**LEGAL ENTITY REFERENCE TERM TEMPLATE - SBQC**

**MINISTRY OF MINES AND ENERGY – MME NATIONAL ELECTRIC SYSTEM OPERATOR - ONS**

**META PROJECT**

Technical Assistance Project to the Energy and Mineral Industries

**WORLD BANK**

INTERNATIONAL BANK FOR RECONSTRUCTION AND DEVELOPMENT - IBRD

Loan: 9074 - BR

# Term of Reference of Subproject 24 of the STEP Acquisition Plan - Consulting

## Subproject 24 - Solar Power Forecast: Study of influential variables and development of a forecast model.

**September/2022**

*TERM OF REFERENCE - TOR of Subproject 24 of the STEP Acquisition Plan - Consulting*

**Subproject 24 - Solar Power Forecast: Study of influential variables and development of forecasting model.**

## *1 CONTEXTUALIZATION*

The expansion of photovoltaic solar plants' installed capacity in recent years, together with the projection of high growth of this source in different Brazilians' regions, mainly in the Northeast, South, and Southeast, imposed to the National Electric System Operator (ONS) the need to improve the inputs of energy and electrical studies, in order to obtain a better representation of this power source, which has high variability. In view of this large insertion, it is necessary to allocate an adequate amount of operating power reserve.

In this sense, it is of paramount importance that the solar photovoltaic power forecast will be done with sufficient precision for the very short- and short-term electrical energy operation planning, as well as for the real time operation of the Brazilian National Interconnected System (SIN).

The solar photovoltaic source has several known benefits for Brazil, in the various spheres: socioeconomic, generating direct and indirect jobs and savings to the consumer; environmental, because it is a renewable resource and presents lower impacts compared to the other power generation sources, mainly with regard to fossil fuels; strategic, given that a high amount of solar radiation reaches the surface in almost the entire Brazilian territory, enabling the implementation of the power closer to the load, which increases energy security.

Currently, the representativeness of solar photovoltaic power is still discreet in the country, representing about 2.5% of the energy matrix. However, it is true that there will be significant growth. For example, the installed capacity, of centralized generation, at the end of 2019 was about 2.5 GW and currently, this value approaches 5 GW. As for the installed distributed power capacity, the amount exceeds 14 GW (March/2022) with a forecast to double this amount by 2025.

The solar photovoltaic power forecast takes into account meteorological variables and neglects the constraints in the transmission system. This issue is only addressed during the Daily Programming, which makes cuts in the expected amount in order to consider the electrical restrictions. In Real Time operation, to meet the load x power generation balance, it may also be necessary to ask agents for reductions in solar generation (curtailment), which results in constrained-off payment.

Currently, this cost is passed on to consumers, as well as the cost of allocating a more significant power reserve value to cope with the variability of the photovoltaic source. In this sense, it is necessary to deepen debates that aim to transfer the responsibility of managing the intermittence of renewable sources to the generators of this energy.

Energy auctions have proven to be one of the best alternatives to promote a greater insertion of renewable energy and are becoming more sophisticated over the years. In developed or even developing countries, auctions have already been held that required a guarantee of supply (firm energy) by the generators, regardless of weather conditions (Maurer, Doyle, Hyman, Loretta, & Torres, 2020). This type of auction tends to encourage the use of batteries to store the excess energy in times of low demand and/or electrical restrictions in order to use it to meet the tip, which consists of a way to transfer the risk of intermittence to the generator. Another point to encourage the use of storage systems is to discuss the remuneration for multiple services provided to the system by batteries, such as power reserve, frequency regulation and voltage control. All these issues can be part of the debates involving the reform of the Brazilian Electric System – SEB.

## *2 JUSTIFICATION*

The increasing insertion of variable renewable sources poses challenges to the planning of energy expansion, operation, and commercialization. Due to the importance of solar photovoltaic generation, combined with its potential growth in the Brazilian energy matrix, the accuracy of the power forecast of this source is extremely important for the planning and operation of the system.

Photovoltaic production has uncertainties associated with meteorological factors, causing inevitable deviations from the forecast, which brings the need for a greater reserve of operating power to meet load variations, and even the need for hydrothermal re-dispatching in cases of significant deviations. Such circumstances increase the cost of operation, generating more charges that reflect a higher cost to the consumer.

Therefore, it is important that the ONS has models and tools capable of assisting in the planning and operation of the SIN with greater predictability and assertiveness of the power forecast from these variable sources.

## *3 ONS SUBPROJECT 24 OVERVIEW*

Subproject 24 aims to provide advances in computational modeling for solar photovoltaic power forecast, considering the real time horizon (minutes up to 24 hours ahead), very short-term (up to 7 days ahead with main focus up to 48 hours ahead) and short-term (up to 1 month ahead). In addition, advances in the analysis of observed and predicted data, meteorological variable forecasting methodologies, exploration techniques and use of these data are expected.

Initially, it is necessary to analyze time series related to solar photovoltaic power. To compose historical data related to these series, verified/observed data acquired by the ONS Supervision and Control System may be considered, as well as verified solar photovoltaic power generation data from other sources of information.

It is noteworthy that, currently, there is redundancy of information observed from solar photovoltaic power generation. The first source of information comes from the Operator's real time supervision and control system, with discretization every 4 seconds, while the second one is sent by the Chamber of Electric Energy Commercialization (CCEE), from the Billing Measurement System with discretization at intervals of 5 minutes and 1 hour.

Considering this information, the data must be combined in order to obtain series that represent the groupings used in the solar forecast models for the short- and very short-term and Real Time. Even with redundancy of histories, it is not always possible to obtain the measured data for all time intervals, requiring the development of methodologies to fill these gaps, as well as the correction of data and reconstruction of the verified power generation information.

Regarding the development of solar photovoltaic power forecast models, the predicted meteorological variables (irradiation, temperature, cloud cover, wind, humidity, etc.) from the existing Numerical Weather Prediction (NWP) models should be used. The forecasts of these meteorological variables from NWP models should be analyzed, allowing the evaluation of the use of different algorithms for their correction and/or improvement. Then, this information should be formatted so that it can be used for solar photovoltaic power forecast in all the aforementioned time horizons. Thus, the solar photovoltaic power forecast should be made by different computational models, according to the discretization and time period considered. In addition, it is necessary to develop models and tools/systems for reading and processing satellite images and surface cameras, which make it possible to associate the radiation that reaches the surface with the density of the clouds.

The algorithms for treatment and adequacy of meteorological variables should be developed separately from the solar photovoltaic power forecasting models. In this way, a modularization is maintained, which will allow the use of several sources and NWP models for solar photovoltaic power forecast. If, during the development of the project, the need to create a specific model for meteorological variables is identified, it should also be separated from the solar photovoltaic power forecast model, maintaining an independence of the origin of the forecasts of meteorological variables in relation to the solar photovoltaic power forecast model.

The power forecast model for real time, essentially, should consider images from satellites and/or sky-cameras on land (when available), among other variables. For this, a tool should be developed capable of converting the images used in numerical data with real time/very short-term discretization, to be defined together with the Operator, so that they can be used as input data of the power forecast model.

If more than one power forecasting model or more than one NWP model is used, the resulting solar photovoltaic power forecasts originating from each model or source shall be combined in order to obtain a single quality forecast higher than the individual forecasts.

It is noteworthy that the forecast for very short- and short-term planning and the forecast for real time have relatively different purposes, so it is proposed that throughout the project different directions are adopted for the development of computational models and their respective tools/support systems.

To achieve the objectives, the products from this project will be validated by the Operator's technical team. Details of validations will be dealt with later in this document. The Operator values the transparency of its processes with the agents of the sector. Thus, it is understood that society should have access to the records and detailed documents of the technologies, mathematical models used and/or developed, and the algorithms of the forecasting models, in open source and documented. Therefore, after the completion of the project, the ONS will hold the rights to the products delivered.

Taking into account these aspects, it is emphasized that, in addition to the monitoring and management of this subproject, the Operator is interested in the technical team participating in all phases of specification and development, maintaining the exchange of information, technical knowledge, experiences, in order to absorb the technologies studied and adopted in this project, considering the possibility of expanding the use of these technologies to other areas of ONS. All models and tools tested and analyzed, even if they do not present good results for this project, must be succinctly documented to meet the interests and objectives of the Operator in order to gain knowledge, since their use may be interesting for other forecast areas within the ONS, such as wind power forecasts, load, flow, etc.

## *4 PURPOSE AND SCOPE*

The objective of the project is to provide solar photovoltaic power forecasting models with high accuracy, using meteorological and other variables considered relevant, to meet the planning processes in the very short- and short-term horizons, as well as real time operation, besides methodologies and tools for data processing and analysis.

The planned products provide additional benefits, such as methodological gains applicable to wind power, flow and load forecasting processes, inputs for the formation of energy prices, and for use in longer-term planning models.

## *5 RESULTS AND EXPECTED PRODUCTS*

**Frame 1** and **Frame 2** list the expected products as results for stages 1 and 2, and their respective phases. In item 6 of this document is presented a detailed description of what each step represents, phases, in addition to a more comprehensive presentation of the activities necessary for the development of each product.

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## Frame 1 - Products of Stage 1, phases 1, 2 and 3 of ONS Subproject 24.

| Phase | Product | Activities |
|---|---|---|
| 1. | **Product 1** | Report with analysis of variables and requirements and measuring instruments |
| | **Product 2** | Development of forecasting models and reports with description of mathematical models |
| | **Product 3** | Report with description of the mathematical models proposed for the solar photovoltaic power forecast |
| | **Product 4** | Prototype of the 1st version of the Solar Photovoltaic Power Forecast Model (very short- and short-term) and Manual |
| | **Product 5** | Report with parameter adjustments as required by the model |
| | **Product 6** | Forecast model performance and sensitivity report |
| | **Product 7** | Documentation and presentation of mathematical models and source code of model algorithms |
| 2. | **Product 8** | Processing chain´s code, fault treatment, process flow and updated execution manual |
| | **Product 9** | Consolidated and validated history for a plant, from a set of 10 plants |
| | **Product 10** | Validation of the execution process´ model for a plant, in the ONS environment |
| | **Product 11** | Consolidated and validated history of the 10 plants |
| | **Product 12** | Validation of the execution process´ model for the 10 plants, in the ONS environment |
| | **Product 13** | Operationalization of the process of execution of the Solar Photovoltaic Power Forecast Model Prototype (very short- and short-term) in the ONS environment, for the 10 selected plants |
| 3. | **Product 14** | Evaluation and improvement of forecasting algorithms |
| | **Product 15** | Prototype of the 1st version of the cloud coverage correction tool |
| | **Product 16** | Comparison report, forecast evaluation and list of meteorological variables |
| | **Product 17** | Delivery of the final version of the Solar Photovoltaic Power Forecast Model (very short- and short-term) |
| | **Product 18** | Operationalization of the Solar Photovoltaic Power Forecast Model (very short- and short-term) |
| | **Product 19** | Report with assessment of challenges, responsibilities and management solutions related to the intermittence of renewable sources |

**Frame 2 - Products of Stage 2, phases 1, 2, 3 and 4 of ONS Subproject 24.**

| Phase | Product | Activities |
|---|---|---|
| 1. | **Product 20** | Satellite and/or sensor image acquisition and quality control system |
| | **Product 21** | Study, identification and vectorization model for cloud fields |
| 2. | **Product 22** | Cloud motion detection system (pixels) |
| | **Product 23** | Assessment of meteorological conditions and applicability of a radiative transfer model under multiple scattering conditions in the presence of clouds |
| | **Product 24** | Solar radiation prediction model on the surface |
| 3. | **Product 25** | Evolution of the model algorithms of the very short- and short-term planning (Stage 1) to obtain power generation data in real time |
| | **Product 26** | Report with evaluation of performance and cost x benefit of the inputs used to evolve these models |
| | **Product 27** | First version of the Solar Photovoltaic Power Forecast Model for Real Time: documentation and results |
| 4. | **Product 28** | Documentation of the Solar Photovoltaic Power Forecast Model for Real Time in the ONS environment |
| | **Product 29** | Validation of the forecasting process for real time and delivery of the model's documentation and source code |
| | **Product 30** | Operationalization of the execution process of the Solar Photovoltaic Power Forecast Model for Real Time in the ONS environment and User Manual |

# 6 SCOPE OF WORK AND PROJECT BOUNDARIES

This project is divided into two stages, where: (i) the first stage refers to the development of the solar photovoltaic power forecast model for very short- and short-term planning; (ii) the second stage is the development of a forecast model for real time and/or the evolution/adaptation of the model developed on stage 1.

For products that require the use of historical data, ONS will provide the contracted institution with the data it has from, initially, at least 10 plants supervised by the Operator.

The following items describe in detail the products of each stage, presented **in Frame 1 and Frame 2**.

## 6.1 Stage 1: Development of the Photovoltaic Forecasting Model for very short- and short-term planning

This stage is divided into 3 phases, and in phase 1 the predictive models which best fit the theme will be chosen. In addition, it will be developed methodologies and systems for data processing, as well as the creation of a first prototype of the solar photovoltaic power forecast model for the very short- and short-term. Phase 2 refers to the application of the first prototype, with the suitability for compatible temporal and spatial scales, and operational implementation with optimization and validation for the selected photovoltaic solar plants. In phase 3, the activities related to the implementation of the developed product will be outlined.

Initially, power forecasting models will be developed from a data set of at least 10 (ten) photovoltaic plants. The form of availability of this data set and other quantities will be agreed with the Contractor, requiring the establishment of a confidentiality agreement.

### 6.1.1 Phase 1 – Proof of Concept and development of predictors

This phase aims to verify the various possibilities regard to existing mathematical and computational models, concepts, variables and theories that have the potential to predict the power generation of the renewable sources. Seven products are expected at the end of this phase.

#### 6.1.1.1 Product 1: Report with analysis of variables and requirements and measuring instruments

This product aims to obtain a survey of the information necessary to improve the minimum requirements of measuring instruments, variables and criteria for data acquisition, with a main focus on the needs of solar photovoltaic power forecasting models and for wind power, which are also target in the second product. Thus, improving the process of supervising the data in real time and, consequently, providing a better quality input for the solar photovoltaic power forecast model.

The data of power generation, air temperature, irradiation and number of inverters are acquired by the Operator through the Supervision and Control System with a frequency of 4 seconds. However, there is no minimum specification required regarding the location and height of meteorological instruments, type and number of sensors, which reflects on the quality of the data.

In order to improve the quality of the data sent to the ONS, the need to specify the measurement requirements should be considered, as well as for the installation of other measuring instruments that provide better information for use in the power forecasts.

Some needs raised by the Operator's technical team to subsidize the construction of this phase are:

I. Identify the variables necessary to obtain a better solar photovoltaic power forecast, the location and height of the instruments in the park, the measurement requirements, collection frequency and the instruments necessary to provide a quality measurement of these variables, indicating the standard equipment to be used in the measurement of each variable. If it is proposed to install other sensors in the photovoltaic parks, the minimum distance between them must be specified.

II. Specify and evaluate cost-effectiveness of which equipment should be used to capture images of the sky to assess cloud coverage, justifying the need for, and cost-effectiveness of such equipment. Additionally, define and detail the need for other forms of cloud data acquisition.

III. If the park has tracking technology, it must be specified how this information will be considered in the model. Whether in the form of data acquisition and representation in the models.

IV. Specify which types of satellites and channels are most suitable, informing the history of available cloudiness and/or radiation data, as well as spatial and temporal resolution.

V. Specify how satellite images will be used in the very short-, short- and medium-term models. Describing/evaluating the alternatives of these satellite image acquisition processes in ONS and their post-processing.

VI. Specify whether satellite data can capture the vertical profile of the atmosphere with relative quality, with respect to the optical depth of the clouds, as well as their spatial representativeness.

VII. Specify the gain associated with the incorporation of data observed by satellite in the forecast or if this information would be used to correct and improve the cloudiness of the models, by creating a history of cloudiness. UCSD (University of California San Diego), for example, uses satellite imagery to forecast up to six hours ahead. Studies conducted by the Fraunhofer Institute for Solar Energy Systems ISE, on the other hand, showed that the gain with the inclusion of this information is not so relevant.

VIII. Perform analyzes and comparisons of the accuracy of different NWP models for all variables with potential use in the products of this project, such as irradiation, temperature, cloud cover, wind, humidity, etc. Analyses using the GFS (Global Forecast System), WRF (Weather Research and Forecasting) and IFS (Integrated Forecast System) models of the European ECMWF (European Centre for Medium-Range Weather Forecasts) are proposed, and other numerical models may be considered, if relevant. The project must obtain the histories of these models together with the agencies holding them.

The detailed study of the cloud forecast and coverage variables should be described in the report, explaining the impacts on the results of the solar photovoltaic power forecast model and on the initial calibrations.

#### *6.1.1.2 Product 2: Development of forecasting models and reports with description of mathematical models*

This product consists of the development and delivery of mathematical methodologies and models for more generic power forecasting, applicable to renewable sources, such as wind, photovoltaic, etc., through their respective codes and reports. When it comes specifically to photovoltaic forecasting, there is the scope of Product 3. There are several models that can be explored, namely: physical models, which use NWP and relate these predictions to power through a productivity function; statistical models, which use historical data in order to relate the availability of the meteorological resource to wind/solar photovoltaic power (usually use time series analysis and artificial intelligence techniques); and hybrid models, which combine characteristics of physical and statistical models, i.e., make use of time series analysis, including NWP as input.

The methodologies of all models should be described and their performances compared. In the future stages of this project, the best-performing methodologies for photovoltaic forecasting will be adapted in later products. The best methodologies for wind forecasting, for example, can be used by the ONS forecasting model, but it is not part of the scope of this project to carry out this adaptation, however, the models should be created already thinking about this purpose. The deadline for delivery of the report will be defined during the project and will depend on the number of models and methodologies explored.

The codes to be developed must follow the same standard of data input and output. The modularization of the process should also be the same for all power generation models, that is, if there is a module for data processing in the prototype of a model, this module should also appear in the codes of all other models presented. The code execution manual must be made available by the contracted institution.

The indicative themes that should be addressed in this product are:

I. Use of distributional information from ensembles.

In addition to accurate deterministic forecasts, it is increasingly necessary to obtain information about the uncertainty corresponding to this forecast. Numerical weather prediction models can be used to generate probabilistic predictions from ensembles. However, this distributional information is currently not taken into account in ONS forecasting processes. A model capable of absorbing the complete information of this ensemble is desirable, which also returns a distributional forecast (Möller, 2018), (Grönquist, 2021), (Tateo, 2019) and (Robertson, Shrestha, & Wang, 2016).

II. Identification/correction of meteorological systems

In general, NWP models have difficulty in predicting the evolution of mesoscale weather systems, such as convective clouds, negatively impacting the power forecasting, and incurring severe errors for the operation. It is desirable to have a model that can determine, having a history of these systems previously classified, the probability of occurrence of these events in the forecast days, using any explanatory variables that are available during the power forecast operational process.

III. Incorporation of climatic variables in the forecast.

Large-scale climatic indicators, such as the Oceanic Niño Index (ONI) and sea surface temperatures, are modeled at time scales much broader than the daily one, in which solar photovoltaic power is predicted. It is interesting to evaluate how meteorological variables, such as cloudiness and wind, vary depending on the climatic condition determined by these indices, and how to incorporate these effects in the prediction process of photovoltaic and wind power. Considering the time scale difference, models with Markovian switching (Ailliot, 2021), (Hering, 2015) and (Kang, 2014), or hierarchical structures (Gilbert, 2019), (Croonenbroeck, 2015) and (Fawcett, 2006) are attractive options: the first because it can indicate explainable latent states, but not necessarily corresponding to climatic variables; the second because it removes effects of different scales at different levels of modeling. It is still possible to incorporate this information in the form of *dummy* variables with the same average monthly value repeated over the days, although this option is considered less interesting.

IV. Bias correction and spatiotemporal modeling.

Although NWP are performed in a spatially "multivariate" manner, in the sense that these models simulate and predict multiple points in space together, the bias correction currently performed by the Operator is univariate for each plant. It is possible that in this process some information of the interaction between regions is being lost. Nevertheless, it is also plausible that numerical models are not capable of capturing all spatial dependence. Combining these factors, we seek tools/systems that can correct the explanatory variable in a multivariate way or perform the multivariate prediction directly (Tastu, 2011), without an intermediate correction step. Methods based on copulas (Zhang, 2013) and (Arrieta-Prieto, 2022) can be a viable alternative, since it is expected relative sparsity in dependence between plants. Classic methods for modeling multivariate series such as VARMA – Vector ARMA (Hering, 2015), (Browell, 2018), and State Space (Kang, 2014) may also be useful. Considering the high dimensionality, it is possible that clustering or shrinking approaches (LASSO, Elastic Net, etc.) are useful or even indispensable. Finally, still due to the high size and volume of data, network methods (Huang, 2022) can prove to be more computationally efficient and capable to provide a better performance.

V. Data set augmentation approaches for forecasting.

For real applications, Deep Learning techniques require a large amount of data for training, which can often go against the operating reality, in which an increase in sensing and data acquisition is disproportionately costly, in particular for the reality of ONS, which manages data from all facilities in the country. One approach to improving the performance of learning techniques is through Data Augmentation approaches. When performing a data set transformation, some other approaches can be facilitated, such as mixing between observed (exogenous) variables and predicted by NWP models and also possible removals of existing biases in the data (Chen, Birkelund, & Zhang, 2021). Thus, it is proposed to investigate techniques to increase the data set for use in Recurrent Neural Networks, in particular LSTM - Long Short Term Memory.

VI. Adoption of multiple predictive models.

The power prediction from alternative energy sources is a challenge, with several approaches already presented, but so far without a unanimous winner method in all situations. In this context, the use of several predictive models simultaneously can be considered. The models are trained with some spatial grouping and the input and output data of the validation are used in a later processing step for the selection of the best model for prediction of each range of future samples (Wang, 2021). Currently, the model used by ONS for wind power forecasting (WEOL) combines several predictions of NWP models, which are applied in the same regression model. The proposal is to expand the decision-making space beyond data sources, also encompassing models of different natures, which can deliver better performances at certain times of the day, for certain regions. Detailing models that can be implemented and tested:

a) Series decomposition using VMD (Variational Modal Decomposition) or Wavelet;

To make the prediction of future values in a time series more robust, one of the possible features is to obtain components that define the series, performing the prediction on these components. In this way, the predicted values of the time series are recovered from the predicted values of each component. In this case, predictive models that do not have physical interpretation are applied, such as ARMA or RNN.

b) LSTM Neural Networks;

Unlike autoregressive models, which have constant factors in the contributions of a sample lagged in time to a future sample, recurrent neural networks, in particular the LSTM, perform the prediction considering maintenance rates of recent values and forgetfulness rates of past values. Although the training of LSTM is more time-consuming in relation to conventional neural networks MLP, the application of the models is fast and has been widely used in the short-term power generation prediction for renewable sources.

c) Convolutional Neural Networks (CNN);

Widely applied in image processing, CNN performs data processing considered "close" in some way, for extraction of patterns and inferences. This type of network is usually built with a large number of layers, which allows extracting patterns that are often not apparent through a mere visualization of the data. During its training process, weights are learned for the construction of *kernels*, weighting units for nearby data, to summarize a set of nearby data into a single value. In the context of time series forecasting, CNN has been used with one-dimensional *kernels* to identify patterns in a data time window, and thus infer the next values of the series.

d) *Extreme Learning Machine* (ELM);

They are neural networks specialized in tasks that do not require the extraction of deep data characteristics, *i.e.*, cases in which deep multi-layered neural networks are used. ELM networks are *feedforward* models and have only one layer. Its training algorithm is more efficient, allowing several networks to be trained to process only one category of data, contributing to the operationalization of its application.

e) Metaheuristics such as GA, GWO and DA applied to the optimization of parametric models;

Many of the predictive models are based on parameters, which are estimated in some way based on verified historical data or the error of previous predictions. Estimation techniques are often deterministic, usually being improved with features such as data augmentation or other preprocessing of input data. An alternative approach that has been widely studied is the use of biologically inspired optimization techniques, such as Genetic Algorithms (GA), Grey Wolf Optimization (GWO) and Dragonfly Algorithm (DA) in the estimation of model parameters, contributing to calibrations possibly better than those previously obtained.

f) Hybrid models;

In general, prediction models use more than one mathematical/computational technique. Some examples can be highlighted: (i) series decomposition using VMD + LSTM Networks (Jiandong, 2021); (ii) decomposition with VMD + ELM optimized with GWO (Hao & Tian, 2019); (iii) decomposition with VMD + CNN, with temporal convolution (Yildiz, Acikgoz, Korkmaz, & Budak, 2021); (iv) decomposition with Wavelet transform + ELM robust to outliers (Liu & Duan, 2021).

As it is a generic product of methodologies applicable to other energy sources, if it is necessary to use different data, other than data associated with solar power forecast, ONS will agree with the Contractor the feasible way to make the availability.

Minimally, this product should address the indicated themes and models. However, the contractor may indicate other relevant themes and models that it deems pertinent. This product must be delivered in codes and partial quarterly development reports.

#### *6.1.1.3 Product 3: Report with description of the mathematical models proposed for the solar photovoltaic power forecast*

This product will be a delimitation of Product 2. The models developed in Product 2 must be adapted to the solar photovoltaic power forecast. The revision of this product may occur whenever there are developments, of better performance, of Product 2, being necessary the standardization/modularization of the algorithms developed for later products.

Product 3 should provide a study with the indication of possible methodologies, existing mathematical models, concepts and theories that have the potential to be used in the solar photovoltaic power forecast. Although the base product is a report, for its preparation, advanced analyzes should be carried out, as well as the implementation and testing of models adapted to photovoltaic forecasting. This product should not be a report based only on bibliography reviews.

To support this study, some points and questions raised by the ONS technical team are presented as following:

I. Identify methodologies of data processing, for correction of both power and meteorological variables, such irradiance, temperature, humidity, among others.

II. In the ONS wind power forecast model, a relationship between wind and power similar to a logistic curve is observed. For solar photovoltaic power, it can be seen that the power is almost linearly related to the influential variables. However, in a multivariate model it is necessary to specify the transfer function to be adjusted. Could it be a hyperplane?

III. If it is decided to use a parametric model, specify which form of adjustment would be best to adequately represent the data.

IV. It is known that solar plants have distinct characteristics, such as the implementation or not of tracking on both axes or combined positioning of two panels in order to maximize radiation uptake under various conditions. Specify whether there is a need to insert these characteristics in the power forecast models through angle measurements of the tracked ones or whether the effects of the trackers could be estimated with the observed power generation and irradiance data itself.

V. Specify whether there is any characteristic behavior of solar photovoltaic power generation to be observed and modeled with annual or multiannual seasonality.

VI. The most representative variables and models in forecasting processes vary with horizon, region, etc. Specify whether there is any process for defining the variables to be used in the model, as well as detailing the choice of the most appropriate models and/or techniques considering this variation.

VII. Detail the existence and/or predominance of any observed variable, satellites, Sky Camera or meteorological models that better represent solar photovoltaic power generation in the very short-, short-, medium- and long-term models.

VIII. Specify the data to be used in the calibration of the models, *i.e.,* observed data, weather forecasts or both.

IX. Specify what data is required to model the clear sky conditions.

X. Specify the data of the numerical models to be used, cloud coverage data, in low, medium and high layer, as well as propose a way to correlate or correct the predicted cloud coverage data with the satellite information.

XI. NWP models provide the total radiation. Specify whether separate modeling of direct and diffuse radiation is required, detailing the separation models in these two components.

XII. Specify the possibility of modeling the effects of air pollution and particulate matter on the incident radiation, indicating the gain in the use of this information.

XIII. Specify any other information not mentioned, but which has been identified as relevant to the project.

XIV. After literature review and implementation of some forecasting models, it will be necessary to adjust the parameters and improve the algorithms in order to perform a good forecast for a given set of plants, and thus quantify performance and sensitivity of the predictor for a test period to be defined.

#### *6.1.1.4 Product 4: Prototype of the 1st version of the Solar Photovoltaic Power Forecast Model (very short- and short-term) and Manual*

This product should provide prediction algorithms considering the ONS data structure, as well as conclusions of the studies made in Products 2 and 3. The model used in the very short- and short-term planning needs, minimally, forecasts for the following day (D+1) and thirty-five more days ahead (D+2 to D+35), with semi-hourly discretization. To meet the ONS processes, the results of the models must be available daily until 9 am of the day (D) to meet at least until the seventh day ahead (D+1 to D+7). For the larger horizon (D+8 to D+35), due to processing time, it can be completed by 12 pm on the day (D).

The models developed should provide solar photovoltaic power forecasts by individualized plants. However, it is possible that the spatial resolution for the predictions can be changed, but, in maximum clusters corresponding to the electrical buses in which the plants are connected. Such groupings must outperform the consideration of individualized plants. However, if any grouping greater than the plant level is adopted, it will be necessary to develop mechanisms for separating the forecast by individual plants.

The historical of power generation data and other observed variables acquired by the Operator's supervision and control system may be used as inputs for the forecast model. In the case of the quantities provided by the NWP models, which will also be used as input, they will be defined during the development of the project, depending on the cost x benefit to the Operator, since there are already contracts in force to acquire the forecast of some meteorological variables.

At the end of the development of the first version of the model, a detailed documentation must be produced and a presentation must be made to the ONS. Then, the form of construction of the processing chain, treatment of failures and validation of the results with historical data of the plants used will be defined together.

**Presentation, documentation and execution manual:** Together with the prototype, the contracted institution must provide the manual containing the description of the operation and structure to operate and execute the prototype.

Provision should be made for the provision of training meetings for the use of the prototype. At least one training will be necessary, and there may be a need for further meetings for clarification. The number of trainings required will depend on the complexity of the prototype, to be defined by the ONS and the contracted institution of the project. The training will be offered to the ONS technical team.

#### *6.1.1.5 Product 5: Report with adjustments of parameters and variables as required by the model*

A report must be delivered containing all the parameters and meteorological variables used as input and configuration for the execution of the model, highlighting those that presented a better performance in the results. It should also be described how they were considered and the techniques for the selection of parameters and the methodologies used for processing these variables to be used as input of the prediction model.

#### *6.1.1.6 Product 6: Forecast Model Performance and Sensitivity Report*

A report should be delivered with detailed performance and sensitivity analyses of the model results for the plants used. The analyses must include the performance of the predicted and corrected meteorological quantities, as well as the power forecasts of the proposed model. The historical period of analysis must be representative enough to validate the conclusions, having at least one year of history.

#### *6.1.1.7 Product 7: Documentation and presentation of mathematical models and source code of model algorithms*

After the delivery of the prototype and performance analyzes, and evaluation and representation of ONS considerations, the detailed documentation of the forecast model, the source code of the algorithms in the language in which the prototype was developed, as well as a presentation of the mathematical models adopted in the construction of this version, must be delivered.

### *6.1.2 Phase 2 – Application of the prototype with suitability for temporal and spatial scales*

This phase consists of the application of the first prototype, with the suitability for compatible temporal and spatial scales. Then, the adjustment for operational scale must be made with optimization and validation for the selected photovoltaic solar plants. At this phase there should be a greater iteration between the ONS and the contracted institution, as it refers to the necessary adjustments for the prototype to be operational in the ONS.

### *6.1.2.1 Product 8: Processing chain´s code, fault treatment, process flow and updated execution manual*

This product consists of mapping and creating the process to execute the model, considering the data processing routines to eliminate failures, the execution flow of routines, the availability of results, the execution manual and the source code that triggers the execution of the entire process.

At the end of the development of the first version of the model, a detailed documentation must be produced, and a presentation must be made to the ONS. Then, the form of construction of the processing chain, treatment of failures and validation with historical data from at least one of the plants will be defined together.

### *6.1.2.2 Product 9: Consolidated and validated history for a plant, from a set of 10 plants*

In this product, the data processing techniques applied to the history of one of the photovoltaic plants should be evaluated. The delivery includes the consolidation of the data history of this plant, highlighting the entire process of consistency, methodologies and techniques used.

### *6.1.2.3 Product 10: Validation of execution process' model for a plant, in the ONS environment*

Validation of the forecasting model execution process considering data from at least one of the selected plants, with consolidated historical data and consistent registration data. If any inconsistency is identified in the process, it must be reviewed and adjusted according to the need of the ONS.

### *6.1.2.4 Product 11: Consolidated and validated history of the 10 plants*

Delivery of the consolidation of the data history of the ten previously selected plants.

This product is a generalization of Product 9. The main purpose of delivery of this product is the possible correction of problems that can be identified after delivery of Product 9.

### *6.1.2.5 Product 12: Validation of the execution process´ model for the 10 plants, in the ONS environment*

Validation of the forecasting model execution process considering the data of the 10 previously selected plants, with consolidated historical data and consistent registration data.

If any inconsistency is identified in the process, it must be reviewed and adjusted according to the need of the ONS. This product is a generalization of Product 10.

#### *6.1.2.6 Product 13: Operationalization of the process of execution of the Solar Photovoltaic Power Forecast Model Prototype (very short- and short-term) in the ONS environment, for the 10 selected plants*

This process should be operationalized in the ONS environment, considering the existing structure, for daily execution. At least ten plants selected previously will be adopted. The contracted institution must monitor the execution in the ONS environment for a minimum period of 02 (two) weeks. The operationalization process of the power forecast model must be done in loco at the Operator, with the participation of the ONS technical team that received the training offered to complete Product 4.

After the operationalization of the first prototype, there should be an interaction between the ONS and the contracted institution so that possible improvements are identified and implemented to the forecast model, in order to optimize and improve the robustness of the process, and in the process of making the results available.

### *6.1.3 Phase 3 – Implementation of the Solar Photovoltaic Power Forecast Model for very short and short-term planning*

In this phase, the other plants supervised by ONS will be gradually inserted so that the appropriate analysis of the model results and the evaluation of the execution process are carried out. The main goal is to identify possible improvements in the model and the process, from the consolidation of input data and historical data until the result of the model. Thus, at the end a final version of the solar photovoltaic power forecast model should be produced, including all the improvements verified during the development and validation of the process, culminating in the product of this stage of the project.

Therefore, at the end of this phase, the execution of the process must be implemented in the homologation environment and the contracted institution must carry out with the ONS team the monitoring of the execution of the process and the respective results of the model.

#### *6.1.3.1 Product 14: Evaluation and improvement of forecasting algorithms*

During the inclusion of the plants, the contracted institution will verify, with the ONS technical team, the possibilities of improvements in the forecasting algorithms. In this phase, all improvement needs pointed out by the ONS and the Contractor's technical team must be addressed. In addition, it is foreseen in this product the incorporation of all models (identified as best) of Product 2, adapting Product 4.

#### *6.1.3.2 Product 15: Prototype of the 1st version of the cloud coverage correction tool*

The prediction of real time solar photovoltaic power generation, from minutes to a few hours ahead, in general, is carried out based on cloud movements. In this way, the ONS needs tools/systems capable of collecting satellite images and/or ground cameras, processing these images and transforming them into numerical data with real-time discretization that are written in files, with specific formats, so that they can be used as inputs for power forecast models. It should be noted, however, that this product is not related to real time forecasts, for which the focus will be addressed in another product.

The main objective of this product is to carry out studies to evaluate whether cloud coverage images also have predictive information for very short-term forecasts, especially in the next day forecasts D+1.

Therefore, the product should contain a simple open-source system for: (i) collecting and processing cloud images, from both satellite and surface observations; (ii) conducting cloud identification studies.

Additionally, this product should analyze the cloud coverage data of different NWP models. The product should comprise: evaluation of the forecast history of the cloud coverage variable in different forecast horizons; evaluation of satellite image data and/or consideration in the very short- and short-term models; development of a tool to correct the cloud coverage of the numerical models using the information from the two items aforementioned for use in the very short- and short-term forecasts; delivery of the code that performs the correction of cloud coverage and other necessary codes, which should be separated from the solar photovoltaic power forecast code.

#### *6.1.3.3 Product 16: Comparison report, forecast evaluation and list of meteorological variables*

The contracted institution must deliver a comparison and evaluation report for the forecast of all variables necessary for the photovoltaic forecast model. This product is expected to evolve from the more generic analyzes performed in Product 1. Thus, the product must contain:

I. Performance comparison of different global (GFS, IFS/ECMWF, BAM etc.) and regional (WRF, Eta, RAMS etc.) NWP models;

II. Evaluation of the accuracy of the forecast between the models and the combined model;

III. List of meteorological variables with better cost x benefit for the solar photovoltaic power forecast model.

#### *6.1.3.4 Product 17: Delivery of the final version of the Solar Photovoltaic Power Forecast Model (very short- and short-term)*

After the deliveries and considerations of the previous products, the contracted institution must deliver the final version of the Solar Photovoltaic Power Forecast Model for the very short- and short-term planning, containing:

I. Source code of the Model in the language in which it was developed;

II. Documentation of the methodology and techniques of data processing and others;

III. Technologies used in the development of the model;

IV. Operating manual of the model containing a description of the input and output files;

V. Description of the execution process and process data flow;

VI. Presentation of the Solar Photovoltaic Power Forecast Model for very short- and short-term planning, which is the objective of this stage.

The codes and documents of this product will be used to make available the model to all society.

#### *6.1.3.5 Product 18: Operationalization of the Solar Photovoltaic Power Forecast Model (very short- and short-term)*

This product consists of the operationalization of the final version of the forecast model in the corporative environment, considering all plants supervised by ONS. Upon delivery, ONS will verify the accuracy of the information for a minimum of 180 days. This period can be defined by ONS to ensure that it contains months of greater variability in solar photovoltaic power generation, that is, months with greater predictive difficulty. In addition, there may be situations of failures in the process not previously foreseen, requiring corrections, if associated with the development of the Contractor.

#### *6.1.3.6 Product 19: Report with evaluation of challenges, responsibilities and management solutions related to the intermittence of renewable sources*

It is also the product of this project to deliver a report discussing the challenge of managing the intermittence of renewable sources, which is currently the responsibility of the Operator. The report should present solutions found by other operators in the world, including ways of transferring this responsibility to generators.

It is known that the current form of energy contracting does not give any incentive to the intermittence management by the producer, either by the installation of batteries or by the combination of different energy sources in the same bid. One form of incentive is the contracting of renewables through auctions that require a guarantee of supply by the generator, regardless of climatic conditions.

Another issue that should be addressed in the report is the allocation of operational reserve to supply intraday variations in solar photovoltaic power generation, especially in the late afternoon period, in which there is a drop in photovoltaic production and the system load tends to increase. In addition, the significant growth of distributed solar photovoltaic power should intensify the debates about managing the intermittence of this source.

It is important to evaluate how operators represent forecasts of renewable sources in the very short-, short-, medium- and long-term planning models. Pointing out aspects of the forecast and proposing the necessary solutions, especially for the medium/long-term horizon that is not the main focus of this work.

## *6.2 Stage 2: Development of the photovoltaic forecast model for Real Time*

This stage consists of the development of the Solar Photovoltaic Power Forecast Model for Real Time and it is divided into 04 (four) phases. Phase 1 refers to the development of the system of collection and quality control of satellite images, and ground-based cameras, when available. In phase 2, algorithms will be built to predict cloud motion vector (CMV), one of the main products of this stage. In phase 3, a real time forecasting model will be developed. And in phase 4, the operationalization of the forecast model in the ONS environment will be addressed.

It is desirable that the system and models are implemented according to the ONS architecture. In this way, the optimization of the *cloud motion vector* model will occur naturally and easily for the forecast areas.

As in the previous step, the detailed documentation must be delivered, with technical note(s), codes and execution manual, when applicable, for all products of this stage, as well as the description of the architecture of the system processing chain and the model according to the ONS environment.

At the end of this stage, the contracted institution must make a presentation of the final model and execution of the code in the ONS system and must follow this process for a minimum period of 2 weeks. As in the previous stage, the training should be mapped in ONS partnership and contracted institution.

The following items describe in detail the products of each phase of this stage.

### *6.2.1 Phase 1 – System for acquiring satellite images and/or sensors, numerical interpretation and automatic cloud identification*

The prediction of real time solar photovoltaic power generation, from minutes to a few hours ahead, in general, is carried out based on cloud displacement. Thus, ONS needs systems capable of collecting satellite images and/or ground cameras, processing these satellite images and transforming them into numerical data with real-time discretization that are written in files, with specific formats, so that they can be used as inputs for solar photovoltaic power forecast models.

In this phase, an (open source) system of collection and quality control of satellite images and/or irradiance sensors should be developed. Such images will be used as input for cloud identification and vectorization studies of cloud fields.

Following, a more detailed description of the products to be delivered at this phase is presented.

#### *6.2.1.1 Product 20: Satellite and/or sensor image acquisition and quality control system*

The contracted institution shall evaluate the possibility of contracting and/or developing a system to collect satellite images and/or observations made by ground-based cameras or other sensors capable of continuously identifying the presence/absence of clouds. Such observations should be processed and evaluated in order to obtain inputs for cloud identification studies. In addition, physical and optical properties of the cloudiness should be extracted, allowing its subsequent application to radiative transfer models, as well as evaluation of the characteristic of the cloudiness and its relationship with the power generation of photovoltaic energy. The system must be developed in open source in a programming language defined in conjunction with the Operator, as well as the necessary architecture and database. The source code and detailed documentation of the proposed system must be delivered.

#### *6.2.1.2 Product 21: Study, identification and vectorization model for cloud fields*

Based on the results of Product 20, the contracted institution must develop a model/methodology capable of enabling the study and identification of clouds according to their characteristics, with the objective of analyzing the impact on solar photovoltaic power generation, including its forecasting. The contracted institution should develop a system for vectorization of cloud fields, that is, a tool capable of converting the collected images to the vector format. The determination of these vectors, which will later be used in cloud motion algorithms, is done by analyzing subsequent images. For this product, delivery can be made via report. The algorithms that may be developed can be delivered in later products.

### *6.2.2 Phase 2 – Development of the cloud motion vector model*

At this phase, the development of the main algorithm of the Real Time forecast, called cloud motion vector, is planned.

#### *6.2.2.1 Product 22: Cloud motion detection system (pixels)*

The result of the vectorization of the cloud fields is used in Phase 2 to extrapolate the future cloud pattern from the current cloudiness map. For the selection of the vector that best represents the displacement of the cloud, *block matching* criteria are usually applied. In this product, in addition to the model code, a report describing its methodology must be delivered. Cloud motion forecasts should consider satellite images in order to enable the reproduction of this methodology for all photovoltaic plants. However, in cases where cloudiness observation through ground-based cameras is available, such observations should be used to validate the system based on satellite observations.

#### *6.2.2.2 Product 23: Evaluation of meteorological conditions and the applicability of a radioactive transfer model in multiple scattering conditions in the presence of clouds*

The sudden change in intensity and/or wind direction due to mesoscale systems (such as sea-land breeze, valley-mountain breeze) or the advance of synoptic-scale weather systems can significantly alter cloud coverage. These changes are not always correctly predicted by NWP models.

This product must be able to predict these changes continuously from the numerical forecasts and the variation of the observed and satellite meteorological data, informing the trajectory and intensification/weakening of the meteorological systems for a 24-hour horizon.

Additionally, the results of this prediction should be used in conjunction with the CMV algorithm in a direct application to solve the radiative transfer equation in multiple scattering condition in the presence of clouds. From the identification of the clouds and the forecast of their displacement, resulting from the previous products, it is possible to calculate the amount of solar energy that reaches the surface. The optical, micro- and macro-physical characteristics of the clouds should be derived from satellite observations and/or results of a NWP model, and a radiative transfer model should be used, considering different methodologies and/or parameterizations, such as the 2-streams method. The final product includes the assessment of the employability of radiative transfer models to obtain the solar energy that reaches on the surface, in addition to a system that detects the variations of meteorological systems in the region. It is also necessary to provide a report with the description of the methodology used.

#### *6.2.2.3 Product 24: Surface solar irradiation forecast model*

This product consists of the development of a model to predict solar irradiation considering the effects of cloudiness. The model must combine the cloudiness information, provided in the scope of Product 22, with radiation forecasts considering a clear sky. Meteorological variables, such as wind, humidity, temperature, cloud cover, etc. obtained from NWP models, such as the WRF model, can be used to support the attenuation calculation of solar radiation reaching the surface. The model created may also be based on machine learning techniques and/or computational intelligence, which are capable of concatenating all available information. Moreover, wind data obtained from the NWP models should be used to evaluate the impact of cloudiness, as well as its performance in wind power forecast models.

Finally, the contracted institution must deliver a report describing the methodology used to develop the model, in addition to the results and evaluations obtained.

### *6.2.3 Phase 3 – Development of the Solar Photovoltaic Power Forecast Model for Real Time*

The power forecast model for real time operation should provide forecasts for up to twenty-four hours ahead and may or may not be coupled to the forecast model for very short- and short-term planning. In case of coupling with the very short-term model, for use in Real Time operation, it is desirable for the model to make a division into two distinct horizons for twenty-four hours ahead.

The temporal discretization of the predictions can begin with a few minutes, but should end in 30 minutes. Thus, the operation for the following hours would have forecasts that capture the effects of the ramps on solar photovoltaic power generation, while for more distant times ahead a coarser temporal resolution would have the advantage of not needing to manipulate very large files. During the development of this product such definitions can be made more flexible, if it is proven that the advantages of this approach are not significant or do not meet the purpose of the product.

Below is presented the description of the products to be delivered at this phase.

#### *6.2.3.1 Product 25: Evolution of the short and short-term planning model algorithms (Stage 1) to obtain power generation data in real time*

For this product, the contracted institution must evaluate the construction of a forecast model for real time having as a starting point the forecast model of solar photovoltaic power generation for very short- and short-term planning. Thus, it is expected the development of a model to for real time based on the forecasts for very short- and short-term planning: 1st forecasts per minute up to 10 minutes ahead; 2nd forecast for few hours ahead, discretized at intervals of ten minutes or less; and 3rd from a given hour ahead, the following forecasts will have a time interval of thirty minutes, considering the observed power generation of the last half hour. The discretization and moment of transition of each discretization can be changed, once its benefits have been demonstrated.

It is noteworthy that the validation of this product will take place in the ONS environment, considering all photovoltaic plants supervised by ONS, since the historical data were consolidated in stage 1.

In addition, the use of cloud coverage indexes and cloud characteristics, performance and cost-benefit ratio of this and other inputs considered for this model should be evaluated.

For this product, the source code must be delivered in the language in which it was developed. Moreover, it is expected the description of the flow and execution of the forecast process in the ONS environment, the methodology and models used, whole documented, and the user manual with the description of the input, process and output data. Sufficient technical training should be provided for the reproduction of the model in the ONS.

#### 6.2.3.2 Product 26: Report with evaluation of performance and cost x benefit of the inputs used to evolve these models

This product consists of the availability of a report containing:

I. Performance evaluation of the forecasts obtained with the developed models;

II. It may be that for some variables considered important, forecasts need to be purchased by ONS for the forecasting operational process, such as that of the European Centre for Medium-Range Forecasts (ECMWF). In these cases, the cost-benefit ratio of the use of different meteorological variables, including cloud coverage indexes, as well as solar radiation on the surface and wind, should be evaluated.

#### 6.2.3.3 Product 27: First version of the Solar Photovoltaic Power Forecast Model for Real Time: documentation and results

The contracted institution must deliver the final version of the Solar Photovoltaic Power Forecast Model for Real Time containing:

I. Model source code;

II. Documentation of the methodology;

III. Model execution manual, including description of the input and output files;

IV. Presentation of the Solar Photovoltaic Power Forecast Model for Real Time.

The codes and their documentation will be made available to all society.

### 6.2.4 Phase 4– Operationalization of the Solar Photovoltaic Power Forecast Model for Real Time in the ONS environment

At this phase, the prototype of the generation forecast model should become operational in order to consider all photovoltaic plants supervised by ONS. The Operator will monitor the performance of the forecasts for a minimum period of 180 days, and part of this period should include months of the year of greater variability in photovoltaic energy production.

#### 6.2.4.1 Product 28: Documentation of the Solar Photovoltaic Power Forecast Model for Real Time in the ONS environment

The contracted company must build the operational process of the forecasts with the ONS systems, respecting some basic specifications to allow the maintenance of the process by the ONS. Therefore, the product must describe the process flow being properly documented and delivered to ONS within the agreed period.

#### 6.2.4.2 Product 29: Validation of the forecasting process for real time and delivery of the documentation and source code of the model

Validation of the forecasting process for real time considering the data of ten pre-selected photovoltaic plants. In case of inconsistency in the process, the model should be reviewed and adjusted. After the interactions between the ONS and the contracted institution, the final version of the code, as well as the general documentation (report, manual) of the model must be delivered.

#### 6.2.4.3 Product 30: Operationalization of the execution process of the Solar Photovoltaic Power Forecast Model for Real Time in the ONS environment and User Manual

The process must be operationalized in the ONS environment for executions every half hour considering the existing structure and a minimum number of ten photovoltaic plants. The contracted institution must monitor the execution in the ONS environment for a minimum period of 02 (two) weeks. The responsible institution must also provide a model execution manual for users. As required for Product 13, the operationalization process of this power forecast model should also be done *in-loco,* at the Operator, with the participation of the ONS technical team that should receive the necessary training.

## 7 EXECUTION TERM/SCHEDULE

Given that the photovoltaic solar forecasting project will be divided into two stages, the following schedule will treat each of them independently.

The deadlines are defined in calendar days and the period of some partial products can be executed in parallel. The total contract period counting the two stages must be 24 months.

### 7.1 Stage 1 – Development of the photovoltaic forecasting model for very short and short-term planning

Stage 1, which refers to the solar photovoltaic power forecasting model for very short- and short-term planning, is divided into 3 phases. A phase for proof of concept, in order to verify the possibilities, the existing mathematical models, concepts and theories that have potential for the prediction of solar photovoltaic power generation. In this phase, one or more predictive models will be chosen, which best fit the theme, as well as the creation of a first prototype. Table 1 illustrates the schedule of activities to be developed in this first phase of the project. For all products, the form of payment in installments is being considered, according to the specificity of each product. The number of deliveries is described in the "Deliveries" column of Table 1, and each delivery must occur at the end of the period allocated to it, calculated by the ratio of the total time of the product to the quantity of deliveries. For example, for Product 1 a partial report must be delivered at the end of the 2nd month (containing all developments and research within these two months), another partial report at the end of the 4th month (containing only developments and research within these two months), and in the 6th month a final report (containing everything that was performed within the first 6 months). It is worth noting that the final delivery should comprise all partial deliveries, however, there may be separate documents, since not all research items during the development of the product can be used at the end of it.

**Table 1: Schedule of activities (STAGE 1 – Phase 1 Proof of concept).**

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| Product | Type | Description | Deliveries | | |
| 1 | Analysis and report | Report with analysis of variables and requirements and measuring instruments | 2 partial reports + Final report | 6 months | 5% in 3 installments |
| 2 | Studies and development | Development of forecasting models and reports with description of mathematical models | Quarterly development codes and reports | 18 months | 18% in 6 installments |

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| Product | Type | Description | Deliveries | | |
| 3 | Report | Report with description of the mathematical models proposed for the solar photovoltaic power forecast | Partial report + Final report | 5 months | 5% in 2 installmen ts |
| 4 | Code development and delivery | Prototype of the 1st version of the Solar Photovoltaic Power Forecast Model (very short- and short-term) and Manual | Monthly reports containing development status and/or codes, with detailed documentation and execution manual + Development presentations + Training at the end | 5 months | 5% in 5 installmen ts |
| 5 | Report | Report with parameter adjustments as required by the model | Final Report | 2 months | 2% in 1 installmen t |
| 6 | Report | Forecast model performance and sensitivity report | Final Report | 1 month | 1% in 1 installmen t |
| 7 | Code, documentation and presentation of the model | Documentation and presentation of mathematical models and source code of model algorithms | Source code of all developed algorithms, with detailed documentation + Presentation of the adopted models. | 2 months | 2% in 1 installmen t |

Phase 2 of stage 1 of the project refers to the application of the first prototype, with the suitability for compatible temporal and spatial scales. Subsequently, an adjustment for operational scale must be made with optimization and validation for the selected photovoltaic solar plants. Table 2 describes the main activities of this phase of the project.

**Table 2: Schedule of activities (STAGE 1 – Phase 2 Scales, optimization and validation of the predictor)**

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| **Product** | **Type** | **Description** | **Deliveries** | | |
| 8 | Code | Processing chain´s code, fault treatment, process flow and updated execution manual | 1 partial report + source code for execution of the entire process, with detailed documentation and execution manual + Development presentations at the end | 2 months | 2% in 2 installments |
| 9 | Validation | Consolidated and validated history for a plant, from a set of 10 plants | History of consolidated data, with a report containing a description of the techniques and methodologies used. | 1 month | 1% in 1 installment |
| 10 | Validation | Validation of execution process´ model for a plant, in the ONS environment | Final Report | 2 months | 2% in 1 installment |
| 11 | Validation | Consolidated and validated history of the 10 plants | History of consolidated data. | 2 months | 2% in 1 installment |
| 12 | Validation | Validation of execution process´ model for the 10 plants, in the ONS environment | Final Report | 1 month | 1% in 1 installment |

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| **Product** | **Type** | **Description** | **Deliveries** | | |
| 13 | Operationalization of the prototype | Operationalization of the process of execution of the Solar Photovoltaic Power Forecast Model Prototype (very short- and short-term) in the ONS environment, for the 10 selected plants | Installation, execution and operationalization of the model in ONS + Training + Support | 1 month | 1% in 1 installment |

In phase 3, the last phase of stage 1 of the project, the activities related to the implementation of the developed product will be outlined. Table 2 illustrates the main activities of this phase.

**Table 3: Schedule of activities (STAGE 1 – Phase 3 Application of the forecast model to the ONS system)**

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| **Product** | **Type** | **Description** | **Deliveries** | | |
| 14 | Studies and development | Evaluation and improvement of forecasting algorithms | 2 partial reports + Final report + codes when necessary | 6 months | 5% in 3 installments |
| 15 | Development | Prototype of the 1st version of the cloud coverage correction tool | 1 partial report + codes, with detailed documentation and execution manual + Final report | 2 months | 2% in 2 installments |
| 16 | Report | Comparison report, forecast evaluation and list of meteorological variables | Final Report | 1 month | 1% in 1 installment |

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| Product | Type | Description | Deliveries | | |
| 17 | Code delivery | Delivery of the final version of the Solar Photovoltaic Power Forecast Model (very short- and short-term) | Model source code, with detailed documentation and execution manual + Final presentation | 1 month | 1% in 1 installment |
| 18 | Operationalization of the model | Operationalization of the Solar Photovoltaic Power Forecast Model (very short- and short-term) | Installation, execution and operationalization of the model in ONS + Support | 6 months | 2% in 2 installments |
| 19 | Report | Report with assessment of challenges, responsibilities and management solutions related to the intermittence of renewable sources | Partial report + Final report | 6 months | 6% in 2 installments |

### *7.2 Stage 2 – Development of the photovoltaic forecast model for Real Time*

Stage 2 is regard to the development of the solar photovoltaic power forecasting model for Real Time, and it is divided into four phases. Table 4 represents the schedule of activities required in the first phase of this stage, which deals with the construction of the system, information collection, evaluation and processing of satellite images.

**Table 4: Schedule of activities (STAGE 2 – Phase 1 Development of the satellite image collection and quality control system)**

| **Expected Product** | | | | **Duration** | **% of contract value** |
|---|---|---|---|---|---|
| **Product** | **Type** | **Description** | **Deliveries** | | |
| 20 | Development | Satellite and/or sensor image acquisition and quality control system | System source code, with detailed documentation and execution manual + Final presentation | 3 months | 3% in 1 installment |
| 21 | Study and development | Study, identification and vectorization model for cloud fields | Final Report | 3 months | 3% in 1 installment |

Phase 2 is the most important phase of stage 2. In this phase, the main algorithm of the Real Time predictor, called cloud motion vector, will be built. Table 5 details the main activities of this phase.

**Table 5: Schedule of activities (STAGE 2 – Phase 2 Development of the *cloud motion vector algorithm*)**

| **Expected Product** | | | | **Duration** | **% of contract value** |
|---|---|---|---|---|---|
| **Product** | **Type** | **Description** | **Deliveries** | | |
| 22 | Development | Cloud motion detection system (pixels) | System source code, with detailed documentation and execution manual + Partial report + Final report | 5 months | 5% in 2 installments |

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| Product | Type | Description | Deliveries | | |
| 23 | Development | Assessment of meteorological conditions and applicability of a radiative transfer model under multiple scattering conditions in the presence of clouds | Source code(s) of the developed system(s)/model(s), with detailed documentation and execution manual + 2 partial reports + Final report | 6 months | 6% in 3 installments |
| 24 | Development | Solar radiation prediction model on the surface | Source code of the developed model, with detailed documentation and execution manual + Partial report + Final report | 6 months | 6% in 2 installments |

In phase 3 of stage 2, the development of the Real Time forecasting model should be carried out, based on the model used in the very short- and short-term planning, previous studies and the cloud motion vector algorithm. Table 6 specifies the main activities that should be developed.

**Table 6: Schedule of activities (STAGE 2 – Phase 3 Elaboration of the forecast model for Real Time)**

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| Product | Type | Description | Deliveries | | |
| 25 | Development | Evolution of the model algorithms of the very short- and short-term planning (Stage 1) to obtain power generation data in real time | Partial report + source code, with detailed documentation and execution manual + Training | 3 months | 3% in 2 installments |

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| **Product** | **Type** | **Description** | **Deliveries** | | |
| 26 | Report | Report with evaluation of performance and cost x benefit of the inputs used to evolve these models | Final Report | 2 months | 2% in 1 installment |
| 27 | Development | First version of the Solar Photovoltaic Power Forecast Model for Real Time: documentation and results | Partial report + template source code, with detailed documentation and execution manual + Final presentation | 3 months | 3% in 2 installments |

Phase 4 of Stage 2 is explained in Table 7. At this stage the model will be deployed operationally to the ONS system, being validated and operationalized.

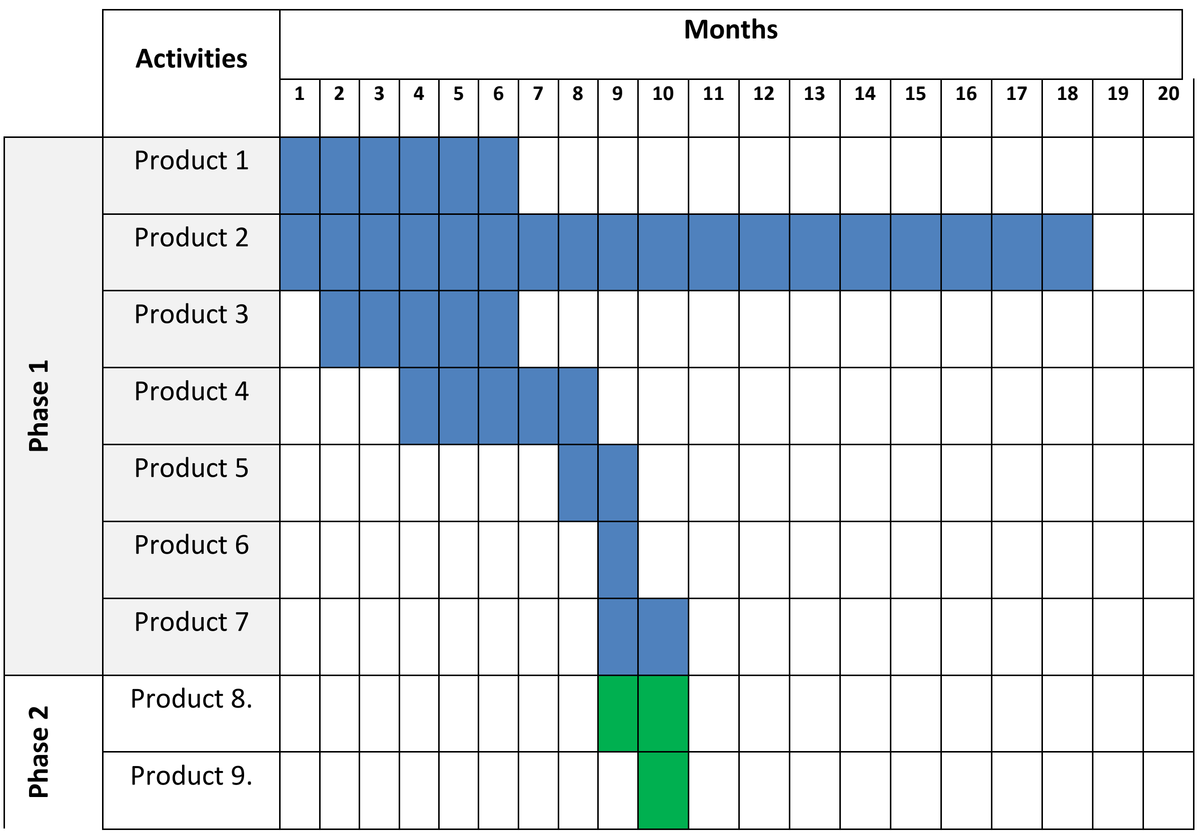
**Table 7: Schedule of activities (STAGE 2 – Phase 4 Application of the forecast model to the ONS system)**

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| **Product** | **Type** | **Description** | **Deliveries** | | |
| 28 | Report | Documentation of the Solar Photovoltaic Power Forecast Model for Real Time in the ONS environment | Final Report | 2 months | 2% in 1 installment |
| 29 | Validation | Validation of the forecasting process for real time and delivery of the model's documentation and source code | Template source code, with detailed documentation and execution manual + Final report | 2 months | 2% in 1 installment |

| Expected Product | | | | Duration | % of contract value |
|---|---|---|---|---|---|
| Product | Type | Description | Deliveries | | |
| 30 | Operationalization of the model | Operationalization of the execution process of the Solar Photovoltaic Power Forecast Model for Real Time in the ONS environment and User Manual | Installation, execution and operationalization of the model in ONS + Training + Support | 2 months | 1% in 2 installments |

Table 8 shows the start and end months, approximately, of each activity in the schedule of the solar photovoltaic power forecast model for very short- and short-term planning.

**Table 8: Schedule of activities of the photovoltaic forecasting model for very short- and short-term planning**



| | Activities | Months | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| | Product 10. | | | | | | | | | | | | | | | | | | | | |
| | Product 11. | | | | | | | | | | | | | | | | | | | | |
| | Product 12 | | | | | | | | | | | | | | | | | | | | |
| | Product 13 | | | | | | | | | | | | | | | | | | | | |
| Phase 3 | Product 14 | | | | | | | | | | | | | | | | | | | | |
| | Product 15 | | | | | | | | | | | | | | | | | | | | |
| | Product 16 | | | | | | | | | | | | | | | | | | | | |
| | Product 17 | | | | | | | | | | | | | | | | | | | | |
| | Product 18 | | | | | | | | | | | | | | | | | | | | |
| | Product 19 | | | | | | | | | | | | | | | | | | | | |

Table 9 displays the schedule of activities of the solar photovoltaic power forecast model for Real Time.

**Table 9: Schedule of activities of the photovoltaic forecast model for Real Time**

| | Activities | Months | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Phase 1 | Product 20 | | | | | | | | | | |
| | Product 21 | | | | | | | | | | |
| Phase 2 | Product 22 | | | | | | | | | | |
| | Product 23 | | | | | | | | | | |

| | Activities | Months | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| | Product 24 | | | ■ | ■ | ■ | ■ | ■ | ■ | | |
| Phase 3 | Product 25 | | | | | ■ | ■ | ■ | | | |
| | Product 26 | | | | | | | ■ | ■ | | |
| | Product 27 | | | | | | | ■ | ■ | ■ | |
| Phase 4 | Product 28 | | | | | | | | | ■ | ■ |
| | Product 29 | | | | | | | | | ■ | ■ |
| | Product 30 | | | | | | | | | ■ | ■ |

## *8 TEAM QUALIFICATION AND SPECIFICATION*

The contracted institution must have a multidisciplinary team, consisting of technical profiles that are in accordance with the characteristics and needs of this project. In general, the institution should have a project manager and the professionals essential to meet the objective of this ToR.

The ONS technical team should actively participate in the project, and can support the development, since it already has some knowledge on the topics covered and can provide the necessary support for better progress of the project.

### *8.1 Key Team*

**Meteorologist / Physicist (Specialist, PhD):** Higher level in Physics or Meteorology with postgraduate, master's or doctoral degrees in areas related to the products of this project. It is necessary at least 10 years of experience in research, studies and developments related to the scope of the project, and fluency in English.

**Engineer:** Higher level in Electrical Engineering, Civil Engineering, with master's and/or doctorate in areas related to the products of this project. It is necessary experience of, at least, 10 years in research, studies and developments related to the electricity sector, power from intermittent sources, solar photovoltaic power. Desirable fluent English.

**Computer Scientist:** Higher level in Computer Engineering, Computer Science, Information Technology or Mathematics, with postgraduate, master's and/or doctoral degrees in areas related to the products of this project. It is required experience of, at least, 8 years in machine learning techniques, artificial intelligence, neural networks, programming languages focused on forecasting models, construction of tools for data processing, processes, studies and development of programs related to the scope of the project.

**Mathematician/ Statistician:** Higher level in Mathematics or Statistics, with postgraduate, master's and/or doctoral degrees in areas related to the products of this project. A minimum experience of 8 years in development, studies, research related to forecasting models, mathematics and/or statistics, data processing is required. Desirable knowledge in optimization, machine learning techniques, neural networks and fluency in English.

**Project Manager:** Higher level professional, master's and/or doctorate in the area of IT, Engineering, Administration or related areas, with a minimum experience of 10 years in project management aligned with the good practices of PMBOK® 6 or 7. Necessary fluency in English and Brazilian Portuguese, leadership skills of multidisciplinary teams, mediation of interests and communication. Some knowledge related to the electricity sector is desirable.

**Technical Coordinator:** Higher level in Engineering, Meteorology, Computer Science, Mathematics or Physics with postgraduate degree in related areas of this project. Minimum experience of 5 years in research related to the products of this project, as well as the energy sector. Acting as coordinator of multidisciplinary teams and monitoring of projects. Fluency in English and Brazilian Portuguese is required.

### *8.2 Characteristics of the team*

It is desirable that the technical team is formed by professionals with knowledge and experience in the following subjects: image processing, computer intelligence, artificial intelligence, multivariate statistical methods, photovoltaic solar energy, data processing methods and methodologies, prediction models, advanced programming in languages, such as: R, PHYTON, JULIA, among other languages aimed at data analysis and prediction models, machine learning, artificial intelligence, NWP models and in models of atmospheric phenomena, besides mathematical modeling for prediction.

The team should be able to develop and implement existing time series forecasting models to evaluate performance and propose new methods; artificial intelligence, machine learning models, computational modeling and process flow creation to meet the scope of this project.

It is also expected that the consultant's team to be composed by professionals at the junior, intermediate, senior and specialist levels. In addition, if the contractor identifies the need for a professional with a profile different from that described, it will be up to them to define and quantify the profile of this professional. Furthermore, the number of professionals who should compose the key team will be defined by the contractor, according to the need of the project.

### *8.3 Consultant's Required Profile*

In order to carry out the projects, the contractor must prove:

I. Minimum experience of 5 years in work related to the electricity sector and intermittent sources, mainly solar photovoltaic power generation;

II. Experience with the development and application of NWP models, technological solutions and technical consulting services in the electricity sector;

III. Experience in studies and development of methodologies for forecasting meteorological variables and solar power forecasting;

IV. Experience in meteorological data analysis;

V. Experiences in artificial intelligence and machine learning techniques;

VI. Experience in image processing technologies, and satellite data;

VII. Experience in project management;

VIII. Knowledge in forecasting models involving meteorological variables, national and/or international competence in photovoltaic energy.

## *9 FORM OF PRESENTATION OF THE PRODUCTS*

The products must be delivered in Portuguese, in the form of reports, in electronic form, according to the following format:

I. Texts: MS Word® version 2013 or later, with delivery of .doc;

II. Spreadsheets, Graphs and Tables: MS Excel® version 2013 or later;

III. Figures in general: JPG, GIF or BMP;

IV. Presentations: MS PowerPoint® version 2013 or later;

V. Products in the form of Reports must present the appropriate logos, to be inserted in the following order: ONS, META Project, World Bank and MME/Federal Government;

VI. Any electronic spreadsheets developed must be delivered unlocked and without editing restriction;

VII. Computer programs, mathematical models, forecast models developed or evaluated to compose this project must be delivered with the documented source code, technical notes and user manual.

Initially, the computational tools used in this work should be those currently used by ONS. If the need to use any tool that requires the acquisition of a license by ONS is identified, it must be informed and agreed upon in advance.

The products from this project will be owned by ONS, and may, in due time, be made available to the electricity sector.

In the products/reports, in addition to the aforementioned logos, the following information must be recorded: Research/Product/Work performed with funds from the Loan Agreement No. 9074-BR, formalized between the Federative Republic of Brazil and the International Bank for Reconstruction and Development – IBRD, on July 21, 2021.

## *10 PAYMENT METHODS*

The percentage estimate of the total value of the Contract for each product is contained in Item 8 of this document. The forms of payment, as well as the deadlines for delivery and approval of the products, will be linked to the Draft Contract, an instrument that is an integral part of the Bidding Notice Instrument.

## *11 SUPERVISION*

The beginning of the work object of this ToR, as well as the presentation of the planned products, must be preceded by a meeting with the ONS technical team for general guidance of the process and monitoring of the consultancy.

Given that ONS will actively participate in the project development stages, the ideal is that the construction is done following the phases described in item 8, with intermediate deliveries of the products described in each phase. The ONS will have up to 15 (fifteen) days after the delivery date of each product, to validate it. After validation, the formal acceptance will be issued by the technical team designated by the ONS.

## *12 AVAILABLE INPUTS AND ELEMENTS*

The ONS will provide the contracted institution with the information necessary for the development of the project, however, confidentiality agreements must be drafted regarding the data that will be used. It should be noted that not all data necessary for the project can be obtained in ONS, so it is up to the contractor to list the sources for obtaining these data.

The ONS will provide, whenever necessary, the appropriate physical environment to enable scheduled work meetings between the parties in their offices in Brasilia or Rio de Janeiro, or virtually, if the condition of removal due to COVID-19 is maintained.

## *13 NEED FOR TRAINING*

In item 7 that describes the scope of work and the limits of the project, the training for each stage/phase is already described.

## *14 THE WORLD BANK'S ENVIRONMENTAL AND SOCIAL FRAMEWORK*

All activities supported by the project, including studies to propose policies and regulations should be analyzed in accordance with the World Bank's Environmental and Social Standards, which establish the guidelines for identifying, evaluating, mitigating and managing potential risks and impacts associated with projects financed by the Bank.

The adoption of Environmental and Social Standards aims to support borrowers in the adoption of international best practices related to environmental and social sustainability, fulfilling their national and international environmental and social obligations, as well as increasing non-discrimination, transparency, participation, accountability, governance and improvement of sustainable development results of projects through continuous engagement of stakeholders. In addition to the World Bank's Environmental and Social Framework, the World Bank Group's Health, Safety and Environment Guidelines (IFC-EHSGs) will be observed, including specific guidelines for the mineral, electrical and oil and gas sectors.

The preparation of the work should consider the World Bank 's Environmental and Social Framework, which came into force since October 1, 2018, assessing the potential social and environmental impacts of the subprojects, when necessary. In Subproject 24 in question, the most relevant standard is the Environmental and Social Standard 2 - Working Conditions and Labor of the team that will perform the studies.

## *15 INSTITUTIONAL AND ORGANIZATIONAL ARRANGEMENTS*

The management of Subproject 24 will be carried out by organizational structures linked to the Ministry of Mines and Energy (MME) and the National Electric System Operator (ONS), as determined by the Project Operational Manual – MOP, which can be consulted on the MME website www.mme.gov.br.

In the MME, the management will be the responsibility of the Project Management Committee (CGP) and the Central Project Management Unit (UGP/C).

In ONS, the management will be the responsibility of the Sectorial Project Management Unit (UGP/S), as schematically presented in Figure 1.

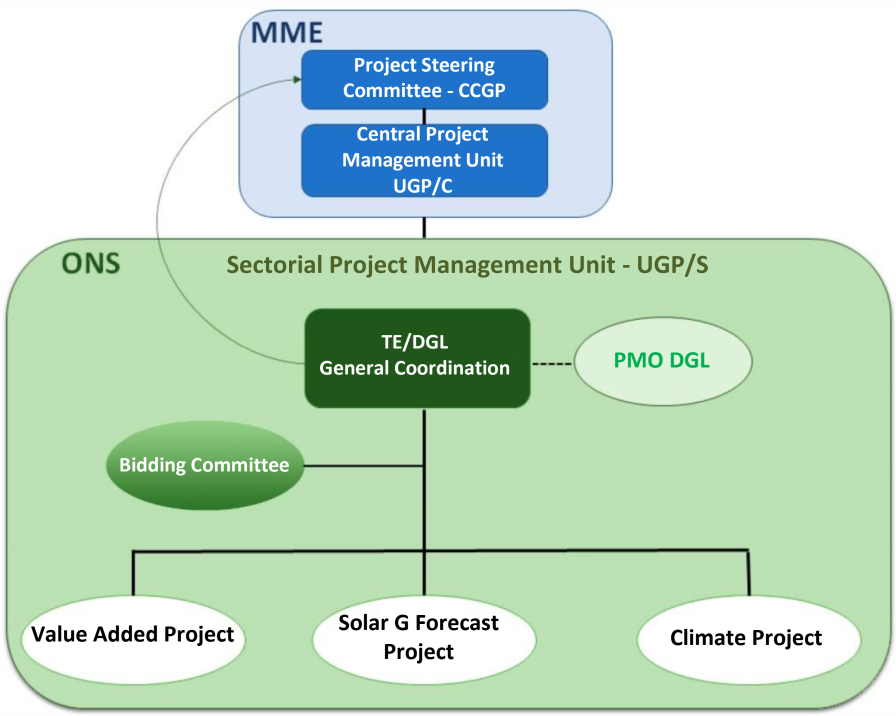



**Figure 1 Functional structure of the ONS Sectorial Project Management Unit – UGP/S**

**Table 10 ONS UGP/S Formation**

| UGP/S | Management |
|---|---|
| **General Coordination** | Strategic Transformation Senior Management |
| **DGL Project Office** | Strategic Transformation Senior Management |
| **Bidding Committee** | Financial Senior Management |
| | Legal Senior Management |
| | Water Resources and Meteorology Management |
| | Methodologies and Energetic Models Management |
| | Calculation, Analysis and Costs of the Operation Senior Management |

| | |
|---|---|
| | Supply Senior Management |
| **Solar Project(*)** | Methodologies and Energetic Models Management |

(*) Solar Project is the short name of Subproject 24 within ONS

## *16 LIST OF REIMBURSABLE EXPENSES*

Reimbursable expenses are applied to products 13 and 30, corresponding to travel and daily expenses for implementing the models in the ONS environment, as well as training the Operator's technical team.

## *17 LEGAL INTERDICTION*

It is forbidden to hire, in any capacity, active employees of the Federal, State, Federal or Municipal Public Administration, directly or indirectly, as well as employees of its subsidiaries and controlled companies, within the scope of international technical cooperation projects. Art. 7 of Dec. 5.151 of 07.22.2004.

## *18 TECHNICIANS RESPONSIBLE*

**Name:** Paulo Sérgio De Castro Nascimento
**Body:** Methodologies and Energetic Models Management - Operation Planning Board

**Signature:**

**Name:** William Cossich Marcial de Farias
**Body:** Methodologies and Energetic Models Management - Operation Planning Board

**Signature:**

## *19 APPROVAL*

**Name:** Maria Aparecida Martinez
**Position:** Senior Manager of Energy Planning

**Signature:**

## *20 REFERENCES*


Ailliot, P. &. (2021). Markov-switching autoregressive models for wind time series. *Environmental Modelling & Software*.

Arrieta-Prieto, M. &. (2022). Spatio-temporal probabilistic forecasting of wind power for multiple farms: A copula-based hybrid model.

Browell, J. D. (2018). Improved very short-term spatio-temporal wind forecasting using atmospheric regimes.

Chen, H., Birkelund, Y., & Zhang, Q. (2021). Data-augmented sequential deep learning for wind power forecasting. *Energy Conversion and Management*, v. 248, p. 114790.

Croonenbroeck, C. &. (2015). Censored spatial wind power prediction with random effects.

Fawcett, L. &. (2006). A hierarchical model for extreme wind speeds.

Gilbert, C. B. (2019). Leveraging turbine-level data for improved probabilistic wind power forecasting.

Grönquist, P. Y.-N. (2021). Deep learning for post-processing ensemble weather forecasts. *Philosophical Transactions of the Royal Society*.

Hao, Y., & Tian, C. (2019). A novel two-stage forecasting model based on error factor and ensemble method for multi-step wind power forecasting. *Applied Energy, v. 238, ed. 107941*.

Hering, A. S. (2015). A Markov-switching vector autoregressive stochastic wind generator for multiple spatial and temporal scales.

Huang, Y. Z. (2022). Spatio-temporal wind speed prediction based on Clayton Copula function with deep learning fusion.

Jiandong, D. e. (2021). Short-term wind power forecasting using the hybrid model of improved variational mode decomposition and Correntropy Long Short -term memory neural network. *Energy, v. 214, ed. 118980, 1 dec. 2021*.

Kang, K. H. (2014). Estimation of state-space models with endogenous Markov regime-switching parameters.

Liu, H., & Duan, Z. (2021). Corrected multi-resolution ensemble model for wind power forecasting with real-time decomposition and Bivariate Kernel density estimation. *Energy Conversion and Management, v. 113, ed. 107941*.

Maurer, L., Doyle, P., Hyman, E., Loretta, B., & Torres, P. (2020). *Creating a Level Playing Field for Battery Energy Storage Systems Through Policies, Regulations, and Renewable Energy Auctions*.

Möller, A. S. (2018). Vine copula based post-processing of ensemble forecasts for temperature.

Robertson, D., Shrestha, D. L., & Wang, Q. (2016). Post-Processing Ensemble Precipitation Forecasts Using Geometric Model Combination.

Tastu, J. P. (2011). Spatio-temporal analysis and modeling of short-term wind power forecast errors.

Tateo, A. M. (2019). A statistical method based on the ensemble probability density function for the prediction of "Wind Days".

Wang, J. e. (2021). A regional pretraining-classification-selection forecasting system for wind power point forecasting and interval forecasting. *Applied Soft Computing, v. 113, ed. 107941*.

Yildiz, C., Acikgoz, H., Korkmaz, D., & Budak, U. (2021). An improved residual-based convolutional neural network for very short-term wind power forecasting. *Energy Conversion and Management, v. 228, p. 113731*.

Zhang, N. K. (2013). Modelling and simulating the spatio-temporal correlations of clustered wind power using copula.