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Enabling Hybrid Projects through Appropriate Market Design

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Abstract

Large-scale hybrid power plants, composed of two or more generation sources and with the participation of energy storage systems, have driven important electricity Market Design regulation discussions worldwide. Regulatory framework ought to be adapted to support technical particularities of these new generation arranges. This paper presents an assessment of the main requirements to be met by Market Design to enable hybrid power plants by means of assertive market incentives. Assessing regulatory adjustments promoted in Australia, United States, India, China, and Brazil, emphasizing the latter one, the authors presents a case study by applying specific computational simulation and optimization model to a hybrid Hydro-Solar plant, that supports the findings for the necessary evolution needed in the national regulatory framework in order to enable hybrid projects. The evaluation of international experiences indicates that the insertion of hybrid projects is associated with the design of the market they belong to and demand regulatory adjustments so that their attributes can be properly valued for the benefit of all stakeholders, especially for the electricity consumer.

Keywords

Hybrid Projects, Renewable Generation, Electricity Market Design, Regulation

1. Introduction

Investors and developers seek private profitable and yielding opportunities while policymakers look forward to social, environmental, and public well-being. Matching these different and paradoxical-looking aims, from the two faces of the same coin, is as challenging as worthwhile.

Incentives are efficient tools used to match public and private interest and whenever incentives provide accurate signals, efficiency leads to the lowest cost solutions that fit the public interest while being attractive from the investor perspective [1].

The hybrid project framework emerges from existing local complementarity in the generation profiles of different sources, which leads to a more stable electricity output and, consequently, reduces the energy trading financial risk as well as provides a more reliable meeting of demand curve [2].

In addition to commercial benefits, when generation sources share the same site, hybrid projects can also take advantage of sharing land and facilities, as well as construction, maintenance, and operation workforce, thus optimizing power plants CAPEX and OPEX. Additional benefits can also emerge from more efficient use of the transmission network when power plants are installed in the same location or share the same grid connection [3].

Due to these benefits, hybrid projects have been incentivized to electricity systems, and as the incentives address hybrid projects, the first step is to properly define what a hybrid project is. This definition is not consensus worldwide and defining hybrid projects is challenging somehow.

Depending on the regulatory framework this definition is necessary to allow regulation rules to distinguish hybrid from single source projects. For most of the regulatory framework around the world, for instance, in the US, the association of a generation source with a storage system is considered a hybrid project [4], but for some of them, the storage is not considered a generation source and a hybrid project must arrange more than one generation plant technology, as in India [5] and Brazil [6]. Another issue to be faced is whether the characterization of a generation project as hybrid requires the singularity of the transmission network connection point or not as well as if it is allowed to storage system to charge with energy from the grid [7].

Taking advantage of these benefits for electricity investors and consumers' interests demands appropriate market design, capable to match system generation and transmission reliability needs with developers' interest, considering natural resources availability and exploitation attractiveness from economic and environmental point of view [8].

Renewable generation, mainly from wind and solar sources, has spread worldwide in the last decades and for accelerating the pace on a path to climate safety, representative investment efforts to renewable electricity industry are required, as the following quotation.

"Abu Dhabi, UAE, June 30, 2021—Accelerating energy transitions on a path to climate safety can grow the world's economy by 2.4 per cent over the expected growth of current plans within the next decade, a new analysis from the International Renewable Energy Agency (IRENA) shows. The Agency's 1.5˚C pathway foresees the creation of up to 122 million energy-related jobs in 2050, more than double today's 58 million. Renewable energy alone will account for more than a third of all energy jobs employing 43 million people globally, supporting the post-COVID recovery and long-term economic growth" [9].

On the other hand, it is necessary to consider that paving this path requires appropriate consideration of the consumer's needs, demanding more quality and availability of electricity. As human societies evolve, electricity demand grows not only in availability but in quality as well, since more sophisticated goods production technologies take place.

Hybrid projects may facilitate the integration of variable generation sources. However, incentives should be made feasible by appropriate market rules and benefits must be properly remunerated, demanding improvements in market design to accommodate this new reality.

Energy transition period must be considered, since several researchers, such as [10] and [11] have concluded that to welcome massive non-controllable renewables, electricity industry should diversify the generation matrix and provide more flexible transmission controlling devices to shorten system response to electrical disturbances.

This paper seeks to present an assessment to be considered by policymakers when adapting electricity market design to prepare appropriate technical, commercial, and regulatory environment to support the inevitable and relevant growth of human dependence on renewable electricity generation, in which context hybrid projects play an important role.

In addition to the vast bibliography that treats renewable generation in general and hybrid projects in particular, this paper presents the point of view of the barriers to be overcome in the regulatory framework that supports market design worldwide and makes it evident that either the market design develops to enable hybrid projects through assertive market incentives, or the benefit of hybrid arranges will not be accessible to stakeholders.

Assessing the bibliography on the issue, the authors present in this paper an innovative perspective of the problem, providing strong arguments for the evolution of the market design by quantifying the costs that these barriers impose on the electricity industry. In the conclusions is mentioned a perspective for further studies with a focus on the model's development to support this cost/benefit evaluation.

This paper is organized as follows. Section 2 debates power system requirements and the value of adding hybrid projects. Section 3 describes the international experience about hybrid projects implementation and the main regulatory issues to be addressed. Section 4 shows results from a case study of a hybrid project connect to the Brazilian Interconnected Electricity System (National Interconnected Electricity System—SIN). Section 5 presents the proposed methodology and finally, Section 6 examines the main conclusions of the paper.

2. Identifying System Requirements

System requirements depend on load, supply, and transmission network characteristics. As demand grows differently among regions and consumers seldom choose areas with available natural resources for electricity generation, it is usual to observe demand growth driving generation growth in other regions along with huge transmission interconnections to link generation with consumption.

This matter is, indeed, addressed when the system operation is conditioned by expansion planning and, just from the relation between expansion and operation planning emerges the accurate identification of the system needs, once the signals to expand generation or transmission systems depend on the issues faced during the operation phase.

A power system safe operation must rely on flexible and secure generation sources and transmission network to respond to demand variations. In this context, flexibility is not inherent to renewable generation sources such as wind and solar plants. Thus, hybrid projects are effective and efficient solution to provide operational flexibility through renewables. This is the main reason to consider the association of generation source with storage system as a hybrid project.

According to the Federal Energy Regulatory Commission (FERC) [4], hybrid projects can add value to the electric grid by allowing intermittent or duration limited resources to reach higher capacity factor, making operation more efficient by reducing congestion and curtailment in electric systems with high concentration of intermittent generation, as well as providing the system operator of more controllable ancillary services, as quoted below:

"The addition of another generation or electric storage system to an intermittent resource may allow those resources to provide services that they alone could not provide" [4].

To tailor costumer profile changes, system requirements have changed. Decentralized generation and demand for electricity quality from more sophisticated connected equipment have demanded more accurate operation interventions in the network, which have enhanced ancillary services provision.

Long run expansion planning has also been demanded for improvement since rapid growth of intermittent generation have made generation and transmission planners to select appropriate plants of different regions of the electric systems to eliminate and/or avoid system congestions. As an example, Brazilian auctions for renewable electricity procurements have considered the transmission capacity of the connection point of the plants as a limit of the capacity to be installed in the generation plants to be connected to the network [12].

Supply Flexibility and Reliability

Generation system must provide flexibility for operator to meet demand with reliability. Since every source of the generation matrix has specific attributes, the best solution is to incentive, by means of accurate prices signals, those sources that present attributes more adherent to the expansion and operation planning needs.

India represents a good example on how to take advantage of the benefits that hybrid projects provide. Based upon public auctions tendered by Solar Energy Corporation of India (SECI), the country has innovated in contracting hybrid projects by applying the round-the-clock (RTC) [13] and the meeting peak load contracting mechanisms [14]. This innovation makes India's experience a benchmark to be mirrored around the world.

To achieve their aim of inducing investments in hybrid projects, customized auctions were carried out to meet requirements of some specific utilities. One of the contractual rules establishes that the energy delivery must perform a minimum of 80% Capacity Utilization Factor (CUF) per year and at least 70% monthly. The regulatory framework was adjusted to enable hybrid projects implementation.

Generation diversity is a key point for accurate assessment of hybrid projects. Complementarity among generation sources is essential for the economic and technical feasibility of this sort of plant.

Thermal powerplants have played important role to electrical system stability including generation/load balance, and as paradoxical as it seems, these plants may play relevant role in the transition phase of electricity matrix generation through renewables. According to [15] flexible generation operating as reserve is the best support to improve renewable non-controllable generation participation in the electricity matrix. However, as hybrid projects can supply enough flexibility to operation, thermal plants tend to be replaced by these renewables arranges.

Nowadays, for electricity industry worldwide, the increasing need for flexibility in power systems is driven by wind and solar plants massive development [16]. The first step to provide flexibility is to increase efficiency to existing and operating assets. This statement includes 1) to operate thermal plants with higher generation costs to help meeting the spinning reserve requirements, 2) to improve transmission network technology, and 3) to adapt renewable non-controllable sources by means of hybridization. Another feasible approach, in hydro-thermal systems, is to add thermal plants with reduced variable costs, providing economic base load operation, leaving to the hydro plants to follow the load variations.

3. International Experience

International experience presents countries like Australia, USA, India, and China with recent market design improvements to promote the insertion of hybrid projects in their electricity sectors. The key regulatory changes to be addressed consist of: 1) the definition of hybrid projects and the dispatch and operation rules to be apply; 2) services that could be provided and their remuneration framework; 3) how to value their contribution and capacity to the system.

In 2020, the Australian National Electricity Market (NEM)[1] have presented 3.4 GW of implemented or under construction projects composed by two or more sources, with or without associated energy storage, and sharing the same transmission connection [18].

[1]Australia has two electricity markets: the National Electricity Market (NEM), which represents 85% of the electricity consumption in Australia and is composed by the states of Queensland, New South Wales (NSW), Australian Capital Territory, Victoria, South Australia and Tasmania; and the Wholesale Electricity Market (WEM), responsible for 10% of the Australian electricity market and constituted by the state of Western Australia. The remaining 5% are isolated systems [17].

Due to the expansion of hybrid projects, the Australian Energy Market Operator (AEMO) published in July 2019 a document containing guidelines on various configurations of hybrid projects that could be developed within the current regulation [19].

The set of configurations is divided in two frameworks: in the first one, the entire hybrid project is represented by a single market agent for accounting and dispatching purposes and it is not possible to distinguish generation and load between different components of the project; in the second set, the system components only share the local infrastructure and physical network connection and there are multiple meters behind the meter connected to the network, thus, in this case each system component represents an independent agent for accounting and dispatching purposes.

Under current Australian regulatory context, hybrid projects are allowed to participate in the energy and ancillary service markets. However, there is not a clear definition of the agent that represents the hybrid project's characteristics under the market rules.

Thus, as such agent can consume or inject energy in the transmission network (especially in case of associated energy storage), the system operator applies both registration and dispatch rules established for generation and consumption agents, requiring two registries and two offer bids for central dispatch (one for load and other for injection). This rule is also applied for hybrid projects without storage but with consumption and generation assets behind the same network connection [20].

Aiming to simplify the rules, in September 2020 the Australian regulator (Australian Energy Market Commission—AEMC) opened a public hearing for discussion on market operator registration, participation in electricity and ancillary service markets, charges and taxes definitions, and use of the distribution and transmission systems, to be applied to standalone storage systems and hybrid projects [21].

In this context, the AEMO suggested the creation of a new type of agent under the market rules that englobes the bidirectional characteristic of energy storage systems and hybrid projects. The objective is to simplify the rules of projects' registration and centralized dispatch participation.

The United States is another country with relevant amounts of installed hybrid projects. The study [22] account that until 2019 there were 125 hybrid projects with aggregated capacity higher than 1 MW, which in total represents a capacity of 13.4 GW. Of this total in operation, 53 are compounded by a photovoltaic or wind source with storage systems. It is important to realize that both the US and Australia consider the aggregation of a generation source with energy storage as a hybrid project.

Following the recent expansion of hybrid projects in the US, by July 2020 the US regulatory agency (Federal Energy Regulatory Commission—FERC) promoted a conference titled "Technical Conference Regarding Hybrid Resources", where different types of stakeholders discussed change proposals in regulation and market rules that should be addressed to accommodate the hybrid projects insertion [7].

The conference had the participation of the following system operators: California Independent System Operator (CAISO), Pennsylvania New Jersey Maryland Interconnection LLC (PJM), Midcontinent Independent System Operator (MISO) and New England Independent System Operator (ISO-NE). The main discussions focused on: 1) the definition of hybrid project, configurations, and control operations; 2) the network connections, such as the numbers of meters needed, the connection process and the outflow limits to be applied; 3) the participation of the energy, capacity, and ancillary services markets.

Similar to the definition applied by the Australia regulator (AEMO), US regulatory context considers two configurations of hybrid projects: the "co-located" and "hybrid resources". Co-located projects consist of two or more generation technologies, associated or not with energy storage systems, sharing the same physical connection with the network but being considered as independent agents by the system operator for dispatch purposes, control, and contractual obligations. Hybrid resources, on the other hand, represent a single agent to the market, where the project's components are jointly controlled for dispatch and generation purposes, being carried out by a single operator [7].

The CAISO's understanding is that a hybrid resource with presence of energy storage is considered as a "non-generation" resource which could be operated as generation or load, being dispatched at any level of its capacity. Otherwise, the hybrid project should be treated as generation [23]. In case of co-located projects, each component is defined according to its generation technology and operating characteristics [24].

In case of hybrid resource configuration, CAISO proposes the project's owner being responsible to manage the whole components operation. This flexibility brings benefits concerning the fulfillment of the contractual obligations, tariff incentives, and the project's operation and maintenance expenses. On the other hand, in the case of co-located projects, the operator states that dispatch must be coordinated by the market operator aiming to simplify the segregation and fulfillment of contractual responsibilities between the different components of the project.

The PJM suggests that in case of a hybrid project with associated energy storage, the operation management should be carried out by the project operator and not by the system operator, due to the better knowledge about the current and forecasted generation of the renewable source and storage system. For co-located projects, where each project's component represented a different and independent market participant, the dispatch and operation must be carried out by the system operator to avoid unfeasible dispatch orders [25].

Hybrid projects can participate in the energy, capacity, and ancillary services market at CAISO, PJM and ISO-NE considering both configurations, co-located and hybrid resource. Although, the ISO-NE operator recommends the hybrid resource framework for the participation in the ancillary services market in the case of a project compound by an energy storage system associated to a renewable source. The operator emphasizes that the project owner has the fast knowledge about the current state of generation and storage, thus, is more capable to efficiently manage the project [25].

India is seeking to expand its renewable matrix, where the development of hybrid projects stand out due the complementarity pattern between the generation resources of the country [5]. Since 2018, the Solar Energy Corporation of India (SECI) has issued auctions to contract hybrid capacity (with or without energy storage), which have resulted in 4.29 GW auctioned installed capacity [26].

The discussion and regulatory improvements in India have started in 2018 with a normative published by the Ministry of New & Renewable Energy aiming to promote the insertion of hybrid projects composed by solar and wind resources and, as a result, to improve the efficiency use of the transmission network [5].

Under the definitions established by the Ministry of New & Renewable Energy [5], a project in India is considered hybrid when one of its resources has a nominal capacity higher than 25% of the other one. Also, it is suggested that the project should have more capacity allocated to the resource with higher generation potential at the project location, considering natural resources availability.

The normative also indicates that a hybrid project can trade energy in the free market or establish contracts with the system operator by auction processes. India's auction experience represents an important benchmark case for other countries.

China is another highlighted country, where the insertion of hybrid projects and storage energy represents a solution to reduce the curtailment of intermittent sources. Some of its provinces, such as Shanxi, Hunan, Qinghai, Henan, Inner Mongolia, Xinjiang, Anhui, and Jiangxi, have established guidelines for new wind projects to be hybridized with storage systems [27].

In August 2020, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA), both of which are regulatory bodies in China, published a technical document entitled "Guideline on Wind-Solar-Hydro-Thermal Integration and Generation-Grid-Load-Storage Integration Development".

The document proposes three possibilities for combining generation sources and storage systems: 1) solar, wind, thermoelectric and storage; 2) solar, wind, hydroelectric, and storage; 3) solar, wind and storage systems. The document also indicates that regulatory improvements should be implemented in the ancillary services mechanism, to allow frequency modulation and peak-demand to be delivered by hybrid projects [28].

Auctions and Capacity Mechanisms for Hybrid Projects

Investments in the electricity sector are susceptible to cycles because are capital-intensive and have long lead-time for new generation facilities start-up [29]. The increase of competitivity in electricity markets has raised regulation's responsibility to evaluate if practiced prices were providing enough incentives to maintain resource adequacy [30], therefore, different market designs around the globe have emerged promoting different initiatives in this regard, such as centralized auctions and capacity mechanisms.

Besides, energy transition policies to a low carbon economy have provided greater penetration of variable and decentralized energy resources, which raises the attention of system operators to different sources attributes, like operational flexibility. For ex-ample, recent discussions have proposed the reformulation of capacity mechanisms to consider flexible attributes such as ramp capability and duration of discharge [31], requirements that could be easily met by a hybrid resource project.

In the Wholesale Electricity Market (WEM), hybrid sources, which could be a combination of conventional, intermittent sources, and storage behind a single connection point, can participate in the market's Reserve Capacity Mechanism. As discussed by [32], there are two methodologies to calculate a Certified Reserve Capacity for each facility, depending on their combination of components. For schedulable plants the Capacity Certificate considers the output of the plant in air conditions of 41 Celsius degrees and for intermittent plants the certificate consider the plant expected contribution during the peak load demand, according to the so-called Relevant Level Methodology (RLM).

In WEM, a price-driven approach is employed regarding forward coordination mechanisms and facilitating forward contracting. A draft rule on the Retailer Reliability Obligation is discussing the participation of hybrid sources in this mechanism [33].

In the US markets, it is found different examples. In the PJM, hybrid projects are allowed to participate in the capacity market, however, very few are currently operating as an integrated hybrid resource [7] [34].

Studies and discussions have been undertaken to ease projects operation as single units [25]. In the New England ISO, hybrid projects are allowed to participate in their Forward Capacity Market as separate sources or as a single source, with 75 units al-ready qualified or to be qualified in 2020, being 32 requested to be modeled as a single integrated source [7]. In the New York ISO, studies have been also undertaken proposing to enhance the eligibility and participation of hybrid projects in the capacity market [7].

The Indian Ministry on New & Renewable Energy has promoted auctions to support the development of hybrid projects in the country [5]. The first two auctions were held in 2018 and 2019. In August 2019, a third auction took place, where projects needed to have co-located storage system and the remuneration was segregated into two tariffs, one of which for peak-load supply [26].

A fourth auction occurred in October 2019, in a "round-the-clock" modality, which means 24 hours of uninterrupted supply under a requirement of meeting

70% of annual and 80% of monthly total capacity supply, where the exceeded production is al-lowed to be traded in the free market. As discussed by [35], the projects in this auction could be both co-located and multi-located, being the obligation to have a storage system connected to a renewable source installation.

In 2019, Portugal performed an auction on photovoltaic and photovoltaic plus storage system in three modalities: storage, system compensations, and contracts for differences. This auction was considered a success by the government. For example, in the first modality, winners decided not to take capacity premium payments offered and, instead, decided to pay capacity premiums to the system [36].

In Germany, the government has also promoted auctions to foster hybrid projects. In September 2020, seeking for new investments, the German Federal Network Agency (Bundesnetzagentur-BNetzA) promoted an "innovative auction" for energy. Twenty-eight combined projects accounted for 394 MW of installed capacity, of which twenty-seven projects combining solar with storage system and one project combining wind with storage [37].

Brazil represents other country with potential to hybrid projects auctions due to high complementarity between renewable sources (especially between wind and solar at the northeast region of the country) and long-term renewable auctions experience [8] [12] and [38].

4. Case Study

The case study presented in this section aims to illustrate the benefits of hybridization of Hydro Power Plants, in terms of generation gains, that an eventual change in the operational dispatch rule of hydroelectric power plants associated with photovoltaic solar (hybrid project) could result, in the context of the Brazilian electricity market.

The electricity industry in Brazil relies mainly on hydropower generation. Nowadays some 65% of the total electricity generated in the country comes from this type of plant, making relevant to address this issue as it is essential to provide more efficient use of existing assets, especially when these assets are the more important ones. The Brazilian power system is centrally operated and regulated, respectively, by the national system operator (Brazilian ISO) and the electricity industry national regulatory entity ANEEL.

The system operation is based upon centralized global optimization provided by computing models of mathematical optimization that represent all the plants operating in a 5-year horizon operation planning, as well as the transmission limit capacity that connects 4 different electrical regions throughout the Country.

The computing model referred in this paper is named NEWAVE [39], and it does not consider hybrid associations. Thus, for the simulation of the operation of hybrid power plants in Brazil, it is applied a simulation model of the optimized operation of a hydroelectric plant associated with other generation sources, such as wind and solar originally developed by [40]. In the model, it is possible to configure a single hydroelectric power plant or several in the same cascade, allowing the assessment of local or regional benefits of joint operation. For more on the simulation model, see **Annex**.

The hydropower plant (HPP) chosen to be considered in the hybridization is the São Simão HPP, with an installed capacity of 1.7 GW. As regulatory Brazilian framework determines, the transmission services must be contract up to the plant installed capacity, meaning that São Simão HPP can export up to its installed capacity. This regulatory enforcement often provides a transmission capacity slack for a HPP in Brazil, as a Capacity Factor of about 60% is typical to the Brazilian hydro plants. Therefore, in average, the transmission capacity slack is of about 40% of the plant in-stalled capacity. This fact opens an important opportunity for hybridization.

The case study considered two different possible approaches to centralized operation from Brazilian ISO (ONS). The first one, the "as is" approach, considers that the ONS does not recognize that there is any other connected plant to the same transmission connection point of the HPP. In such situation, the operation of the HPP is optimized by the ISO under a tight pool framework, being not feasible to reduce the local HPP generation to accommodate higher solar PV generation considering the exportation limit.

The second approach considers that the ONS recognizes the hybrid plant allowing it to decide by itself whether to export from the HPP or from the solar PV. In this approach it is allowed some de-centralized operation of the Hybrid Plant as far as the exported energy in the transmission connection point determined by the centralized operator is attended.

Note that in the second approach it is possible for the hybrid plant to optimize its own operation, taking more advantage of the complementarity among the electricity exportation sources within the hybrid project. **Figure 1** shows the adopted approaches and the expected operational consequences of each one.

Note that in the alternative approach, as the ONS centralizes the hydric balance of the HPP's cascade, whenever the decentralized operation of the hybrid project alters the HPP generation, all the HPP cascade will operate in a different way than it would in the "as is" situation.

This is a relevant point that drives to a market design improvement when considering hybrid projects, allowing a decentralized dispatch decision of the HPP, even impacting other plants generation, providing that the global result is optimized, what is not allowed by current regulation that supports the Brazilian market design.

Taking into consideration both approaches, the hybridization of São Simão HPP by installing a solar PV unit associated were simulated under different levels of PV participation (installed capacity). The simulation considers 83 months period, from June of 1949 to April of 1956, considered as the worst SIN precipitation period.

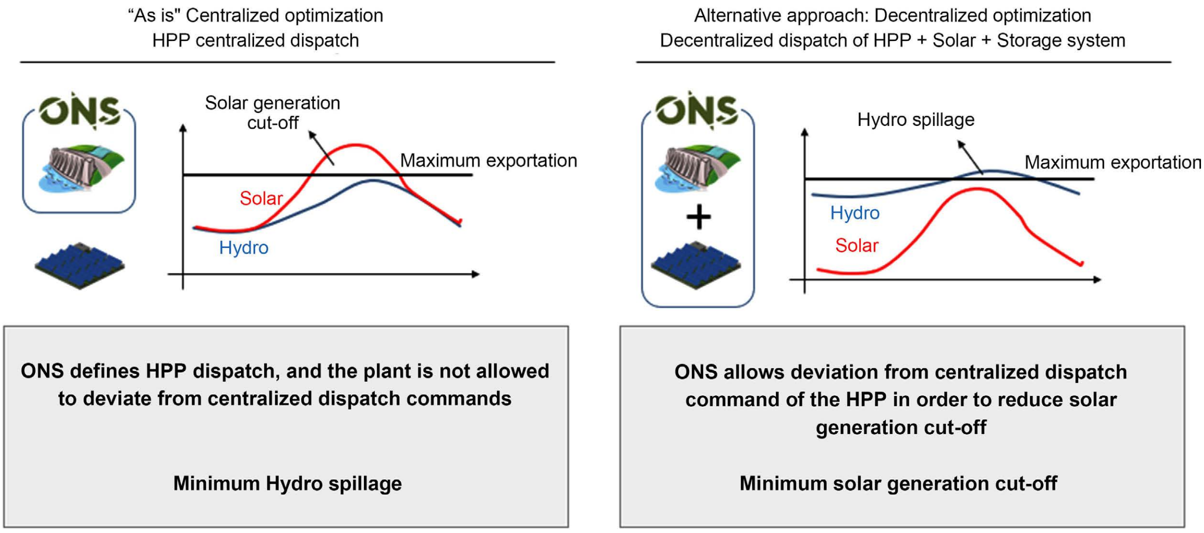

Figure 1. Schematics of the two simulated dispatch approaches: Centrallized and Decentralized optimizations.

The solar generation estimation for this period considered a seasonalized average solar generation, calculated based on the last 10 years data obtained at SolarGIS time series. A generic Solar Power Plant near São Simão HPP would have capacity factor of 20.23%, meaning that for each 100 MW installed the average annually output would be 20 avgMW, assuming no output limitation.

Simulations results is shown in **Figure 2**, where it is possible to notice that as solar PV installed capacity increases, the average generation increases, however, the decentralized dispatch makes generation output higher than current operation centralized method.

The difference in the generation output is related to the HPP flexibility and controllable generation and the results show that when the hybrid project take advantage of this flexibility, allowing the HPP to accommodate the non-controllable solar PV generation, the whole simulated system generates more energy.

Considering the "As is" dispatch of the HPP, the Solar PV power plant (SPP) would have an energy generation loss of 76% because of output constraint, considering the Decentralized dispatch the energy generation loss drops to 3.2% for a 100 MW SPP and 6.0% for a 1.000 MW SPP.

Based on the results, it is concluded that the operation of the hybrid project composed of solar and hydroelectric power plants can be optimized with changes in the dispatch rules. Considering the existing installed capacity of the hydro power plant and the investment and operation costs it is possible to optimize the solar and storage capacity that would bring the Interest Rate Return desired by the developer and investor.

The main result of the case study is that market design in Brazil does not provide appropriate signals to hybridization of hydro power plants centrally operated because the tight centralization reduces the energy output of the plant and optimization proceeded regardless of regulatory rule of centralized dispatch brings better benefits to the plant.

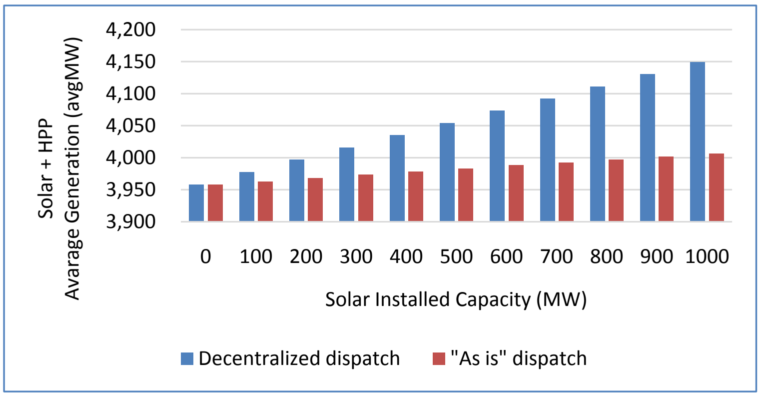

Figure 2. Scenarios of Itumbiara HPP hybridization.

5. Main Points to Be Addressed Concerning Hybrid Projects

This section presents the main points to be addressed concerning hybrid projects. It should be realized that there is not a single methodology to be applied to every situation due to the vast diversity of arranges, so that this section highlights the main issues and provides an overall assessment.

Some countries, as mentioned earlier in this article, have created credit to incentivize storage system expansion as well as discussed how to improve market design to allow participation of hybrid projects in the electricity market.

The first step to enable hybrid projects is to identify the available natural resources. It is essential to understand the natural aptitude of the different geographical regions where the projects might be developed. Data is essential to properly evaluate the generation and the complementarity of different generation sources operating in a hybrid project. To illustrate this assessment, Figure 3 shows the complementarity of solar PV and wind generation for two different regions in same Federal State of Brazil – Pernambuco, northeast region.

There are significant differences in wind-solar generation complementarity be-tween these cited regions, and a hybrid project in region 2 will likely have a more stable generation output than a project in region 1. If a policy maker is interested in stable out-put, its policies and market design improvements should foster projects in region 2.

A recurrent issue to be addressed by policy makers is related to isonomic treatment of the stakeholders. This issue demands reasonable and clear pricing of the different project's attributes and the best way to do so is by mean of public auctions that beyond been regional could allow considering pricing of different attributes.

The needs of the system must be evaluated considering different time frames for operation and expansion. Operation requirements are related to the system stability and reliability and must be addressed by providing an ancillary services market where stakeholders are paid for providing the needed services. Regional contracting of these services is essential, as locational signals are relevant in the operation time horizon.

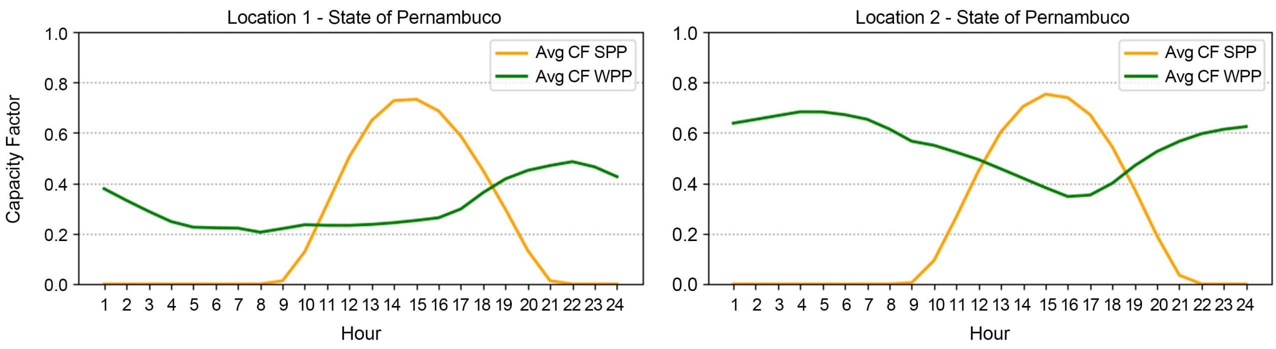

Figure 3. Example of regional Wind-Solar complementarity in Brazil.

The operation requirements must be considered in the expansion planning and the operator, and the planner entities must work together to give the proper signal of desirable sources for the long run expansion planning and for the short run operation planning. This includes contract expansion from specific sources instead of others. In such proposal, it would be paid less to a stand-alone project than to a hybrid project that brings operational flexibility, if this attribute is demanded by the system operator. Thus, desirable projects must be welcomed in desirable areas.

And finally, it is relevant to improve market design, if it does not fit the expected evolutions. This issue demands a comprehensive and difficult assessment of the market design: comprehensive as it is important to address all the issues involving the stakeholders that already operate in the market and difficult because transition from one to another market design brings along needs to handle ongoing operations from different stakeholders in a new market environment.

Figure 4 presents a flowchart of activities to be considered, described as follow. Regional system requirements are assessed considering electric transmission system and regional generation resources considering a time horizon compatible to the expansion planning. In this step it is necessary to simulate the generation conditions, flexibility, and reliability of the several regions of the interconnected system. The assessment must allow identifying the regions with excessive not controllable plants under operation and other regions with lack of generation.

To identify regional system resources availability related to hybrid projects it is necessary to identify natural resources as hydro, wind, tide, and solar. Simulations must be carried out to identify sources complementarity and to evaluate the attributes of the potential hybrid projects to be implemented, as well as benefits of hybridization of existing plants. The result of this step is to identify aptitude of different regions to provide hybrid projects.

By matching system requirements and resources availability it is possible to identify some advisable adjustments to market design aiming at more Incentives to projects that bring more benefits to the system due to their individual attributes. The adjustments require agility and flexible market design to provide accurate signals for stakeholders, including the equipment's industry. The main

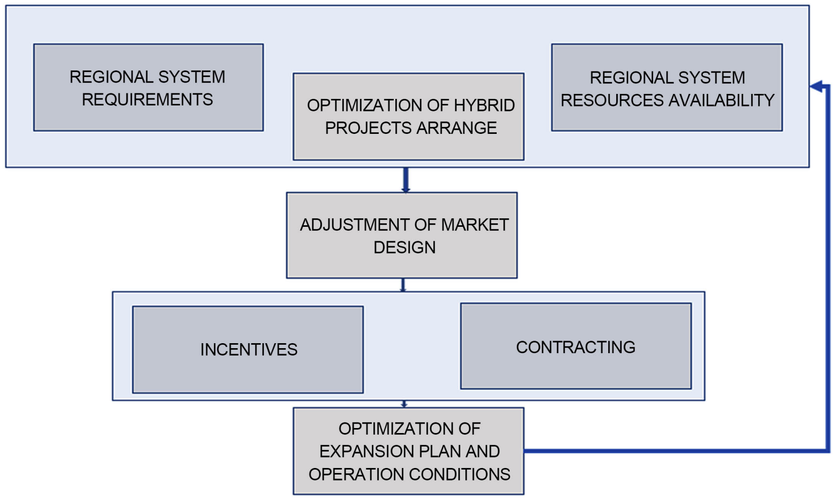

Figure 4. Steps of the proposed methodology.

concern at this point is to guarantee isonomic treatment to different stakeholders and the best answer is an incentive-based approach to meet the system requirements, allowing tariff payers to by the products they really need, and providers must adapt to the consumers, not the opposite.

An appropriate market design imposes accurate incentives and plants' contracting. The more efficient way to contract generation plants services is by means of public auctions. However, when it comes to hybrid projects it is relevant to explicitly consider the different attributes of the plants and properly pay for these attributes to guarantee fair incentives.

As the process is recursive, it is systematically important to assess the expansion planning findings and the operative conditions, by re-starting all the process always it is observed some unbalances to meet demand, lack of reliability or even lack of flexibility in the system.

Optimization of hybrid projects arrange: the proposed arrange of the hybrid project in terms of installed capacity of each generation source and storage system must be result of an economical investment and operation costs optimization process based on simulations from specific operation model develop to show the energy and capacity output of the project. This optimization process makes assertive the incentives and contracting supported by the market design.

In addition, there are some key themes that must be addressed to improve market design and regulation to enable hybrid projects, as presented below:

- Hybrid project concept, considering: 1) generation sources and storage system participations; 2) numbers of meters needed; 3) specificities of transmission ser-vices contracting; 4) operational priority among sources.
- Storage Systems role in terms of their connection to the network (charging/discharging) and possible definition for this type of agent (generation, load, or both).
- Network connection constraints.
- Project coordination responsibilities—by the owner or the system operator.

- Outflow limits and curtailment management, for operational and commercial purposes.
- Identifying System Requirements—depend on load, supply alternatives, and transmission network characteristics—considering the role that storage systems can play in benefit the system.
- Identifying the expansion and operation planning needs to incentivize those sources that have attributes as supply flexibility and reliability by means of accurate prices signals.
- Participation in the energy, capacity, and ancillary services markets definition of adequate remuneration mechanisms, based on the attributes of hybrid projects. Incentives must be created by appropriate market rules and benefits must be properly remunerated.
- Incentivize mechanisms for "hybrid" energy contracting: Auctions and contracting model as, for instance, the round-the-clock (RTC) and the meeting peak load contracting mechanisms.

6. Conclusions

Considering international experience studied in this paper and the results of the case study of a centrally operated hydropower plant, it is possible to confirm that enabling hybrid projects depends on appropriate market design, which must be modernized as technology and customer profile evolves.

The assessment done in this paper presents a set of issues to be addressed according to the local conditions and natural resources availability and considers the market design as the efficient tool to support hybrid projects expansion. The operation of hybrid projects allows the optimization of the arrange in terms of optimal installed capacity of each generation source and storage that delivers the optimal investment return from the economical point of view.

This optimization is relevant for the market design to set appropriate incentives and assertive prices signals for investors and developers, as well as to make it feasible for the optimization of the system generation expansion plan by considering optimal hybrid project arranges.

The market design and electricity industry regulation must provide the matching of the sources attributes with system requirements by means of clear price signal and efficient incentives allocation. These signals must be considered in modern tariffs structure design, giving fair treatment to different customers profiles, observing that it becomes more and more relevant to assure a tariff rational aiming at to connect cause to effect, charging who causes more costs to the system and benefiting who reduces the costs for the whole system. So, market players are looking forward to a market design evolution that makes tariffs fair and appropriate to support technological evolvement represented by hybrid projects.

The novelties presented in this article, in particular, in relation to the consolidation of recent international experiences open an important field for future research focusing, for example, on the analysis of the effects of the insertion of these projects in the regulatory frameworks adapted to them, as well as on regulatory adaptations in others markets not evaluated in this study.

Regarding the proposal for decentralized dispatch of hybrid solar-hydro hybrid power plants in the Brazilian regulatory framework and other issues to be treated as transmission contracting, as future work, it is aimed to be analyzed the results of the application of the model in other locations of the national grid and to develop models to provide economical assessment of cost/benefit of market design evolution in benefit of stakeholders. In addition to the strong arguments raised in this paper, considering the amount of generation, the economical evaluation of market design barriers costs by including the prices signals might be essential to regulatory development that aims hybrid projects enabling.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Annex

This annex presents a conceptual description of the model that was applied at the Case Study section. As this study focus on market design and not on the optimization model, the mathematical detail of the model that was implemented is not detailed.

This model was developed simulates and optimize the operation of a Hydroelectric Power Plant (HPP) associated with a Solar Photovoltaic Power Plant (SPP), composing a hydro-solar hybrid power plant operating in the Brazilian Interconnected System. In such arrangement, it is possible to simulate the joint operation or individually.

The model can be configured on local or regional scale. At local scale, configuration considers the hydro-solar plant isolated of the generation system. On the regional scale, the whole hydrographic basin (or even the whole system) is configured. To explaining the model, we hereafter consider the local case, which understanding can be expanded to the systemic under the same conceptual logic.

The model objective function (Equation (1)) aims to maximize the average generation of the arrange (e.g., hybrid power plant) within a given period, considering the demand curve, for example, peak and off-peak hours, that represent the periods in which energy has the greatest or lowest value to the system. As a result, operational management optimizes the allocation of energy to the most valuable hours.

$$\text{Maximize}\left\{\text{Average Hybrid Generation}\right\} \tag{1}$$

Average hybrid generation is obtained by simulating the power plants hourly operations (Equation (2)). The Solar Power Plant (SPP) generates energy according to the solar irradiation available at the site while the Hydro Power Plant (HPP) according to operating and hydrological conditions. When performing the joint operation, the effect of solar generation on the operation of HPP (which has the capacity to store energy in its reservoir) is considered.

$$\text{Hybrid Generation}\left\{\text{HPP} + \text{SPP}\right\} \tag{2}$$

The hourly generation scenarios of the SPP are estimated based on historical irradiation series obtained from SolarGIS platform, for a given location and by applying a pre-determined technical configuration (e.g., photovoltaic panels and inverters).

To estimate the HPP hourly generation, the operational configuration and historical flow series used in the NEWAVE model are used. NEWAVE is the official model used by the Brazilian National Independent Operator System for the centralized operation of the whole Brazilian integrated system. For reference on the representation of hydraulic generation in the context of the Brazilian electricity sector, see [41]. As a reference for the functioning of the Brazilian dispatch model NEWAVE and the representation of HPP, see [42] and [43]. The HPP operation configuration is represented in the model by a set of constraints and equations that govern the generation of this type of plant. For more see [44] and [45].

Describing the model in a generic way, it has the following main elements:

Input Variables:

- Effective and Minimum Inflow/outflow
- Hydraulic Loss
- Specific Producibility
- Reference Fall Height
- Polynomials: Volume-Quota; Area-Quota; Downstream flow-level
- Maximums and Minimums: Reservoir Area; Volume; Quota
- Installed Capacity/Maximum Capacity
- Downtime factor
- Affluent natural flow; Deviation flow
- Evaporation Coefficient
- Hourly Generation (SPP; HPP)
- Peak and off-peak hours profile; Market Load Factor

Calculated Variables:

- Discharge flow
- Water released (outflow)
- Total Inflow (affluent flow)
- Initial/Final Volume; Evaporated Volume
- Upstream/downstream water levels
- HPP Power/Generation
- Hybrid, System, HPP Total Generation

Decision Variables:

- Total Water Discharge flow
- Total Water Released (outflow)

$$\text{Total Defluent flow}\left(\text{outflow}\right) = \text{Spilled flow} + \text{Turbined}\left(\text{discharge}\right)\text{flow} \quad (3)$$

Constraints:

- Volume, Quota and Area Restrictions
- Restriction of Power Generated by the HPP
- Turbinating restriction
- Power Substation restriction (Output Energy < Transmission Limit)
- Fall Height Restriction

Objective Function

- Maximizes Total Generation

Main calculations:

- Inflows and outflows as a function of discharge flow, spillage, natural inflow
- Reservoir Emptying/Filling (water balance)
- Maximum Swallowing and Maximum Hydraulic Power
- Hydraulic Power Generation at the peak and off-peak hours
- Total Power Generated (SPP + HPP) at the peak and off-peak hours

As there is a limit in the energy generation to be drained in each period due to the flow capacity of the energy production and, at the same time, a goal to maximize the average generation in the evaluated period, when the jointly operation (HPP + SPP) is carried out, the model becomes able to decide whether or not to store energy in the reservoir. In other words, the trade-off between generating hydropower in a way that complements solar energy or storing it to generate it at a time when the energy will have more value to the system (peak load periods, for example) is evaluated.

Figure A1 presents an overview flowchart of the model used to support the case study. The equations were implemented in Python language and the model is optimized with the support of Fico-Xpress software.

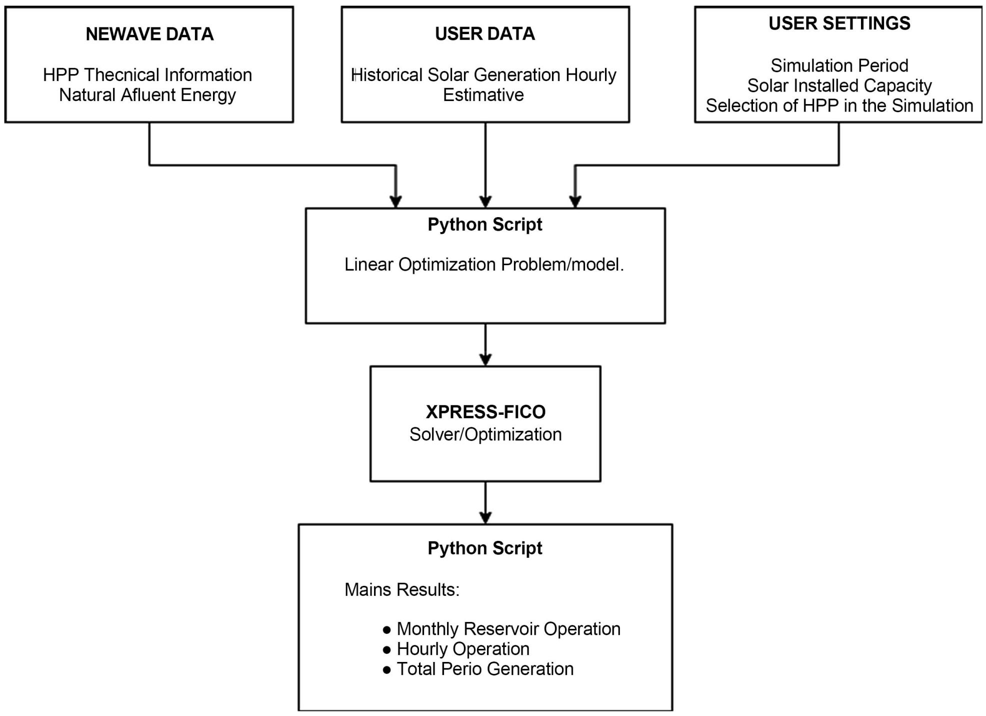

Figure A1. Conceptual flowchart of the Optimization Model of hybrid projects operation.