe, second-use battery systems are required to comply with applicable transport regulations as required for new batteries. When the test criteria described in regulation UN 38.3:2019 “Recommendations on the Transport of dangerous goods, Manual of test and criteria” are satisfactorily met, the battery can be transported as a Class 9 regulated battery – Miscellaneous hazardous substances (lithium batteries, etc.) [20].

Battery-based energy storage systems have a finite lifespan, although users do have some criteria as to deactivation time based on factors such as safety and performance. The decommissioning process involves dismantling the energy storage system and removing it from site in compliance with applicable federal and local regulations governing the safe transportation and disposal of used equipment and waste. Basic processes and end-of-life management considerations are described by ESA [21], along with an assessment of current technology and market status regarding end-of-life options, including recovery for second use and recycling.

According to the ESA [22], the disposal of Li-ion batteries in landfills is not permitted by law and the prospects for reconditioning/recovering batteries for second life applications are still very limited. Although the Li-ion battery recycling industry is in its early stages, in terms of capacity and scale, more efficient and sustainable recycling processes are under development. Therefore, recycling batteries currently qualifies as a best practice for end-of-life management.

The scope of decommissioning depends on the specific conditions of the project, the type of system and the chosen means of disposal. In some cases, the battery modules are removed, while the rest of the system (controls and cabinets) remains and is reused with new battery modules. In other cases, systems are completely replaced in an integrated manner. Once a used battery is removed and intended for end-of-life management it is designated as “Universal Waste”, a special category of hazardous waste under U.S. EPA (Environmental Protection Agency) regulations. These rules generally require record keeping, labeling and storage methods that keep material out of contact with the environment. The energy storage system as a whole can represent a significant amount of materials, including cinder blocks, steel cabinets, cabling and a host of electronics. Concrete and steel are readily recyclable and many cabinets can be reused (particularly if the site is receiving new batteries). Inverters, control systems and other electronic equipment share many of the challenges of e-waste, but useful materials can often be recovered [22].

When batteries are submitted to recycling, the process begins with the disassembly of electrically discharged batteries. The current variety of Li-ion battery types, sizes and chemicals makes automating the process difficult, thus it is largely manual. The steps consist of removing the battery housing, separating the connectors, disassembling the modules from the racks, separating the cells from the modules, and removing the electrolyte. In addition to manual separation, some recyclers employ ultrasound and/or mechanical agitation to remove cathodic material. After crushing, or milling and pre-treatment, the cells undergo one or two types of recycling processes currently available: pyrometallurgical and hydrometallurgical. These processes recover different amounts and types of materials from batteries, which are sold in *commodity* markets. It should be noted that while the market re-introduction of recovered materials can generate environmental benefits, such as reduced use of raw materials, this must be compared to energy use and emissions from the recycling processes themselves, which can compromise these benefits [22].

It is important to highlight the structuring, implementation and operation of the reverse logistics system. In Brazil, Federal Decree no. 10,240/2020 [23] establishes that companies can create contract measures and agreements between themselves, in order to provide an environmentally appropriate disposal of solid waste. Also, Federal Decree no. 10.936/2022 [24] regulates Law no. 12.305/2010 which establishes the National Solid Waste Policy and the National Reverse Logistics Program. It is worth considering that Solid Waste Management Plans (SWMP) provide for the disposal of Li-ion batteries, including the transport procedure, government levels involved and licensing or other relevant legal requirements.

For this case study and analyzing the Bow Tie diagrams generated for the ESS of UFV-AR (as previously presented by Fig. 2, Fig. 3 and Fig. 4), as well as considering the concern with possible negative effects resulting from both the operation and decommissioning of this ESS, the ERP, prepared for the context of Petrobras' UTE-VLA, presents a fire fighting system, with appropriate escape routes in cases of risk, as well as a Map of Surroundings Characterization, including the location of the UFV-AR and its ESS [18].

In cases of chemical product leaks, this same ERP provides kits for controlling leaks for universal use. These kits include absorbent cords and blankets, gloves and disposal bags, among other equipment. There are also kits for working at heights, a first-aid clinic and material for isolating areas, if necessary [18].

Regarding medical emergencies due to intoxication and/or burns, victims must be removed from the scene and then the appropriate responsible bodies must be called (such as the Mobile Emergency Care Service - SAMU, ATP-ARG Emergency Brigade, or the UTE Occupational Health office – the latter, for less severe cases). In the event of a chemical product leak, the strategy includes calling the Emergency Brigade, blocking possible sources of ignition close to the affected area, and containing the leak and collecting the product that was leaked.

In cases of fire, in general, after activating the Emergency Brigade, some measures of its action are provided for in the respective ERP: i) check if there are victims at the scene and arrange for their medical attention; ii) fight the fire, activating the respective systems mentioned above; iii) contain/block rainwater drainage systems and local streams with physical barriers; iv) in case of electrical systems, de-energize equipment/system on site; v) turn off power sources near the affected location.

With regard to other possible negative effects, in the event of decommissioning of the ESS, considering the event of environmental contamination, it is essential to emphasize the importance of meeting the relevant environmental legal requirements (as a way of mitigating or containing a certain contamination), carrying out the treatment and remediation of the affected area (following appropriate regulations for each case), assessing the possible environmental damage generated by any contamination, investigating the possibility of reuse or recycling of some battery components or returning the batteries to the manufacturer (reverse logistics).

Much more than just ensuring that the appropriate assessments, mitigations, and remediations are carried out, in case of a certain event (post-event scenario), it is important to previously analyze the environmental impacts that may be generated, upon any event, and to adopt all appropriate measures in a pre-event scenario.

It should be noted that currently in Brazil, the batteries used are usually imported, as there is no such type of production in the country, which leads to difficulties in reverse logistics, in returning to manufacturers, for environmentally appropriate disposal of the batteries.

As ways to prevent fire/explosion risks and environmental contamination of the UFV-AR ESS, several actions can be listed, such as: maintenance personnel and service providers trained on the safety procedures and processes associated with risk activities; control of electrical ignition sources and instrumentation through hazardous area classification, correct specification of equipment and maintenance thereof.

4.2.2 Biotic Environment

In the present study, analyzing the possible situations of anomaly in its operation and decommissioning phases, fire/explosion events and environmental contamination can lead to the death of organisms, and/or environmental degradation, affecting the biota and its health conditions, behavior and survival over time. The chemical elements that make up batteries cause drastic and in some cases lasting impacts in ecosystems.

In addition, in the event that the batteries are improperly disposed of or in the event of breakage/leakage, most of the metals that compose them are insoluble, being discharged into the environment in an unnatural way. Metals dispersed in the soil do not degrade and cannot be recovered from the soil. A study carried out on the topic showed that unless they come in contact with acid rain, metals remain stationary in the soil and therefore metal pollution gathers in the surface layers, compromising crops that grow in the soil [25].

The effects that arise from chemical contamination are based on many factors. Not only do they depend on the chemical they come in contact with, but the effects are also determined by the "concentration of the element in the environment and the duration of exposure". Since many of these toxic chemicals progressively accumulate in the body (or in the ecosystem), "long-term exposure to low concentrations can lead to adverse effects when the toxic dose is reached" [25].

Still in the scope of the biotic environment, another situation that can occur is the scaring away of individuals of the fauna in the occurrence of any fire/explosion event. Fauna species such as birds and mammals have the ability to move to more distant locations. However, other faunal groups with low displacement capacity, such as amphibians and reptiles, may be directly affected. As to the flora, the vegetation present in the bordering areas can be affected in the event of the spread of flames, and the vegetation of the caatinga is more susceptible to burning in periods of drought in the region.

4.2.3 Anthropic Environment

Predicting the anthropic impacts generated, the possible risks and forms of mitigation, with regard to the operation and decommissioning of the ESS in question, is important both for Petrobras and for the surrounding community.

Considering the specifications of the present study, it was found that improvement in technology, inclusion of renewable energy and supply of electric energy to the COSERN grid are the most relevant positive anthropic impacts of this project. Photovoltaic technology has the potential to be the most used energy matrix in the world, having had a significant increase in its research and implementation, mainly in Brazil [26]. The Brazilian Northeast holds 70.7% of centralized photovoltaic projects and 18.9% of the country's distributed photovoltaic generation [27]. Brazil has levels of solar irradiation higher than those of countries where projects for the use of solar energy are widespread, and the photovoltaic generation capacity in the country corresponds to 8.9 GW [28].

On the other hand, with regard to the negative effects, situations such as increased risks of occupational accidents and of flow of vehicles not belonging to the locality may occur. Such increased flow can cause accidents involving both people and animals, and accidents with other vehicles [29]. These threats can be minimized by studying possible routes, where there is not a large flow of people, for the operation and decommissioning of Li-ion batteries, training and awareness of the company's drivers for defensive driving practices and dialogue with those responsible for signaling and maintenance.

Another identified risk is the fire/explosion of battery containers. Potential hazards are burns from overheated cells, injuries from overheated cells or explosions, injuries from fire, exposure to toxic or corrosive gases or liquids from the battery or its decomposition products [30]. If lithium is burning, both employees and the surrounding population must take distance and avoid exposure to toxic gases from its combustion. In the event of an accident such as an explosion, fire and contact with chemical substances, it is extremely important that the ERP of the plant is followed.

Regarding the possible damage to human health, mentioned as consequences in the Bow Tie diagrams for this case study (Fig. 2, Fig. 3 and Fig. 4) are bodily injuries to both Petrobras' employees and the local population around the area, due to the proximity to residences in the village of São José. The fire/explosion event can affect homes and residents, causing various physical injuries (superficial or serious), as well as loss of structures, if these events cause damage to both Petrobras facilities and nearby residences and surrounding public infrastructure (public roads, squares, among others).

4.3 Application of the Interaction Matrix Method of Environmental Impacts related to the Operation and Decommissioning of the ESS

In Fig. 5, the Interaction Matrix of negative environmental impacts associated with the operation and decommissioning of the UFV-AR ESS is presented. The associated risks were based on the two events listed for this case study, through the application of the Bow Tie method (Fire/ Explosion and Environmental Contamination) and the related environmental impacts (in the event of occurrence of these risks) were divided between the environments: i) physical: contamination of environmental resources (soil and water), emission of polluting gases, and generation of solid waste; ii) biotic: several impacts on fauna and flora; iii) anthropic: noise generation; generation of solid waste, and impacts on human health.

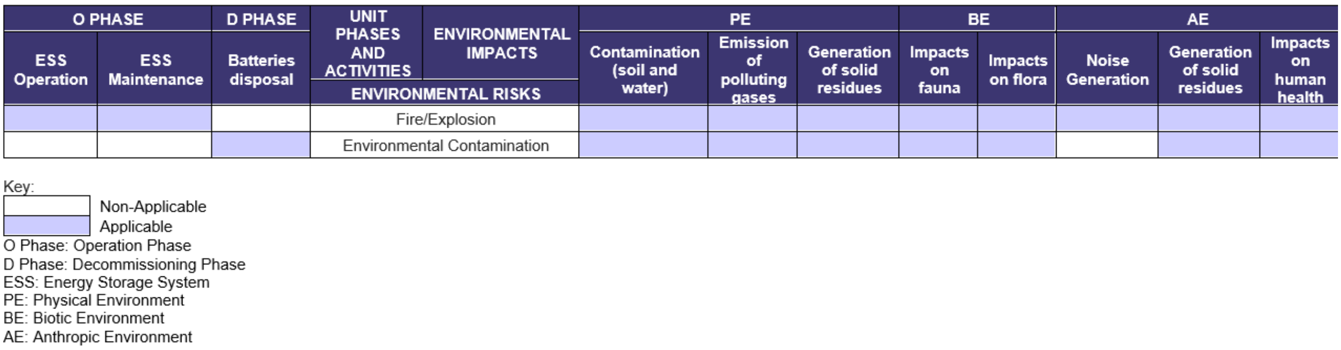

Fig. 5: Interaction Matrix of environmental impacts related to the operation and decommissioning of UFV-AR ESS

Observing the interactions (Fig. 5) between the risks and the environmental impacts that can be generated, in the event of the occurrence of the listed risks, it was possible to show that both for the Fire/Explosion risk (in the ESS operation phase), as for the Environmental Contamination risk (ESS decommissioning phase), all environmental impacts were considered on all environments (physical, biotic and anthropic), with the exception of the impact of noise generation (anthropic environment) for the risk of Environmental Contamination, which ended up not being considered.

Therefore, it was verified the importance of the application of preventive and appropriate measures for the listed risks, in order to avoid, as much as possible, a wide range of impacts on the environment.

V. CONCLUSION

Li-ion batteries are increasingly used internationally, due to their advantages related to efficiency and portability. Its application fits the circular economy model, contributing to a lower generation of negative environmental impacts. In addition, on a global scale, standards increasingly regulate the use and disposal of batteries, encouraging manufacturers and consumers to optimize their use in relation to their useful life.

Energy storage systems require constant supervision and maintenance, and their operation and decommissioning must take place according to technical guidelines from the manufacturing company. The SWMP in these operations must include the appropriate return procedures, so that reverse logistics can be applied. It is the role of the plant manager, together with the manufacturer, to verify the procedures involved regarding the environmentally appropriate and safe transport and disposal, at the end of the useful life of these batteries, since this is already provided for by several international, as well as Brazilian regulations (incipiently: Federal Decree no. 10.240/2020 [23] and Federal Decree no. 10.936/2022 [24]).

One of the most important points that this case study brings to light, considering that the use of batteries as a form of energy storage tends to grow both in Brazil and in the world, is the importance of applying adequate reverse logistics, reconciling with what each country establishes in terms of regulations on this subject, as well as with the most sustainable techniques for disposal and/or recycling of batteries.

Regarding the village located in the vicinity of the project, as well as the vegetation and fauna present in this area, they are the most susceptible, mainly in cases of fire/explosion and/or environmental contamination. Therefore, it is essential to adopt efficient and effective prevention and mitigation measures, and, where necessary, to monitor possible environmental impacts. In this case study, it is emphasized that Petrobras already has an ERP to be followed, in case the risks assessed in the ESS of UFV-AR occur.

Still with regard to the community close to the plant, it is suggested that, through the relationship channel between the village of São José and Petrobras, the community is officially communicated about the operation of the ESS and its importance in the context of photovoltaic energy storage generated at UFV-AR.

The use of the Bow Tie method in this case study made it possible to visualize the causes and consequences, as well as the prevention and mitigation actions for each type of event, both in the operation and decommissioning phase of the ESS, in a very intuitive and clear way, which can facilitate the dynamics of future Petrobras internal training, as well as a more assertive communication regarding the environmental risks identified in this ESS, as a way of raising awareness among employees who are directly involved in the activities of this plant.

As for the Interaction Matrix method applied in this case study, crossing the environmental risks identified for the operation and decommissioning of the ESS, with the environmental impacts that may occur in the physical, biotic and anthropic environments (in the event these risks actually occur), it was possible to note the importance of applying preventive measures, in order to avoid, as much as possible, the chances of a wide range of impacts on the environment.

Both the Bow Tie diagrams and the Interaction Matrix used in this case study are subject to updates, as new needs are identified by the employees involved in the operation and decommissioning activities of this ESS.

Finally, one concludes that the use of the two methods to analyze environmental risks and impacts of energy storage systems, not only Li-ion, but other technologies, is very practical and easy to understand. In this manner, one can ensure that all those involved in the possible environmental risks and impacts linked to a particular plant are aware and know how to proceed in cases where such events may occur.

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