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Issues in Energy Vulnerability Assessment: Looking for a Sustainable Choice of Natural Resource for Power Generation †

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Abstract: The objective of this work is to analyze, through environmental vulnerability (EV), disturbances in the environment caused by anthropic activities for the production of energy resources, focusing on the power generation sector. Methodologically, hydrocarbons (oil and gas) and solar are considered through a qualitative and quantitative analysis of environmental impacts, including the research inside Environmental Impact Studies and procedures like EIA/RIMA (institutional Environmental Impact Reports in Brazil). This study focuses on operation and demobilization of offshore drilling activity, and installation and operation of the Santos Basin pre-salt oil and gas production and disposal activity Stages 1, 2 and 3. The criteria addressed in the EIA/RIMAs are used, focusing on those that correlate with EV and the production of electricity. Impacts for long-term, permanent, partially reversible or irreversible disturbances are filtered, totaling 53 impacts (31 effective/21 potential). We concluded that the criteria and methodologies of EIAs vary between stages. At times, the variation is so drastic that the same impact can have a completely different rating from one stage to another, despite referring to the same area. This condition makes it impossible to define a single vulnerability index for the pre-salt venture. For a final analysis, we propose a cleaner energy production through distributed photovoltaic systems as a more adequate alternative for São Paulo's energy supply in terms of its impact on EV.

Keywords: environmental vulnerability; hydrocarbons; photovoltaic energy

1. Introduction

Electricity can be generated using various types of resources. The essentially inexhaustible energy of the sun, for example, influences many other sources of energy. Several factors affect the availability of solar energy, such as local weather conditions and astronomical factors associated with Earth's orbital and rotational movements [1,2]. Therefore, this is a temporally variable, or intermittent, source of energy with high spatial variability. Comparatively, fossil resources, such as oil and natural gas (NG), are non-renewable, as their formation is on a millennial scale. Unlike solar energy, which is considered "clean", hydrocarbons (HC) damage the planet from the moment of its invasive extraction (that has a risk of spillage) until its use (which releases greenhouse gases (GHG)) [3–9].

In 2017, the state of São Paulo totaled 74,899 GWh of energy generated and 73,422 GWh of energy received, thus 148,321 GWh required, supplying 59.3% of energy sufficiency. In December, the installed capacity through its fossil thermoelectric power plants was 2297 MW (2,296,578 KW), while photovoltaic (PV) represented only 1100 KW of installed capacity [10]. Comparatively, by February 2019, fossil thermoelectric installed capacity increased by 0.75% to 2314 MW (2,313,762 KW), while solar saw an increase of 13.7% to 1512 MW (151,217 KW) [11]. The state also had 102.3 MW of installed generation of distributed PV power [12]. This demonstrates an evolution in the adoption of cleaner, solar energy, but there is also a continued use of non-renewable, fossil energy.

Brazil began the pre-salt oil and NG offshore exploration in the early 2000′s, increasing exponentially the domestic oil and NG production. The main pre-salt reserve is in the São Paulo State. The Geographic Area of the Santos Basin (AGBS, Área Geográfica Bacia de Santos) has an area of 40,663 km^2, approximately 55 to 300 km from the city of São Paulo. In 2006, the Brazilian oil company, Petrobras continued its exploration in order to discover new oil and gas fields, as it hoped to increase its national production: a goal that it successfully achieved. That same year, Petrobras estimated that it would drill 62 wells of the pre-salt reservoirs—25 exploratory and 27 development sites—from 2008 to 2010. In order to drill these wells, Petrobras proposed to use nine floating rigs—five drill ships and four semi-submersible platforms [13]. These processes of mobilization and demobilization of the rigs and the drilling operation have many effective environmental impacts. For example, drilling wells through methods such as blasting, weight, and rotation inevitably cause irreversible damage to rock formations at the bottom of the sea. The blasting process involves the injection of drilling fluids that assist in the disintegration of rocks, which in turn are returned to the surface in the form of gravel, thus damaging all life that depends on these sites (for reasons ranging from suffocation and habitat loss to pollution/intoxication) [14]. There are also a large number of more serious potential impacts, for example in the event of a blowout (uncontrollable flow of gas, oil, or other reservoir fluid) [3,4]. Therefore, it is necessary to understand the effective (actual) and potential environmental impacts before executing a venture.

Once this drilling phase was completed, the oil and NG production and disposal stages began. At the time of this study, two multi-phase steps have been performed, and the third is predicted to be executed before 2024. These involve: Long-Term Tests (LTTs), Production Pilots/Short Pilots (PP/SPs), Early Production Systems (EPS), Production Development Projects (PDP), and Pipeline installation. Through LTTs and PP/SPs, it was possible to conclude in 2017 that there were 1090.10 million m^3 of proven oil reserves and 205,428.87 million m^3 of NG [10]. In the same year, the estimated daily production was about 1.6 million barrels per day. Over time, production has escalated: since October 2018, Petrobras has started operating more than five Floating Production Storage and Offloading (FPSO) vessels on the AGBS pre-salt reservoirs. When they reach peak production, each will produce 150,000 barrels of oil and 6 million m^3 of gas per day. With the exploration of this area, the prediction is that by 2020 Petrobras oil production will reach 2.8 million bpd (445 thousand m^3/day) [15]. At the time of this study, 18 platforms are operating in AGBS fields, with production expected to expand to three more by 2023 [16].

The definition of environmental vulnerability (EV) varies according to its application. In this study, the EV of a system is defined by its sensitivity, resilience, and exposure (terms defined in more detail below). EV analysis is a tool that can be used to manage a given territory's natural resources, usually aimed at reducing vulnerability. Thus, through this kind of analysis, decision makers are equipped with one more tool to optimize the use of natural resources through sustainable development. Sustainable development is classically defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [3,6,17–22]. Thus, this study analyzes, through EV, disturbances in the environment caused by anthropic activities for the production of energy resources, focusing on the power generation sector.

2. Materials and Methods

In this study, EV is defined by an environment's sensitivity, adaptive capacity and exposure to risk, or disturbances:

- **Sensitivity**, or **resistance**, is the extent or degree to which a system can absorb pressures without changing over the long-term.
- A system's ability to adjust to damage, to make use of resources or opportunities, or to respond to environmental changes that occur, qualifies its **adaptive capacity** or **resilience**, which can also be understood as the ability of a system to return to its initial condition, or adapt after modification (thus establishing a dynamic equilibrium).
- The degree, duration, or extent to which the system is in contact with disturbances defines its exposure to risk.

Thus, the higher the exposure and sensitivity, and the lower the adaptive capacity, the greater the vulnerability [23–34].

Since an environment's vulnerability is provoked by impacts (in this case) of a business venture, Environmental Impact Studies and Environmental Impact Reports (EIA/RIMA, Estudo de Impacto Ambiental/Relatório de Impacto sobre o Meio Ambiente) are used to better understand how the environment will be exposed to risks. In accordance with Article 1 of Conselho Nacional do Meio Ambiente (CONAMA, National Environment Council) Resolution № 01/1986, "[…] environmental impact is considered any change in the physical, chemical, and biological properties of the environment, caused by any form of matter or energy resulting from human activities that directly or indirectly affect: I. the health, safety, and welfare of the population; II. social and economic activities; III. the biota; IV. the aesthetic and sanitary conditions of the environment; V. the quality of environmental resources" [35].

Using EIA/RIMAs, this study seeks to understand the environmental impacts (on terrestrial, aquatic, and aerial, physical and biotic environments—III and V above) of the following activities on AGBS:

1. Operation and demobilization of offshore drilling activity;
2. Installation and operation of Santos Basin's Pre-Salt oil and gas production and outflow activity Stages 1, 2, and 3.

This study analyzes these because they are essential to the process of hydrocarbon extraction for the generation of electricity. Thus, in the drilling stage, this study analyzes drilling operation and demobilization, as without these phases, continuation to the other stages would not be possible. This study analyzes the installation and operation of Stages 1, 2, and 3, but does not consider the decommissioning phase, as it is not an essential step in energy production. AGBS was chosen for this case study because it harbors Brazil's largest extractable HC reservoir. In 2006 it represented 25% of the total area of the Petrobras concessions with 52% of its distribution located in São Paulo [36]. This work uses the EIA, as it is an exhaustive multidisciplinary study, required by law, conducted by the environmental agency responsible for licensing the activity, with the intention of generating an understanding of an enterprise's possible environmental impacts. Since there are phases of the stages analyzed that have not been performed at the time of this study, a predictive document, such as the EIA, allows for an understanding of future impacts. Because some impacts have already occurred, such as the drilling stage, a future study monitoring and analyze the actual impacts is recommended.

Article 6 of CONAMA Resolution № 01/1986 states that: "The environmental impact study will develop, at the very least, the following technical activities: 1-an environmental diagnosis of the project's area of influence through a full description and analysis of the environmental resources and their interactions, as they exist, in order to characterize the environmental situation of the area, prior to the implementation of the project…" [35] These can be found in detail in the following documents: **Drilling** [37]; **Stage 1—Physical** [38], **Biological** [39]; **Stage 2—Physical** [40], **Biological** [41]; **Stage 3—Physical** [42], **Biological** [43]. While our original mapping (Our original mapping can be found in Mein, T. Anexo Analise de Dados Vulnerabilidade 2019 [44]) covers all the criteria studied by the EIA/RIMAs, for the purposes of this study the focus of the scope is on the impacts that fit the following definitions, quantifications, and qualifications:

Table 1. EIA/RIMA definitions, quantification, and qualifications used in this study.

Class	Effective	When the impact is 100% likely to occur
	Potential	When an impact has a probability of occurring that is less than 100%
Nature	Positive	When the quality of the affected environmental factor (Specific definitions of environmental factors: [45]) represents improvement
	Negative	When there is a deterioration in the quality of the environmental factor affected
Scale	Local	Impact occurring up to 5 km from project site
	Regional	Impact occurring beyond 5 km from project site
	Superregional	Impact occurs on national, continental or global scale
Duration: Indicates for how long the impact will change the characteristics of the environmental factor.	Short	Impact has a duration of up to 15 years
	Medium	Impact's duration is between 15 and 30 years
	Long	Impact's duration is over 30 years
Permanence	Temporary	Classified as short and medium duration
	Permanent	Classified as long duration
Reversibility	Reversible	The environmental factor may return to the same conditions as prior to impact
	Partially Reversible	The environmental factor may partially return to the same conditions as prior to impact
	Irreversible	The environmental factor cannot return to the same conditions as prior to impact
Magnitude	Low Medium High	Determines the intensity or magnitude of the impact in relation to the alteration it causes
Importance	Little Medium Great	Relevance of an impact assessed by combining the environmental factor's sensitivity with impact's magnitude

Thus, in order to align the definition of EV with the characteristics analyzed by the EIA/RIMA, it can be understood that scale, duration, and permanence are related to exposure; reversibility is synonymous with adaptive capacity; and importance and magnitude are linked to sensitivity. However, in the EIA/RIMA definitions, the magnitude level is determined by an impact's scale, permanence, duration, and reversibility, while the importance is quantified by the magnitude of the impact and the sensitivity of the affected environmental factor. It is thus established that magnitude is a convergence of the exposure and reversibility indicators that define EV.

EV indices are application-specific [23–31,33,34]. For example, in 2004 the Environmental Vulnerability Index (EVI) was created to measure the vulnerability of small Pacific islands [46]. The index is broad and can apply to any country but is not widely used in Brazil. The EIA for Stage 3 presents an adapted index for measuring EV to oil. However, as this study covers all environmental impacts caused by HC extraction in the AGBS, the scope of this analysis goes beyond vulnerability to oil.

First, all the EIA data is analyzed for each selected stage. From this, some indicators that are not consistently present throughout all stages (i.e., frequency), or that are not relevant to this study, were discarded, as the most relevant results are derived from other indicators that remain in the analysis (i.e., immediate or delayed incidence time). After this initial analysis, 142 impacts remain. However, for the purposes of this analysis, which focuses on electricity production, impacts are filtered once again, aiming at disturbances that are long lasting, permanent, partially reversible or irreversible, totaling 53 impacts. It is noteworthy that of the 89 others that are not part of this study, 30 and 25 impacts are classified as being, respectively, of great and medium importance, highlighting the level of sensitivity of the affected environmental factors.

Of the 53 impacts, eight have at least one ambiguous indicator (for example, being classified as reversible and irreversible, or temporary and permanent). In these cases, the negative extreme is considered (i.e., irreversible or permanent).

The 53 impacts are separated first as being effective (totaling 31 impacts) or potential (total of 22 impacts). Since effective impacts have a 100% chance of occurrence, by definition, all of the analysis that follows considers a real impact versus potential impacts that may not happen. Next, the stages are ordered as Drilling (operation and demobilization) and Stages 1, 2, and 3 (installation and operation of each). From this, the magnitude and importance indicators are used to explore the EV of aerial, aquatic, and terrestrial, physical and biotic environments. Thus, through this analysis it is possible to qualify and quantify the interference of disturbances caused by the anthropic environment for energy production in relation to the vulnerability of environmental factors.

3. Results

3.1. Effective Impacts

Of the 31 effective impacts, 10 are classified as being of major importance, two of which are high, seven medium, and one of low magnitude (the change in air quality caused by atmospheric emissions—this being the only one of the ten impacts of temporary permanence, due to its dispersive quality, as it occurs on a superregional scale). Of the 31 impacts, besides those already mentioned, one is of high magnitude, while of medium importance. Thus, these impacts are grouped as the 11 most severe. Of these, two are impacts on the physical aerial environment, while nine are on the biotic environment (one on aerial fauna, eight on aquatic fauna, and four on aquatic flora). Contrastingly, 12 impacts are classified as being of low magnitude and importance, including the impact that contributes to the greenhouse effect. Of the other eight impacts of medium importance, five are of medium, and three of low magnitude. Of the 31 effective impacts, 22 are on the biotic environment, two on the air, and the other 20 on the aquatic environment. The nine impacts on the physical environment are: six aerial, two aquatic, and one terrestrial.

3.1.1. Drilling (Details of Impacts Caused by the Activities of This Stage Can Be Found at: [47])

During the drilling operation, there are two impacts of great importance and high magnitude, both of which refer to the aquatic environment, as they alter the marine biota (through demobilization of the drilling rig and the introduction of exotic species). While this operation is of short-term duration, it is a necessary step in the extraction of HC resources for power generation. For this reason, this high impact procedure is considered in this analysis. Since these are permanent and irreversible impacts, this stage of the drilling process is one that significantly increases EV, specifically of the marine biota (both fauna and flora). This is also the case regarding benthic communities, which are altered due to the disposal of gravel with adhered drilling fluid, which also occurs during the drilling operation phase. This impact is classified as being of medium importance and high magnitude.

In the drilling rig demobilization procedure, both impacts on aquatic fauna and flora are of minor importance and low magnitude, but while one is of negative nature, the other is positive. The negative impact refers to the alteration of the benthic community. This impact is local, permanent, long-term, and irreversible. The short-term, positive impact is regional, permanent, and irreversible, due to the alteration of the pelagic community as a reaction to the removal of the drilling equipment. It is noteworthy that of the 53 impacts selected for this study, this is the only one of positive nature.

3.1.2. Stage 1

The Stage 1 Project consists of a series of ventures for oil and NG production and outflow. The project includes the realization of LTTs and EPS, as well as three PP/SPs, and gas pipeline sections for the outflow of gas [48]. For the execution of these LTTs, FPSO-type Stationary Production Units (SPUs) are used, which are capable of processing and stockpiling oil. This stage of exploration and production aims to significantly increase national production of oil and NG, generating greater reliability in meeting demand [49].

In the installation phase, during the anchorage processes of the FPSOs and installation of subsea systems, there is an alteration of the marine biota due to the introduction of exotic species. This is a permanent, medium-term, irreversible, superregional impact of great importance and medium magnitude. In the removal of FPSOs and subsea systems, during the operation phase, the impact is short-term, but alters the local benthic community permanently and irreversibly. This impact is classified as being of medium importance and magnitude. Thus, the vulnerability of aquatic biotic factors is exacerbated by processes involving FPSOs and subsea systems.

The other impact occurring at this stage is on the physical environment, altering the air quality, due to atmospheric emissions. This impact covers a superregional area. Consequently, the dispersion of emissions minimizes the magnitude to a low rating. At this stage, this impact is also considered temporary, short-term, and partially reversible. However, the impact remains of great importance.

3.1.3. Stage 2

This project includes the execution of EPSs; six LTTs; 12 DPs; and 15 pipeline sections [50] (Details of the inciting actions and the environmental impacts for the physical and biotic environment can be found in [45]). The first definitive production project for this stage began in November 2014 in the Sapinhoá field, which supplies the state of São Paulo. It is expected to be deactivated between 2037 and 2043.

Similarly to Stage 1, this stage has three effective impacts: two during the installation phase and one in the operation phase. None are classified as being of high magnitude or importance. During installation, the alteration of the seabed, due to the presence of pipelines and underwater equipment, causes a permanent and irreversible impact to the biotic environment. This long-term impact (these pipelines will not be removed from the sea floor) is classified as being of medium importance and magnitude. These pipelines (which have an individual maximum area ranging from 43 to 84 km^2; the total area of these subsea structures reaches approximately 746 km^2) are essential for electricity generation, as they allow the outflow of gas.

The change in air quality and contribution to the greenhouse effect during the installation process is considered a small and minor impact, even if permanent and irreversible in the long-term. This impact is understood to be local and superregional in scale. The same impact is present in the operation phase, fitting in the same qualifications, except in relation to importance and magnitude, which increase to a medium rating. Emissions occur as a result of combustion processes for power generation (thermal and electrical) and torch gas burning. The main substances emitted in these activities are nitrogen (NOx) and sulfur (SOx) oxides, carbon monoxide (CO), particulate matter (PM), total hydrocarbons (HCT), and the following greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxides (N_2O) [51–53]. The Stage 2 EIA has the following average GHG estimates (Table 2 and Table 3):

Table 2. Average Estimated Greenhouse Emissions by LTT or EPS Activity in the Stage 2 Project.

Sources of Emission	Estimated GHG Emissions (t CO_2eq per month per LTT or EPS)	
	Installation or Deactivation—(Duration 1–2 months)	Operation—(Duration 4–6 months)
Power Generation (Varies according to the type of power generation (from motor generators or turbogenerators))	3500–10,000	4000–8000
Torch gas burning (Average value considering gas composition of the reservoirs in question)	n/a	45,000

Source: [51].

Table 3. Average Estimated Greenhouse Gas Emissions by PDP Activities in the Stage 2 Project.

Sources of Emission	Estimated GHG Emissions (t CO_2eq per month per PDP)			
	Installation (Duration 3–4 months)	Commissioning (Turbogenerators and turbochargers gradually consuming natural gas from the third month on) (Duration: 8 months)	Operation (Considers all turbogenerators and turbochargers in operation with nominal consumption of natural gas) (Duration 20–25 years)	Deactivation (Duration: 6 months)
Electric Power Generation (Considers the technical specificities of FPSO Cidade de Ilhabela project)	1000	27,000	40,000–43,000	28,000
Torch Gas Burning (Estimated average range of torch gas burning according to the index of associated gas use (more details in item II.2.4.19 of [51]), production curve and gas composition of the reservoirs in question)	n/a	74,000–84,000	3000–14,000	
Turbo Compression (Considers the technical specificities of FPSO Cidade de Ilhabela project)	n/a	2000–2700	5300	

Source: [51].

3.1.4. Stage 3

This stage consists of 23 ventures: an LTT; nine EPS; a PP/SP; a Long Duration Pilot (LDP); 11 PDPs along with gas outflow systems. Similar to the previous stages, Stage 3 also uses FPSOs with processing plants that separate oil, NG, and water ("produced water" or "production water"). In PDPs and LDP, water separated from oil is treated and disposed of at sea. In the case of PDPs, there is also the generation of effluent from production water and the Sulfate Removal Unit (SRU), which reduces the sulfate content of seawater so that it can be injected into the wells. In Pre-salt fields, the amount of gas that is allowed to burn corresponds to a volume equal to or less than 3% of the monthly NG production associated with the field. The main substances emitted are greenhouse gases: CO_2, CH_4, N_2O, and HCT, as well as NOx, SOx, CO, and PM [7,52,53].

Of the 31 effective impacts, 20 occur at this stage (This is partly due to the quality of the EIA which becomes more detailed at each stage, with a greater comprehension of impacts). However, none of these impacts analyzed are rated as being of high magnitude. Thus, the six most severe are of great importance and average magnitude. Nine are of low magnitude and of little importance. Similar to the other stages, the installation phase has fewer impacts (which are also less severe) than the operation phase.

The most serious impact, unlike the other stages, is the contribution to the greenhouse effect during the operation phase. During navigation until operation begins, FPSOs use motor generators for essential power generation. Therefore, regulated pollutants are emitted by the engines of support vessels and diesel power generators during installation. Thus, during installation, this impact is permanent, long-term, and irreversible, but of low magnitude and minor importance. The operation phase involves the production, treatment, and export of oil and gas in FPSOs, which emit regulated pollutants due to fuel gas consumption in turbogenerators, turbochargers, and boilers, as well as the continuous burning of torch gas. During PDP and LDP, GHG emissions are continuous for approximately 30 years. Considering that the average life of atmospheric CO_2 is over 100 years, this permanent and irreversible impact occurs at a superregional scale, consequently provoking effects on a global level [14,15,53,54]. The EIA addresses this issue: "Brazilian GHG emissions are about 4% of global emissions and Petrobras Production and Exploration emissions are 0.04% of world emissions (base year 2010), without considering that the greenhouse effect is a problem caused by the increase in atmospheric concentrations of GHG emissions due to global historical emissions" [55].

While the change in air quality, which contributes to the greenhouse effect, is classified as effectively impacting the climatic environmental factor, which has a high sensitivity, the environmental factor of air itself has a low sensitivity. Consequently, although this change is permanent and of long duration during the operation phase, it is considered reversible, of low magnitude, and minor importance.

Nekton's high sensitivity becomes evident through the analysis of the effective impacts during this stage, as it is affected by six impacts (one during installation and five during operation). The disturbance of nekton due to the installation of FPSOs and collection and outflow systems is permanent and long-lasting. Despite being reversible, it is classified as being of great importance and medium magnitude. These same classifications apply to the operation phase where the nekton is again affected by the presence of FPSOs and collection and outflow systems, as well as by noise and luminosity (which cause serious impacts, especially in mammalian communities, which are affected physically and behaviorally, eventually leading to death). Effluent discharge from produced water and from the SRU permanently affects the nekton and plankton community in the long-term, but was rated as being of low magnitude, as it is reversible. This action has the same impact on the aquatic environment, causing changes in the quality of ocean water.

Seabird disturbances are all permanent and long-term, but reversible. Light generation provokes a more severe impact, being of great importance and medium magnitude, while the presence of FPSOs cause a disturbance of medium importance and low magnitude.

The benthic community is most affected during the installation phase, losing its habitat due to the pre-anchoring of the FPSOs and the collection and runoff lines. This impact is the least severe of all the impacts corresponding to this stage: although irreversible, all other indicators are rated at the least severe level. Comparatively, the presence of FPSOs and collection and discharge lines causes the most severe impact on the benthos, being permanent and long-term, but of medium importance and magnitude because it is reversible. The installation of the drainage system is also permanent, causing long-term repercussions to the benthic community, but reversible and of low magnitude and importance. Since the benthic habitat is on the seafloor, changing the morphology of this physical environment is also classified as an impact with the same definitions.

Thus, the following actions, which are essential to (or consequence of) oil and gas processing for electricity production, cause (20) permanent and long-term (and 3 irreversible) impacts on the (6) physical (14) and biotic systems: the installation of FPSOs, collection and flow systems, light and noise from operations, discharge of effluent from SRU, discharge of effluent from produced water, and atmospheric emissions.

3.2. Potential Impacts

Potential impacts generally refer to chemical spills: mostly during the operation phase of each stage. Of the 22 potential impacts, 18 are rated as being of major importance, 15 of which are of high, five medium, and two of low magnitude. Of the other impacts, two are of medium importance and medium magnitude, and the other two are of minor importance and low magnitude. These remaining four are considered to be long-lasting or irreversible. Of the 18 most severe, 12 may act on the vulnerability of the biotic environment and six on the physical environment.

3.2.1. Drilling

A blowout, due to mechanical or operational failures that lead to the loss of control of a well, causes a large volume of crude oil to leak directly into the environment, impacting vulnerable factors [4,56] (The EV map for this project is found in [57]). The potential consequences analyzed in this project's EIA only take into account the worst-case blowout scenario. In this study, there are six potential impacts during the drilling operation phase. All are of great importance and high magnitude, except for impacts referring to interference in the *restinga* areas, which are of medium magnitude. Although the *restinga* is an environment of extreme biological importance, the impacts on it are temporary, short-term, and partially reversible, as alterations are induced in the biota due to biomagnification.

Mangrove and estuary ecosystems are also considered highly important because they are nurseries for various species of fish and crustaceans (in addition to their high biological productivity) [51]. These environments are considered the most sensitive to alterations caused by oil spills [4]. Thus, these impacts cause permanent and partially reversible damage by acting in an area that, despite having a good degree of resilience, is significantly weakened with each impact, making it increasingly vulnerable.

Although interferences in rocky shores are temporary and short-term, they are exacerbated if oil is bioaccumulated by organisms that can be consumed by others of higher trophic levels. As a result, this can cause biomagnification if it reaches the top of the food chain (such as humans) by concentrating contaminants that have toxic effects.

The National System of Nature Conservation Units (SNUC, Sistema Nacional de Unidades de Conservação da Natureza), established by Law No. 9985 of 18 July 2000 and regulated by Decree No. 4340/02, defines: "Conservation Unit (CU) as the territorial space and its environmental resources, including jurisdictional waters, with relevant natural characteristics, legally established by the Government, with conservation objectives and defined limits, under special management regime, which apply adequate guarantees for protection" [47].

In the worst-case spill scenario, all CUs in the indirect influence area of AGBS would be hit by the oil slick (this study counts 22 CUs in the state of São Paulo), thus having a permanent and irreversible impact. Similarly, benthic communities are permanently affected, as contamination of the sediments in which they live and feed is long-lasting. The impact is also exacerbated due to the relationship between benthic communities and other affected species in the ecosystem, being considered, in this case, of long duration.

Of the six potential impacts analyzed, all occur within the biotic environment, except for the change in water quality, which impacts the physical environment. The aquatic environment, like the air, has the quality of dispersing pollutants, diluting them and reducing the intensity of interference. For this reason, the impact on water quality is temporary and partially reversible. This impact is what leads to the other impacts above, as the stain propagates through water, making it of such high importance and magnitude.

It can be concluded that a blowout in the drilling stage would lead to serious consequences mainly to the aquatic environment, increasing the vulnerability of all biota with which it comes in contact [4].

3.2.2. Stage 1

Potential impacts identified in this step refer to possible chemical, and/or fuel leaks at sea, and/or a possible crude oil leak. All potential impacts are detailed in [58]. The detailed analysis of AGBS' EV to an oil leak for this stage can be found in [59], and a map of it in [60].

This study found eight potential impacts at this stage that are classified as permanent, long lasting or irreversible. Two affect the biotic environment while the other six affect the physical environment. Again, air quality is assessed as least altered, the impact being temporary, short-term, partially reversible, and of medium importance and magnitude. The EIA of this step delineates that: "In the event of an oil spill accident, a hydrocarbon vapor plume is formed from the outset, due to the high volatility of oil components' lower molecular weight, such as BTEX (benzene, toluene, ethylene, xylene). According to hydrocarbon concentrations, a photochemical plume of smog could be formed by the presence of high concentrations of fine particulate matter and pollutants such as: SO_2, NOx, CO, and O_3" [58]. This plume can cause a series of impacts on human and animal health in general [51]. The change in water quality is classified similarly to that in air, except that, since it includes areas with "very high" to "extremely high" conservation priority status, it is classified as being of great importance and magnitude. Considering the likelihood of oil spills on the coast as well as in the ocean regions, there are a large number (about 135) of Conservation Units that could be hit in a worst-case spill. Of these, 34, equivalent to 25%, are located in the state of São Paulo. Interference to UCs—which are areas of high vulnerability—are classified as permanent and irreversible, consequently being of high magnitude and importance.

Benthic communities' high sensitivity makes them exceedingly vulnerable to this type of long-term impact, causing permanent alteration, which classifies this partially reversible impact as being of high magnitude and great importance. Seabirds and coastal birds, another biotic environmental factor, also suffer alteration, classifying the impact on this community as being of high importance and magnitude. However, since they are not in direct contact with the spill (such as aquatic organisms) and have a migratory capacity, they are only temporarily affected for what is considered a medium duration. All organisms that live in the shallow layers of the sea, including seabirds and coastal birds, are especially vulnerable to oil spills.

Of the three remaining impacts to the physical environment—all of high magnitude and importance—the interference to the *restinga* areas is the least severe, as they are temporary, of medium duration, and partially reversible. Even so, *restingas* are classified as priority areas for conservation, given their ecological functions: in the state of São Paulo, *restingas* on the north coast are considered of extreme biological importance [58]. As already analyzed, the mangrove and estuary areas are of high sensitivity and vulnerability. Thus, an interference causes permanent impacts, with partially reversible damage, being therefore of high importance and magnitude. Similarly, even temporary interference with rocky shores may be irreversible. These harbor a wide variety of species of economic and ecological value.

3.2.3. Stage 2

For the focus of this study on electricity production, there are four impacts analyzed at this stage, all of which may occur in the operation phase and three in the installation phase. The only impact on the physical environment refers to the change in water quality caused by chemical leaks. Although this impact is irreversible, it is temporary in nature. Due to the high dilution quality of this local impact, it is classified as being of low importance and magnitude. Long-term damage to mangroves and estuaries, due to fuel and oil spills at sea, is of great importance and of medium magnitude, despite being reversible and temporary. The detailed analysis of AGBS' EV to an oil leak elaborated for the Stage 2 project can be found in [61]. It defines, "ecologically sensitive areas with high ISL (Índice de Sensibilidade do Litoral, or Coastal Sensitivity Index) (8–10), such as estuaries, mangroves, coastal lagoons, marshes, and wetlands, as well as identified coastal and marine protected areas …" At this stage, it is considered that there are about 143 Conservation Units that could be reached in an oil spill at AGBS: 38, equivalent to 26%, of these are located in the state of São Paulo.

However, the most serious impact refers to the change in the marine environment due to the introduction of exotic species through support vessels, both for installation, operation, and decommissioning of oil and NG production, disposal, and outflow activities. These can carry a huge variety of invasive species in large quantities. Most of these bio invaders belong to the benthic community. Once again, the benthic community's high sensitivity makes it more vulnerable to this impact, but it is not the only one affected. The consequences of introducing exotic species are long-lasting, permanent, and may be irreversible. Therefore, this is an impact of high magnitude and importance.

Aspects that generate impacts that disturb seabirds and marine animals range from light generation to the presence of FPSO and subsea equipment. Birds have an average sensitivity to this type of impact. Although these impacts are temporary, reversible, and of medium magnitude and importance, they are long lasting.

Thus, despite the few potential impacts at this stage, they act significantly on the vulnerability of the biological environment.

3.2.4. Stage 3

The detailed analysis of AGBS' EV for oil spill updated for Stage 3 can be found in [62]; first semester map—[63]; second semester map—[64]; Identification/assessment of general impacts [55]

Four potential impacts are addressed at this stage due to the nature of this study, which analyzes only permanent, irreversible, or long-term impacts. All except for one of these four are severe, seriously threatening the EV. Two of these refer to an EV to bio invasion. The introduction and/or dissemination of invasive alien species in the coastal benthic community via transport of FPSOs during the installation phase causes a serious impact, as it is permanent, irreversible, long lasting, and of high magnitude and importance. The same proportions apply to the introduction and/or dissemination of invasive alien species via transit from support vessels during the installation phase—while similar to the previous impact, this is understood as one that compromises marine biotic communities (not just benthos), thus having a broader impact, including to CUs. Meanwhile, the same impact during the operation phase maintains the same levels, but with medium magnitude.

The presence of FPSOs during the operation phase also has the potential to introduce and/or disseminate invasive alien species in the benthic community. However, this impact during this phase is considered of low magnitude and importance, although the biological implications are long lasting, permanent, remaining until the project's deactivation, although it can be reversible when the hull is cleaned and moved to another area or activity [55].

At this stage, the vulnerability of the biotic environment is the most threatened, especially with regard to the benthic community.

4. Discussion

One challenge of analyzing EV sourcing from different projects is that the criteria and methodologies of EIAs vary between stages. Ideally this study would have created a quantitative EV index, but these variations would not guarantee its reliability. At times the variation is so drastic that the same impact can have a completely different rating from one stage to another, despite referring to the same area. There are also analytical discrepancies within each stage: for example, in the analysis of potential impacts from Stage 3, the benthic community is considered to have both high and low sensitivity to the introduction of alien species [55]. This may be due to the broader interpretation of some environmental factors: for example, when a community is made up of a large number of species, such as benthos, generalizing the consequences of an impact is not true to its vulnerability. In Stage 2's EIA, sensitivity is more specifically defined as, "a measure of the susceptibility of an environmental factor to impacts in general, and the importance of this factor in the ecosystemic context. Therefore, it is observed that sensitivity is intrinsic to the environmental factor. That is, it is not related to an impact on the environmental factor" [51].

However, it is a fact that each environmental factor will have different levels of sensitivity to each impact. For example, communities that may be sensitive to impacts caused by noise or lighting may be resistant to bio invaders or oil spills. Thus, the EV maps presented in these EIAs refer only to oil vulnerability, not to other impacts. The 2004 EVI [46], for example, analyzes countries' EV using 50 indicators, each specific to each impact (from climate to policy). A future study may come to understand each factor in detail in order to create a faithful index.

Some of these discrepancies between stages make clear the evolution of human understanding in relation to environmental impacts and how they affect vulnerable systems. For example, the frequency indicator is crucial for risk analysis ("Considering that risk is a function of the frequency of occurrence of possible accidents and the damage (consequences) generated by these unwanted events" [65]), but in the EIA it does not come as a *de facto* indicator until Stage 2, and evolves considerably between Stage 2 and 3. Furthermore, while the drilling stage only analyzes consequences of a blowout, the other stages are more conservative with regard to interpretation of accidental impacts. Again, this highlights the difficulty of creating a faithful EV index to analyze these projects. Despite not having this quantitative EV index, this analysis of the results allows a qualitative view of EV. For example, one can conclude that the vulnerability of the biotic environment is the most threatened by actual and potential impacts. In short, the environmental factors in the physical environment that have their vulnerability affected are: sediment (from the deepest to the most superficial); oceanic water; coastal water; the weather; the air. In the biotic environment, affected factors are: the benthic community; the planktonic community; the nekton; seabirds; the marine biota; the rocky shores; the sandy beaches; the mangroves; the everglades. As analyzed in the drilling stage's effective impacts, the only positive environmental impact in the survey of this study is the demobilization of the equipment. Environmental factors affected by reversible impacts only recover once the activity is concluded. Thus, the end of this type of exploitation would result in a positive impact on systems' EV in the AGBS (and beyond). The RIMA for Stage 1 concludes that: "The non-execution of the activity has positive and negative points. Among the positives, it is noteworthy that the absence of the Projects in the Pre-Salt Reservoirs would contribute to the non-alteration of the environmental quality in the project locations, as well as encourage the search for renewable sources of energy (solar, wind, biodiesel, ethanol, etc.), as oil is a resource that may end due to its widespread use" [49]. In order to use natural resources to generate electricity, it is necessary to know how the environment reacts to imposed anthropogenic pressures, as well as the degree of support for these pressures [66]. Thus, with regard to the exploitation of natural resources for electricity generation, there are alternatives that can save the environmental factors studied above from these risks [3,7,8].

In May 2019, São Paulo had a total of 701 thermoelectric plants with a total reported power of 2,302,762 kW, representing 9.9% of the state's electric matrix [4]. Based on data generated by the Brazilian Solar Energy Atlas in 2006, a study by the Secretariat of Energy and Mining demonstrated the potential of solar energy in the state of São Paulo through a mapping of irradiation levels and ranges. The study pointed out the technical and economic viability for the generation of photovoltaic energy between the annual radiation ranges of 5.61 and 5.70 kWh/m^2/day (considering the best utilization range), which corresponds to 0.3% of São Paulo's territory, resulting in a potential of 12 TWh/year (12,085,166 MWh/year) [10,67]. However, this reported number refers only to the 12 existing photovoltaic plants in the state and not to the potential of distributed PV [68].

Even in its less favorable locations, Brazil still has solar radiation values that are about 20% higher than the best ranges in Germany, one of the world leaders of PV energy [69,70]. Transport losses are minimized, since distributed PV power generation is installed close to where it is consumed, as well as avoiding the need for extensive transmission lines [20]. Also, as they are incorporated into building structures, they do not require additional land use, resulting in less environmental impact [71]. While PV production is more flexible than other resources because it is widely available, it is not of consistent quality: its storage being one of the biggest challenges and impediments to increased adoption [6,8,72–75]. However, measures such as normative resolution №482 issued in 2012 by the National Electric Energy Agency (ANEEL, Agência Nacional de Energia Elétrica) regulate: "III-Electricity compensation system: system in which the active energy injected by a consumer unit with distributed microgeneration is given through a free loan to the local distributor and later compensated with active electricity consumption" [76]. According to Lange [77], in 2012 it was estimated that PV production distributed on domestic roofs in the state of São Paulo could produce up to 5143 GWh/d. Considering the advancement of PV technology, what six years ago was a best-case estimate is now a reality. Still, Miranda [71] concludes that "by municipality, as expected, the greatest potentials are observed in urban areas in large cities, where there is greater availability of residences. The largest capital of the country, São Paulo, had in 2010 the potential equivalent to one tenth of the installed capacity worldwide." In this same study Miranda reports that in 2013 the urban area of São Paulo had an installation potential of 4831.9 MWp. With technological developments, one can expect that this type of energy production will be widely adopted.

Oliveira [78] produced a life cycle assessment (LCA) of PV panels, concluding that: "Photovoltaic technology has everything in its favor to grow in the market and be present in the Brazilian energy matrix, which will help reduce the use of polluting sources, making energy use more sustainable. However, to mitigate pollutant emissions, there must be a proposal for the use of resources that replace the main compounds that contribute to environmental impacts, making photovoltaic technology cleaner from the very beginning of its manufacturing and production. Photovoltaic energy is also a form of energy decentralization, which will provide users of this technology with greater independence, as they will not always dependent on the energy supplied by utility companies." There is hope that through technological developments, PV power will be completely clean from cradle to grave. However, as this analysis considers only the capture of the solar resource (and not the manufacture of the necessary implements to do so), it is understood that it is a clean energy, which stands out exponentially when compared to energy from HCs: resources that, as discussed above, cause a wide variety of environmental impacts, which irreversibly compromise the ability of future generations to meet their own needs, endangering the EV of the AGBS system [6–8,72–75,79]. It is known that various reviews and studies are carried out around the world about EV (with varying degrees of analysis and accuracy, published or not), aiming at the diffuse goal of sustainable development and others such as the objectives of the millennium, as found in [18,19,21,22,31,32,34,80].

5. Conclusions

"Although modern society needs a series of petroleum products in order to be fully functional, coupled with this dependence, there must be a corresponding responsibility to manage these products effectively and safely in order to prevent environmental disasters" [66]. This study demonstrates that the determination of the EV linked to oil and NG production is complex and uncertain. However, by associating the three aspects of EV (exposure, resilience, and sensitivity) with the environmental impacts outlined and explored in the EIA/RIMA documents (scale, duration, permanence, reversibility, importance, and magnitude), this study demonstrates that there are a number of anthropic pressures on EV. Although there are a variety of alternative resources for power generation (and even for petroleum products), the most practical and convenient alternatives are still used. However, in a world of high demand and a growing population, if we are to follow a path of sustainable development, we must change our habits. HCs have devastating impacts even before they are mined from their reservoirs, making environments that are already vulnerable to human impacts become even more sensitive, thereby diminishing their resilience as they are exposed to risks.

Nature creates and operates on solar energy, always using the minimum amount of energy needed, recycling its materials. It relies on diversity for its success, operates collaboratively, and demands local knowledge. It has a quality of self-organization and recognizes its limits. No wonder nature is said to be wise: we should learn from it.

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