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Comité de Operación Económica del Sistema Interconectado Nacional

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Solar and Wind Power Forecasting in Peru Outcomes of a Pilot Project with the National System Operator COES

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energy & meteo systems is an internationally leading provider of sophisticated IT solutions (solar and wind power forecasts, Virtual Power Plants, redispatch platform) for an efficient integration of distributed energy resources into power systems. With its consulting services the German-based company shares its in-depth energy transition expertise on a global level.

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Abbreviations

API	Application Programming Interface
COES	Comité de Opéracion Económica del Sistema Interconectado Nacional (Economic Operation Committee of the National Interconnected System, TSO of Peru)
emsys	energy & meteo systems
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Agency for International Co-operation)
GUI	Graphical User Interface
GW	Gigawatt
MAE	Mean Absolute Error
MINEM	Ministerio de Energía y Minas (Ministry of Energy and Mines)
MW	Megawatt
NWP	Numerical Weather Prediction
PV	Photovoltaic
RMSE	Root Mean Squared Error
SEIN	Sistema Eléctrico Interconectado Nacional (National Interconnected System of Peru)
TSO	Transmission System Operator
vRE	variable renewable energies

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1 Introduction

The Comité de Operación Económica del Sistema (COES), Peru's national power system operator, is aiming to prepare the power system in Peru to adapt to higher shares of variable renewable energy (vRE).

Peru has set the target to increase its non-conventional renewable share (including wind and solar) from 5%[1] to at least 20%[2] by 2030. With the expected rise in vRE shares and installed capacities over the coming years, reliable power forecasts are becoming indispensable.

A previous study[3] analysed the existing vRE forecasting framework in Peru and offered recommendations for improvement. This analysis considered technical operational processes, regulatory frameworks, and historical forecast and measurement data, culminating in twelve specific recommendations to improve national power forecasting, particularly for solar and wind power plants.

One of the key recommendations was to implement a centralised forecasting system. Previously, COES used a decentralised approach, relying solely on predictions from plant operators. A backcast comparison between historic decentralised forecasts from plant operators and centralised forecasts provided by specialised consultants supported the move to a centralised system, demonstrating substantial potential for improving the accuracy and reliability of solar and wind power forecasts in Peru.

In response, COES, in collaboration with GET.transform, commissioned energy & meteo systems (emsys) to provide centralised forecasting services through a pilot project. This service was supported by ongoing consultancy and regular reporting to COES. For eleven months, from February 2023 to December 2023, vRE power forecasts were provided for all large solar and wind power plants in Peru.

The primary goal of this pilot project was to demonstrate that higher levels of accuracy in operational power forecasting is achievable within the Peruvian context. This was achieved by benchmarking the centralised forecasts from the pilot project against those provided by the individual solar and wind plant operators. COES's active participation as the system operator was crucial to the project's success.

[1] Legislative Decree 1002 (2008), the 5% of renewable energies does not include hydropower > 20MW
[2] Supreme Decree N° 003-2022-MINAM (2022), the Ministry of the Environment set a target of 20% by 2030
[3] The Executive Summary of the report is available for download under the following link: https://www.get-transform.eu/wp-content/uploads/2023/11/GET.transform-Improving-vRE-Forecasting-Peru-ExecSum.pdf

This report compiles the results and findings of the solar and wind power forecasting pilot. It details the inception phase for setting up power forecasts, highlights specific operational challenges during the project period, and presents thorough comparison of forecast accuracy between the centralised system and plant operators. The final chapter discusses the value of centralised power predictions from COES´ perspective as a system user.

2 Inception phase of the forecasting pilot

2.1 Forecasted solar and wind power plants

Peru´s power supply is largely dominated by conventional generators, mainly hydro power and gas-fired plants. At the beginning of the forecasting pilot, 7 large solar power and 7 large wind power plants were installed (between 18 MW and 144 MW), contributing around 5%[4] to the generation mix in the National Interconnected System (SEIN). Small-scale PV and wind power plants are not widespread and were therefore not considered in the forecasting pilot.

It was agreed that the forecasting pilot should cover all 14 wind and solar parks located in Peru. During the forecasting service two further wind parks were connected to the grid, Punta Lomitas I and Punta Lomitas II. The two neighbouring wind parks have a combined capacity of 260 MW, which expanded the installed wind power capacity in Peru by 66%, reaching 661,6 MW. Prior to starting the forecasting pilot, it was agreed to flexibly include new vRE plants during the project period, so the power forecasts started covering the additional wind parks from April 2023, increasing the total parks from 14 to 16. A list of the solar and wind parks covered is available in **TABLE 1**.

[4] 4.9% according to the operational annual data 2022 from COES

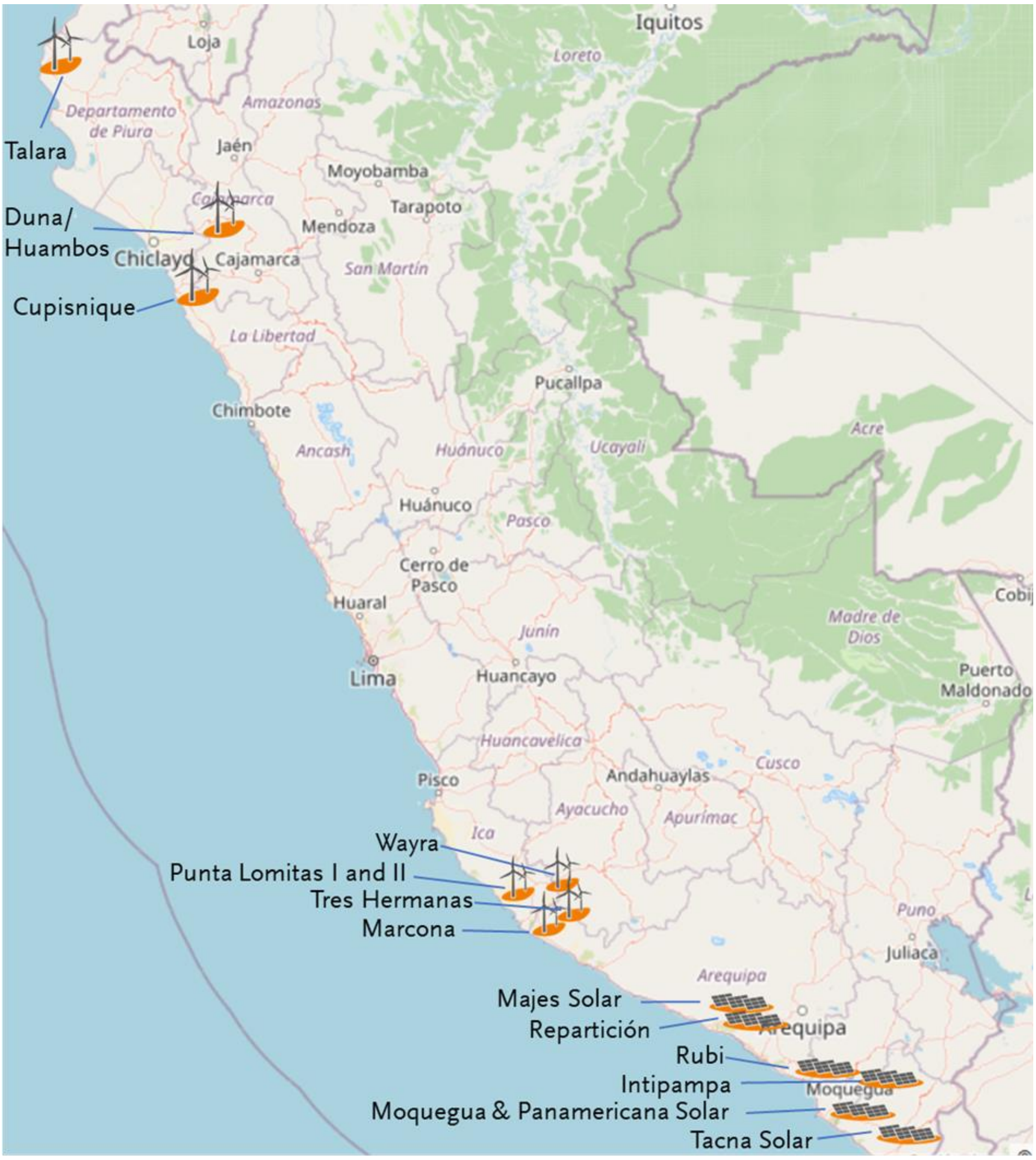
TABLE 1. Overview of solar PV and wind power plants in Peru included in the pilot

TECHNOLOGY	PROJECT	START OF OPERATION	INSTALLED CAPACITY (MW)
Wind	C. E. Marcona	2014	32.0
Wind	C. E. Cupisnique	2014	81.0
Wind	C. E. Talara	2014	30.6
Wind	C. E. Tres Hermanas	2016	90.0
Wind	C. E. Wayra I	2018	132.0
Wind	C. E. Duna	2021	18.0
Wind	C. E. Huambos	2021	18.0
Wind	C.E. Punta Lomitas I	2023	130.0
Wind	C.E. Punta Lomitas II	2023	130.0
Total Wind Capacity			661.6
Solar PV	C. S. Panamericana	2012	20.0
Solar PV	C. S. Majes	2012	20.0
Solar PV	C. S. Repartición	2012	20.0
Solar PV	C. S. Tacna	2012	20.0
Solar PV	C. S. Moquegua	2014	16.0
Solar PV	C. S. Rubí	2018	144.5
Solar PV	C. S. Intipampa	2018	40.0
Total Solar **PV** Capacity			280.5

The map presented in **FIGURE 1** gives an overview of the geographic location of the wind and solar power plants included in the pilot. The sites of the parks are relatively close to the Pacific coastline with good access to the national power network. All of the solar parks are located in the south of Peru where solar irradiation reaches the highest values in Peru. The wind parks are concentrated in the

Marcona area (Wayra, Punta Lomitas I and II, Tres Hermanas, Marcona) and in the north of the country (Talara, Duna, Huambos, Cupisnique).

FIGURE 1. Geographic distribution of solar and wind parks in Peru



Source: COES, Programa de obras de generación.
https://www.coes.org.pe/Portal/Planificacion/NuevosProyectos/Consultawebepo

2.2 Standing data and historic measurements

Different data sets are required to set up a vRE forecast. The standing data of the power plants to be forecasted are indispensable. They contain specific and usually unalterable technical information on a solar or wind power plant.

The following information is therefore required:

- Installed capacity
- Geographic location
- Park name / ID
- Manufacturer
- Curtailments (e.g., regular night curtailments in case of wind parks)

For each, wind and solar generators, additional technology-specific information is important:

- **Wind**: turbine type, rotor diameter, hub height;
- **Solar**: inverter capacity, tracking system or fixed mounting structure, inclination angle of modules.

To train the forecasting system:

- 15-minute resolution production data for a 12 month period, if available.

To improve the accuracy of a power forecast, the forecasting system can be trained with **historic production data** of the vRE plant. These historic measurements are time-series data which ideally cover at least one year of production. They provide valuable information on the production patterns of a solar and wind park, which can be correlated with weather models based on a machine-learning training process. The utilization of historic measurements raises the accuracy of solar and wind power forecasts from the first delivery, compared to an untrained power forecasting model. Fine resolution of historic measurements (at least 15-minute data) is ideal to achieve optimal training of the forecasting system. However, a 30-minute resolution can be also used if other data is not available.

All the required data was provided by COES to emsys, allowing for a timely implementation of the pilot project and optimal training of the forecasting system.

2.3 Configuration of power forecasts

Power forecasts can be customised to user specifications. The following configuration was specified and provided to COES:

- **Update frequency**: hourly
- **Resolution**: 30-minute resolution in line with COES´ operational schedule;
- **Forecast horizon**: next 10 days to cover COES´s weekly programming issued on Wednesday for the period from Saturday to Friday
- **Forecast aggregation level**:
  - Aggregated power forecast for all the wind parks
  - Aggregated power forecast for all the solar parks
  - Aggregated power forecast for 3 wind parks in Marcona (Marcona, Tres Hermanas, Wayra)
  - Aggregated power forecast for 4 wind parks in the North of Peru (Cupisnique, Duna, Huambos, Talara)

In addition, COES decided to use real-time production data feed from the solar and wind power plants for a short-term (intraday) correction of the weather-based power forecast. Taking into account live data from the plants in the forecasting process significantly improves the accuracy power forecasts for the next few hours of the forecast horizon, particularly in the very short-term range (up to three hours).

2.4 Automatic mutual data transfer

Implementing a power forecasting service requires an automatic, quick and reliable transmission of different kinds of data. During this pilot, data were exchanged through a secure sftp (secure file transfer protocol).

Data required and transmitted include:

- **Centralised solar and wind power forecasts**
- **Power forecasts from the plant operators** to verify their accuracy compared to the new forecasting system
- **Non-availabilities of power plants**, e.g. complete or partial plant outages due to maintenance work. For an accurate power forecast the forecasting model needs to know in advance about plant outages
- **Real-time production data**: In order to deliver improved short-term forecasts, real-time production data need to be transmitted instantaneously to the forecasting system. In this pilot, the forecasting system received production data with a delay of 45 minutes to 3

hours. Lower delays would lead to more accurate forecasting. To fully exploit the advantages of the short-term forecasting module, delays should be below 5 minutes. The impact of delayed data transfer on the accuracy of short-term forecasts and the potential improvement if real-time data had been available are presented in **section 3.7**.

- **Historic measurements** with 15-minute resolution from the previous day were sent daily to cover possible gaps in the continuous data feed due to communication failures.

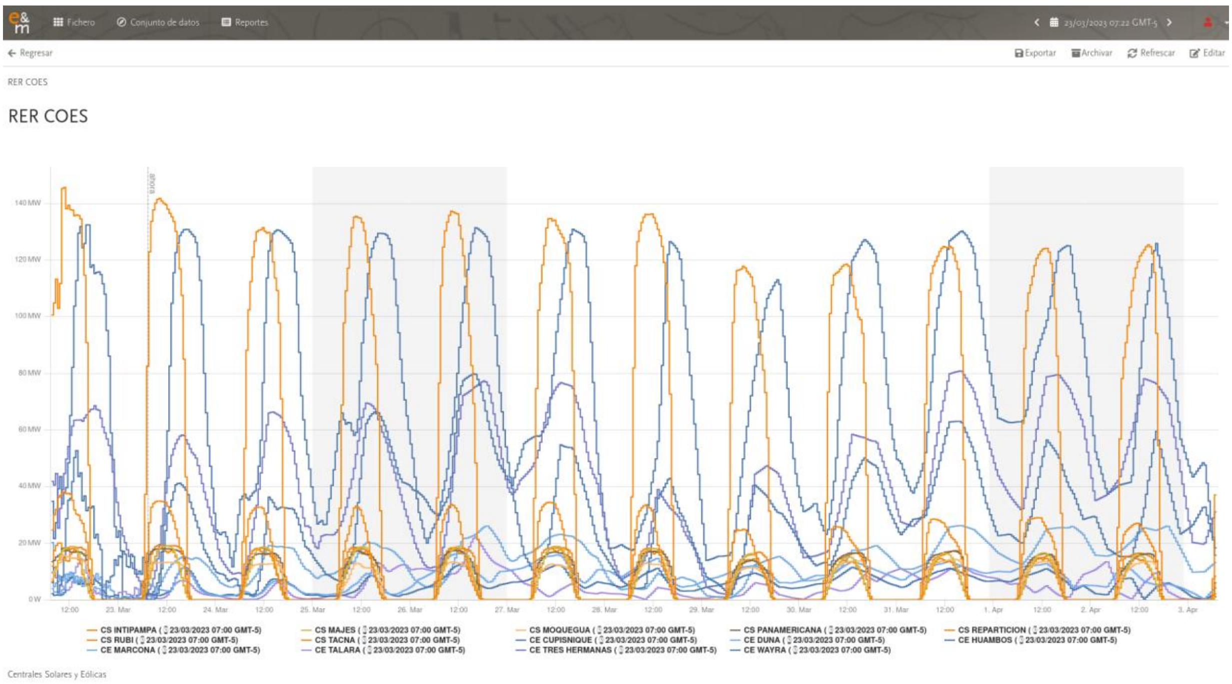
2.5 Visualisations and reporting

2.5.1 Data visualisation

For a convenient visualization of measurement and forecasting data a Graphical User Interface (GUI) was provided to COES. The GUI is a web-based software tool displaying in real-time any available time-series. It offers the user a variety of options to individually arrange dashboards and to export data as csv files.

FIGURE 2 shows a dashboard from the GUI visualizing the forecasts for all the vRE plants in Peru.

FIGURE 2. Dashboard with park-level forecasts



2.5.2 Monthly reporting on forecasting results

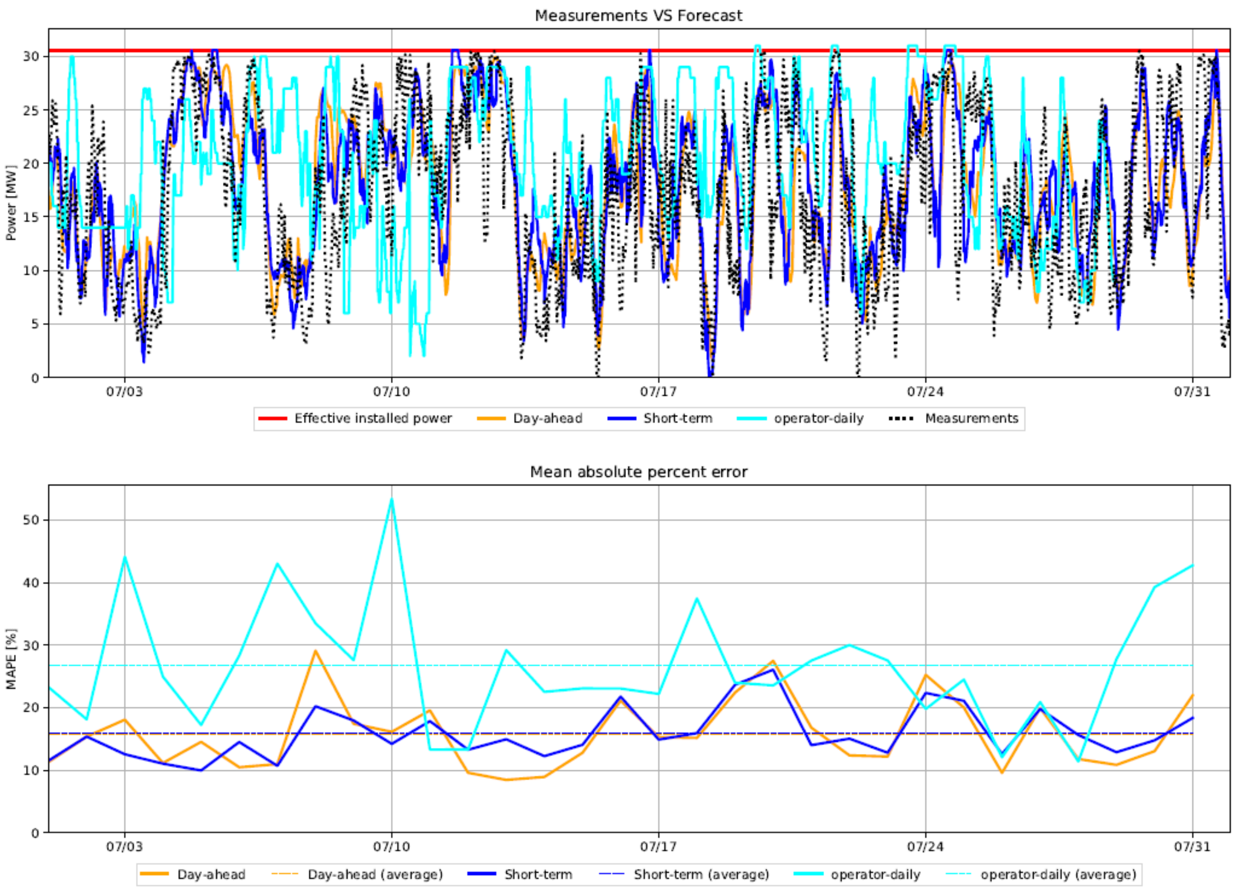
To provide an overview of the forecasting results monthly reports were delivered to COES for analysis, benchmarking and error measurements purposes.

The reporting contained the main prediction results for individual parks and the agreed aggregation levels. The day-ahead forecast and the short-term forecast with 3 hours ahead horizon were taken as reference to calculate error measures. The evaluation of 3 hours-ahead values was oriented towards the identical minimum lead time for COES to adjust production schedules in intraday operations. The plant operators only provide day-ahead forecasts which were used for analysis and benchmarking purposes.

The report included charts showing for each month:

— daily measurements and forecasts provided centrally (day-ahead and short-term) and by the plant operators (only day-ahead);
— daily mean absolute percentage error (MAPE) for both sources of forecastsdaily root mean square error (RMSE) for both sources of forecasts;
— bias for both sources of forecasts.

FIGURE 3. Charts with measurements, forecasts from emsys and plant operator (above) and MAPE values (below) during the month of July 2023



Tables listed the day-ahead forecast accuracy calculated as MAPE and RMSE for single days and the monthly average. The same error analysis was presented for short-term forecasts.

FIGURE 4. Forecast error analysis for a single solar park in Peru (from the July 2023 report)

Day	Day-ahead			Short-term			operator-daily		
	MAPE [%]	Bias [%]	RMSE [%]	MAPE [%]	Bias [%]	RMSE [%]	MAPE [%]	Bias [%]	RMSE [%]
Mean	4.45	3.07	9.37	4.22	2.50	8.90	13.43	0.34	22.69
Jul 01.	3.49	0.21	8.90	3.36	-0.03	8.62	11.61	5.68	19.32
Jul 02.	4.24	1.27	8.98	4.19	0.69	9.02	26.32	-26.32	41.39
Jul 03.	3.31	2.75	8.73	3.08	1.57	6.91	13.02	9.55	21.86
Jul 04.	2.99	2.55	8.24	2.53	1.60	6.48	12.85	12.85	22.53
Jul 05.	7.69	7.05	17.04	7.56	6.76	16.75	12.57	9.81	22.96
Jul 06.	2.77	-0.46	6.43	3.10	-0.57	7.12	7.21	3.05	12.21
Jul 07.	3.64	-1.36	9.08	4.21	-2.32	9.80	8.77	-5.83	18.14
Jul 08.	3.04	2.23	7.35	3.37	1.89	7.43	9.70	9.70	16.88
Jul 09.	4.89	4.75	12.49	4.87	4.20	12.20	10.12	10.12	17.97
Jul 10.	4.24	3.25	6.99	4.03	2.90	6.61	10.27	7.97	16.55
Jul 11.	2.93	1.95	5.47	2.65	1.48	5.08	12.00	12.00	19.08
Jul 12.	2.29	0.53	4.14	2.61	0.52	5.11	12.26	5.05	21.86
Jul 13.	2.74	0.79	4.87	3.40	0.59	6.40	7.20	5.26	11.89
Jul 14.	4.00	-1.74	9.49	4.24	-2.50	10.06	8.10	-6.01	16.43
Jul 15.	4.91	4.91	10.70	3.66	3.60	7.67	9.96	9.96	16.31
Jul 16.	6.03	4.23	13.45	4.60	2.45	10.38	8.95	8.95	14.45
Jul 17.	4.13	3.92	10.25	4.23	4.07	9.95	12.20	9.52	20.30
Jul 18.	2.73	0.90	5.29	2.82	0.86	5.50	9.79	9.79	15.90
Jul 19.	3.26	0.53	6.97	3.14	0.03	7.24	7.54	1.54	13.40
Jul 20.	5.63	5.63	10.89	5.33	5.33	10.45	9.03	7.54	13.99
Jul 21.	4.04	2.83	6.65	3.90	2.55	6.49	8.45	-4.23	15.53
Jul 22.	3.14	2.62	5.27	2.92	2.03	5.15	26.91	-26.91	42.78
Jul 23.	6.08	6.08	13.17	5.27	5.27	11.73	20.20	-20.20	36.51
Jul 24.	11.19	11.19	23.24	9.68	9.68	21.39	18.36	15.45	31.15
Jul 25.	3.44	3.09	6.24	2.84	2.06	5.65	13.70	13.70	22.72
Jul 26.	6.21	5.21	12.06	5.39	4.41	10.54	12.23	7.67	21.51
Jul 27.	4.74	4.61	11.94	3.98	3.76	10.16	10.12	8.34	19.37
Jul 28.	3.52	1.83	6.05	3.58	1.55	6.33	9.20	-5.72	17.18
Jul 29.	4.01	3.38	6.21	3.94	3.11	6.14	27.10	-27.10	42.25
Jul 30.	7.73	6.35	16.08	7.50	6.00	15.94	23.88	-23.88	39.15
Jul 31.	4.99	4.05	7.76	4.86	3.89	7.61	26.80	-26.80	41.73

In the same manner, the results for the aggregated day-ahead and short-term predictions for North, South, Marcona and the entire wind and solar power plants were presented.

3 Results of the forecasting pilot project

To verify the accuracy and the added benefits from the centralised forecasting system, the monthly reports (described in **section 2.5.2**) were prepared. The results of the evaluation are described in detail in the following sections.

3.1 Measuring the forecasting errors

To evaluate the accuracy of the power forecasts, the error measures Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) were used. Both error metrics are widely applied in the energy sector to determine the deviation between forecasted and actual production schedules. The following **BOX 1** provides a brief explanation of both calculation methods and the bias.

BOX 1. Explanation of different error metrics

MAE and **RMSE** are widely used metrics for evaluating the accuracy of power forecasts. Both metrics can range from 0 to ∞ and are indifferent to the direction of errors.

The **MAE** measures the average magnitude of the errors in a set of forecasts without considering their direction, i.e. the sign. It is the average over the test-sample of the absolute differences between prediction and actual measurements where all individual differences have equal weight. It is particularly useful if the cost function for imbalances, i.e. the penalties for forecast errors, is linear. MAE is the standard applied for this error measure and is widely used by traders world-wide and Independent System Operators in the U.S. market.

The **RMSE** is a quadratic scoring rule that also measures the average magnitude of the error. It is the square-root of the average of squared differences between prediction and actual measurements. The RMSE gives greater weight to large forecast errors, i.e. few large deviations dominate this error measure. As in many energy systems, large imbalances are indeed more costly, the RMSE is often used, e.g. by the German Transmission System Operators (TSO).

Bias: A power forecast is biased, if it is calculated in such a way that it is systematically different to the measurements. The bias indicates if production forecasts are continuously over- or underestimated.

3.2 Accuracy of wind power forecasts for individual parks

FIGURE 5 presents an overview of the RMSE for all wind parks for the complete period of the forecasting pilot. The values are also given in **TABLE 2 .**The RMSE is for most parks between 15 and 20% of installed capacity, only for Wayra the error level is higher (the reasons are outlined below in the single farm analysis). The MAE (not shown) is mostly between 13 and 15% of installed capacity, the bias varies between -2 and +7%, except Wayra with a bias of +14%.

In general, the forecast improves with a shorter forecast horizon. For example, the 3 hours-ahead forecast has a better quality than the day-ahead forecast, as the uncertainty of numerical weather predictions increases with a longer forecast horizon. The RMSE for the 3 hours-ahead forecasts is 5-15% lower than for the day-ahead forecasts, the RMSE for the 1 hour ahead forecast yield an additional improvement of a small percentage.

For the day-ahead forecast, a comparison can be made with the operators' forecasts. The forecasts provided by the centralised forecasting system clearly outperform the decentralised operators' forecasts for all wind parks. For most wind parks, the RMSE is reduced approximately 20%, and for some parks up to 45%. Only for Wayra and Tres Hermanas the improvement is less than 10%.

FIGURE 5. Forecast performance in terms of RMSE [in % of installed capacity] for individual wind parks and aggregations. Evaluated period: 2023-02-01 until 2023-12-31.

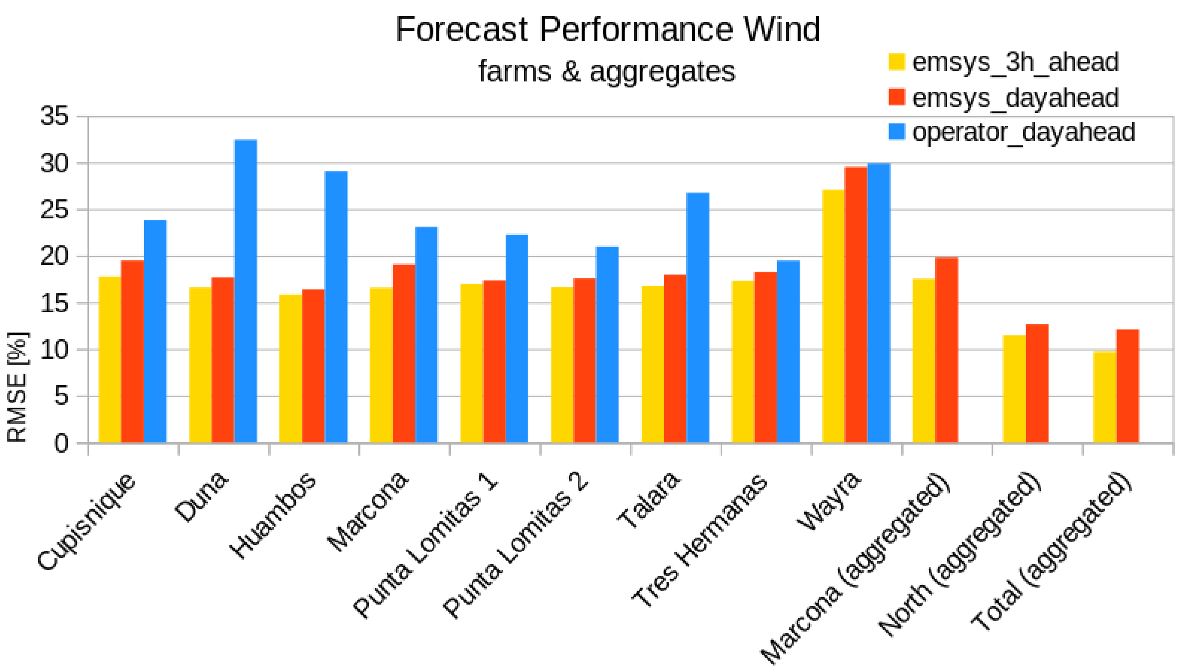


TABLE 2. Forecast performance in terms of RMSE [in % of installed capacity] for individual wind parks. Evaluated period: 2023-02-01 - 2023-12-31.

	Operator forecast day-ahead	emsys forecast day-ahead	emsys forecast 3 h ahead	emsys forecast 1 h ahead
Cupisnique	23.81%	19.49%	17.78%	16.11%
Duna	32.39%	17.71%	16.61%	15.97%
Huambos	29.05%	16.43%	15.88%	15.35%
Marcona	23.05%	19.09%	16.59%	15.49%
Punta Lomitas-BL1	22.25%	17.37%	16.98%	16.81%
Punta Lomitas-BL2	20.98%	17.58%	16.64%	16.36%
Talara	26.75%	17.98%	16.81%	15.87%
Tres Hermanas	19.48%	18.25%	17.31%	17.17%
Wayra	29.86%	29.50%	27.07%	26.07%

The power production characteristics of the individual wind parks and the forecast performance is very different from park to park, which usually depends on the geographic or topographic location of the parks (i.e. very close to the coast or further inland). At most times, three production patterns can be determined for the case of the Peruvian wind parks depending on their location.

The first pattern can be observed at the parks Duna and Huambos (see **FIGURE 6** top and **FIGURE 7** left). Here, production is often very high with short-term fluctuations. There is an underlying diurnal pattern but not very strong. These parks are located in the Andes mountains at approximately 2000 m altitude on mountain ridges. Although the detailed topography cannot be resolved by the weather models, the performance of the forecasts is very good, as winds are dominated by the large-scale flow along the slope of the Andes. The operator's forecasts are missing for many days. When available, they are often deviating significantly from the measurements.

The second pattern can be observed at the parks Marcona, Punta Lomitas 1 and 2, Talara and Tres Hermanas. Here, apart from the underlying diurnal pattern, the mean production level is changing every couple of days. This can be best seen in the time series of the month August 2023 for Marcona (**FIGURE 6** centre and **FIGURE 7** centre). These parks are located very close to the coast and dominated by the marine winds and by large-scale pressure gradients across the Pacific Ocean. As these large-scale features can be well predicted by the weather models, the forecast performance is mostly good. Nevertheless, the forecasts tend to over-forecast - even more so the operator's forecasts, which are generally less accurate.

The third pattern is visible in Cupisnique and particularly Wayra (see **FIGURE 6** bottom and **FIGURE 7** right). Here, the diurnal pattern is totally dominating the power output, with zero or very low power output during the night and morning and typically very high power output during the afternoon and evening. This is valid for almost all days between December and March and for about 80% of days between April and November. On most of the remaining days, high power output throughout the whole day is observed, on a few days also low power output. While the strong diurnal pattern can be generally reproduced by the numerical weather model predictions, they fail to capture the exact levels, especially the minimum during the night and morning. Here, predicted power is very often too high during the night and morning, while it is too low during the afternoon.

The park Wayra is located in a rather flat valley (ca. 8 km wide, 200 m deep) which cannot be properly resolved by the weather models. The lower air layer in the valley becomes decoupled from the air aloft during the night leading to very low or zero wind. In the weather model, there is no valley; hence wind speeds are not reduced that much during the night. This issue could be at least partly mitigated by calibrating power predictions with power measurements. But still, it is very challenging to capture the low level at night. Interestingly, the operator's forecast manages to capture the minima better.

The park Cupisnique has also a very pronounced diurnal pattern of wind speed and power production. In contrast to Wayra, the nightly minimal can be captured very well by the weather models and therefore the centralised forecast because Cupisnique is located in flat terrain very close to the coast that is well resolved in the models. As Cupisnique is in the North of Peru, close to the equator, it is less affected by changing pressure gradients at the edge of the Pacific subtropical high-pressure system.

FIGURE 6. Wind power time series for three parks during August 2023 showing measured power (grey) and day-ahead predictions by emsys (orange) and the plant operator (blue).

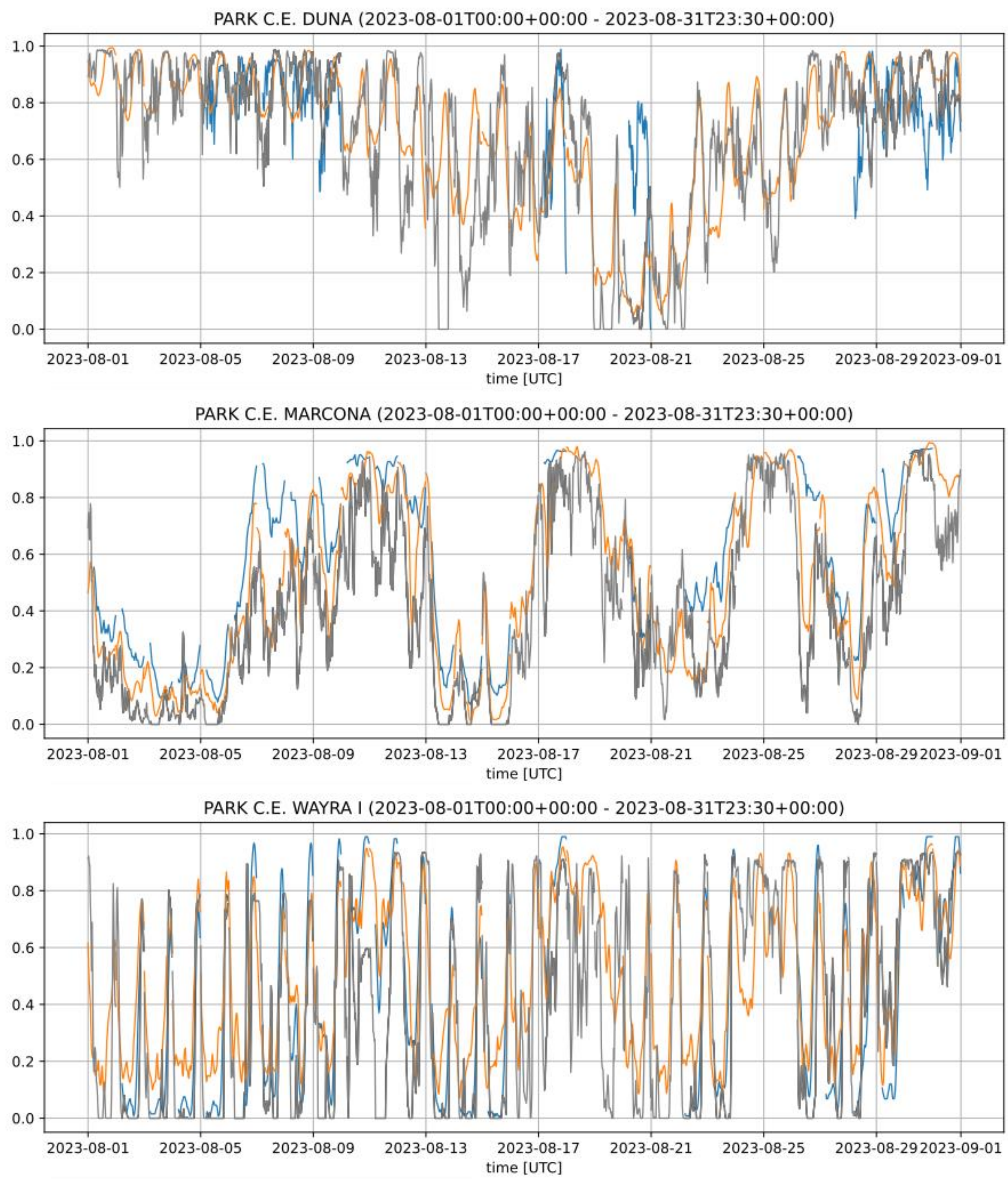
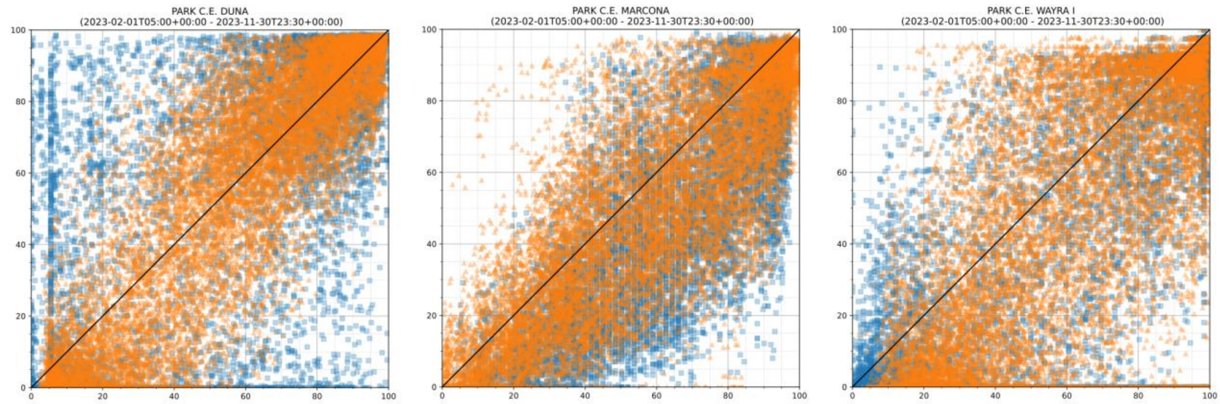


FIGURE 7. Scatter plots of predicted (horizontal axis) vs. measured (vertical axis) power for three parks during the total period of the pilot, showing day-ahead predictions by emsys (orange) and the plant operator (blue).



3.3 Accuracy of wind power forecasts on aggregated levels

Power forecasts cannot only be created for single plants but also for aggregation of assets. This can be useful if, for instance, a TSO needs to know the entire feed-in of a group of wind and/or solar power plants in a certain grid area. Aggregated forecasts were also delivered during the pilot. (see also map in **FIGURE 1**).

TABLE 3. Regional aggregated forecasts supplied to COES

AGGREGATION LEVEL	TOTAL COES	MARCONA	NORTH
Wind park	Cupisnique	Marcona	Cupisnique
Wind park	Duna	Punta Lomitas I	Duna
Wind park	Huambos	Punta Lomitas II	Huambos
Wind park	Marcona	Tres Hermanas	Talara
Wind park	Punta Lomitas I	Wayra	
Wind park	Punta Lomitas II		
Wind park	Talara		
Wind park	Tres Hermanas		
Wind park	Wayra		
Aggregated capacity	**661,6 MW**	**514 MW**	**147,6 MW**

At aggregated levels, the forecast performance is significantly better compared to park level. This can be expected as errors are averaged out, especially when the parks are distributed across a large region ("portfolio effect"). The RMSE values for the three forecasted aggregations are given in **TABLE 4**.

A comparison with the operators' forecasts is not possible, as these are only available on park level. The possibility of generating optimized aggregated forecasts underlines again the advantage of working with a professional forecast provider.

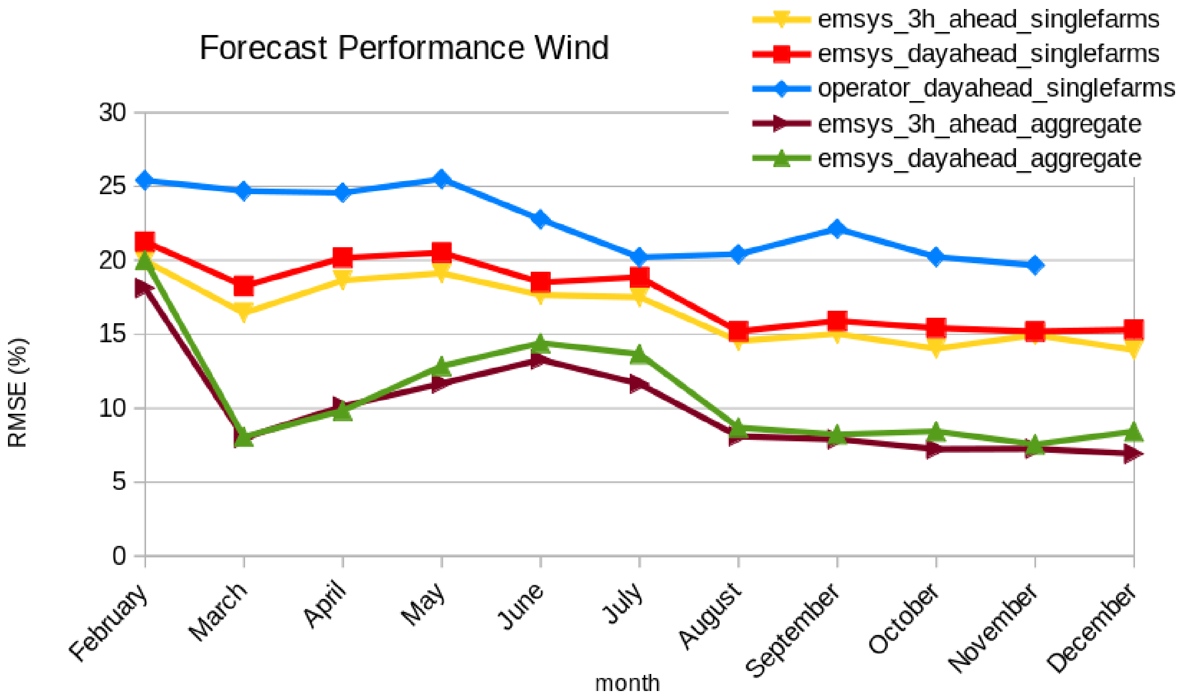
The Marcona aggregation has a clearly enhanced error level as it includes Wayra with its high error values. For the total aggregation, the RMSE drops below 10% in the intraday forecasts.

TABLE 4. Forecast performance in terms of RMSE [in % of installed capacity] for the wind aggregations. Evaluated period: 2023-02-01 - 2023-12-31.

FORECAST AGGREGATION	EMSYS DAY-AHEAD	EMSYS 3 HOUR-AHEAD	EMSYS 1 H-AHEAD
Total	12.11%	9.72%	9.16%
Marcona	19.79%	17.54%	16.77%
North	12.64%	11.50%	10.40%

The forecast performance is subject to slight variations during the period of evaluation as can be seen in **FIGURE 8**.

FIGURE 8. Monthly wind power forecast performance in terms of RMSE [in % of installed capacity] averaged over all wind farms and for the total aggregate. Evaluated period: 2023-02-01 - 2023-12-31.



The performance variations are mostly due to seasonal fluctuations (different levels and patterns of wind speed). Sometimes also technical issues, i.e. non-reported outages or gaps in the measurements, can lead to higher errors. The higher error level in February can be attributed to the inception phase of the pilot. The onboarding of the new parks with limited data availability also caused higher errors, until the model was well calibrated. This was the case when Punta Lomitas 1 &2 were added to the system and caused higher errors in April and May.

In almost all months, the centralised forecasting system outperforms the operators' forecasts when comparing the average of the single farm forecast.

3.4 Accuracy of solar power forecasts for individual parks

FIGURE 9 presents an overview of the RMSE for all solar parks for the complete period of the forecasting pilot. The values are also provided in **TABLE 5**. The RMSE is around 10% of installed capacity for most parks. The MAE (not shown) is mostly between 3 and 5% of installed capacity, the bias varies between -2 and +3%. The errors are generally lower compared to the wind power forecasts, which is due to the more predictable power level as most days feature unperturbed insolation.

In contrast to the wind power forecasts, the forecast quality does not improve from day-ahead to intraday. One explanation is that the numerical weather predictions are already very certain for the day-ahead due to the mostly sunny climate. Challenges as morning fog or clouds developing during the day are the same for day-ahead and intraday, they are not mitigated through model updates.

Another explanation is the poor availability of live measurements. Especially for the solar parks long data gaps were encountered. If data was available, the delay was too long to be able to improve the forecast quality. With the extremely steep ramps in the morning and afternoon, sometimes, the short-term correction of the forecast by measurements may even worsen the forecast.

Comparing the day-ahead forecast with the operators' forecasts, the centralised forecasts clearly outperform the operators' forecasts for all solar parks. Centralised forecasts reduce the RMSE between 10% (Intipampa, Rubi) and 40% Moquegua, Panamericana, Tacna).

FIGURE 9. Forecast performance in terms of RMSE [in % of installed capacity] for the individual solar parks and aggregations. Evaluated period: 2023-02-01 - 2023-12-31.

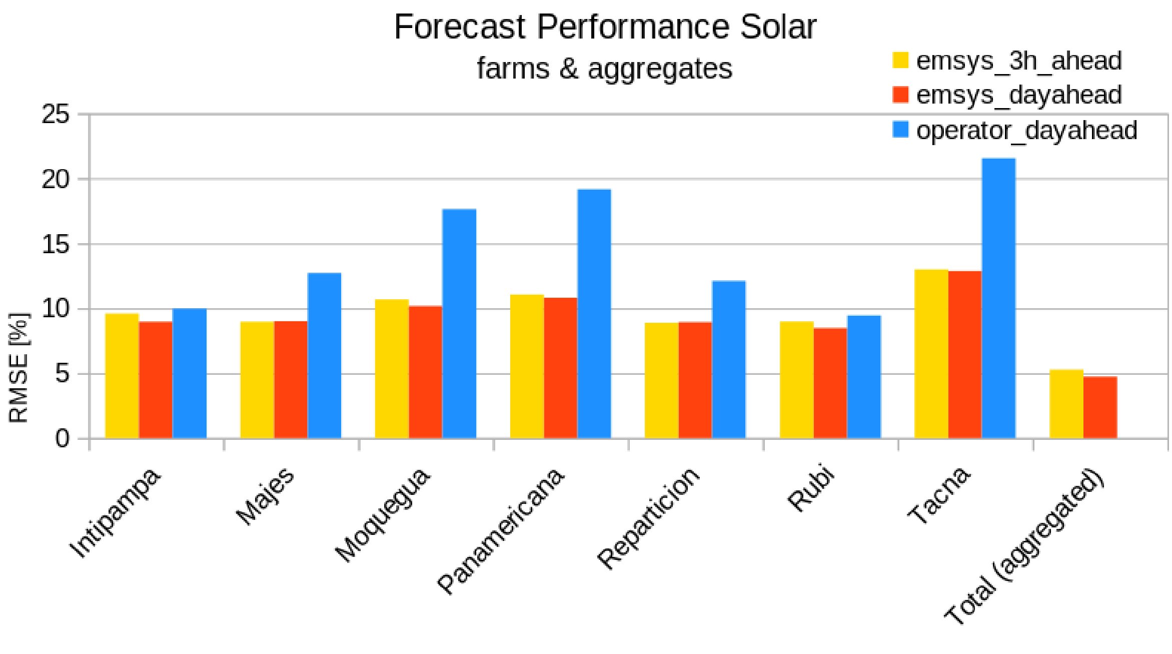


TABLE 5. Forecast performance in terms of RMSE [in % of installed capacity] for the individual solar parks. Evaluated period: 2023-02-01 until 2023-12-31.

AGGREGATION LEVEL	OPERATORS DAY-AHEAD FORECASTS	EMSYS DAY-AHEAD FORECASTS	EMSYS 3 HRS-AHEAD FORECASTS	EMSYS 1 HR-AHEAD FORECASTS
Intipampa	9.98%	8.94%	9.61%	9.56%
Majes	12.73%	8.99%	8.95%	8.95%
Moquegua	17.61%	10.18%	10.68%	10.71%
Panamericana	19.16%	10.81%	11.05%	11.12%
Repartición	12.12%	8.91%	8.87%	8.79%
Rubi	9.46%	8.47%	8.96%	8.94%
Tacna	21.56%	12.87%	13.00%	12.94%

As illustrated in **FIGURE 9** and **TABLE 5**, the operators' forecasts often significantly deviate from the centralised forecasts and the actual measurements. For some parks, the predicted power level is far too high (Moquegua, Panamericana, Tacna), for other parks it is too low (Repartición and Majes). Only for the parks Intipampa and Rubi, the operators' forecasts are matching the power level very well and the performance is only slightly weaker compared to the centralised system.

As most days are free of clouds, the solar power production is often very close to the maximum possible production. Yet, it is challenging to match the shape of the solar power production curve as close as possible - even with correctly specified alignment parameters (in some cases the standing data was not correct and had to be adjusted to improve the forecast quality, which was mainly done before the forecasting pilot).

An example is the solar park Intipampa, where the forecast performance is better than for other parks, as marine layer fog and other clouds occur very rarely, especially between April and December. The time series example from August 2023 in **FIGURE 10** shows that the forecasts produced by the centralised system match the measured power very well, with only slight deviations. The operator's forecast performs similarly well on some days, while on other days it is too high or too low. When evaluated over the total period of the pilot, the centralised system performs better than the operator forecasts (see **FIGURE 11** and **TABLE 5**).

FIGURE 10. Solar power time series for Intipampa during a few days in August 2023: Measured power (grey), day-ahead predictions by emsys (orange) and the plant operator (blue).

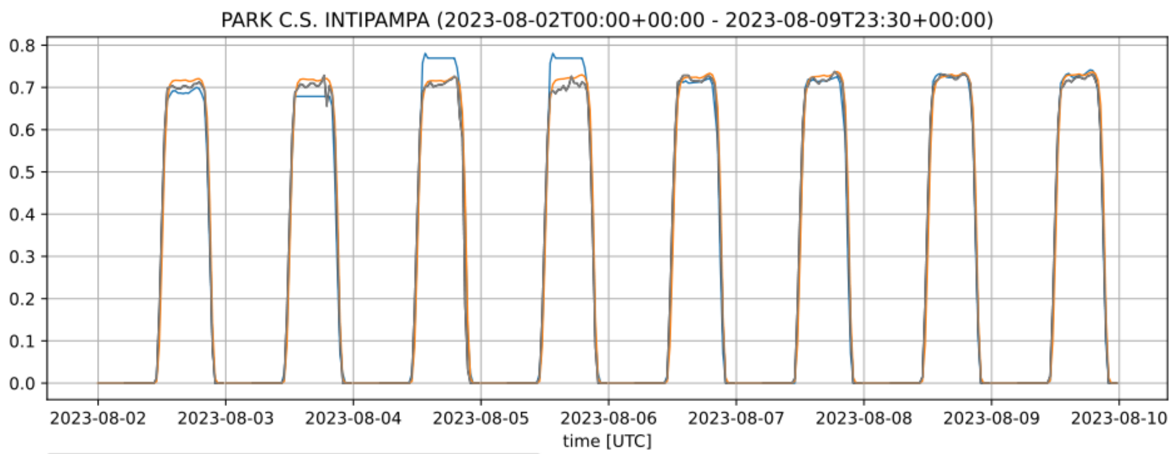
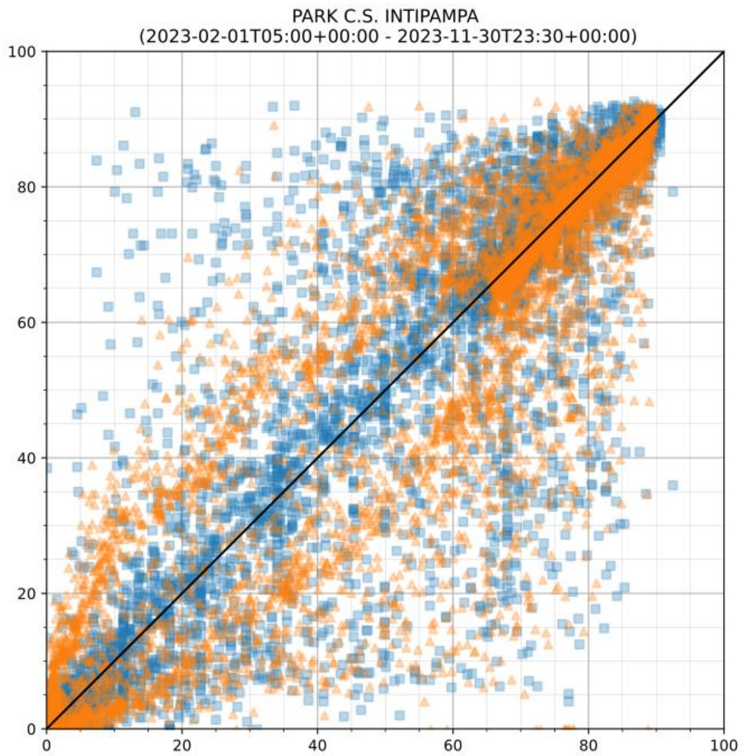


FIGURE 11. Scatter plot of predicted (horizontal axis) vs. measured (vertical axis) power for Intipampa during the total period of the pilot, showing day-ahead predictions by emsys (orange) and the plant operator (blue).



For the solar park Tacna, the initial measurement data was approximately 45 minutes off compared to the production data. This time shift was corrected for the training of the centralised forecasting system.

For Tacna (and similarly also Moquegua), the forecast is challenging mainly due to the marine layer fog which spreads from the coast inland and upslope during the night and leads to reduced production in the morning, sometimes also in the afternoon and evening. On some days the coverage and dissolution of the fog is very well predicted by the weather models (see e.g. May 2nd, May 7th in **FIGURE 12**), on other days fog is not predicted but occurring (e.g. May 1st), on a few days also the contrary (fog is predicted but not occurring, e.g. May 8th). Sometimes also high clouds are drifting across the region which cause fluctuations and lead to errors (e.g. May 10th).

Due to the challenging forecast, the errors are higher compared to other parks. Other parks are less often affected by marine layer fog (as they are located further away from the coast or in higher altitudes).

However, as can be seen from **FIGURE 12** and **FIGURE 13**, the centralised system still outperforms the operator's forecast, which does not capture the effect of fog.

FIGURE 12. Solar power time series for Tacna from 1-10 May 2023 with measured power (grey) and day-ahead predictions by emsys (orange) and the plant operator (blue).

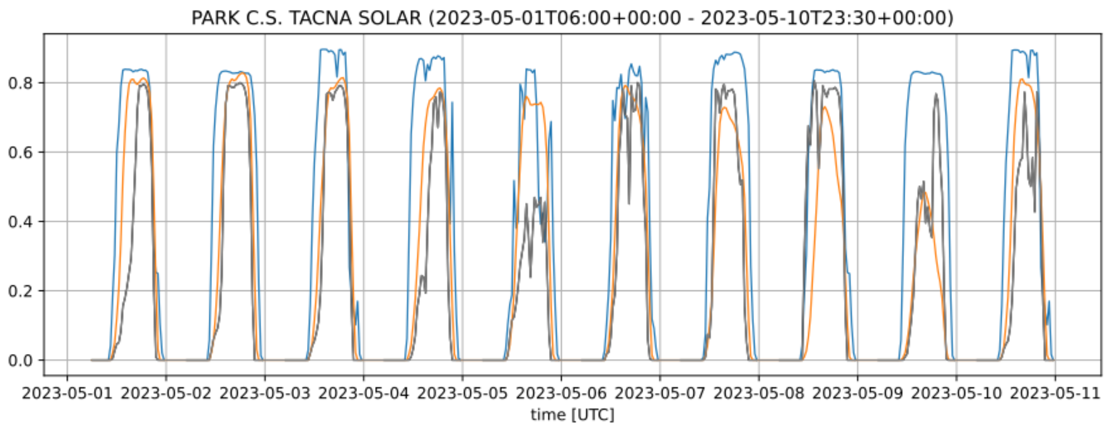
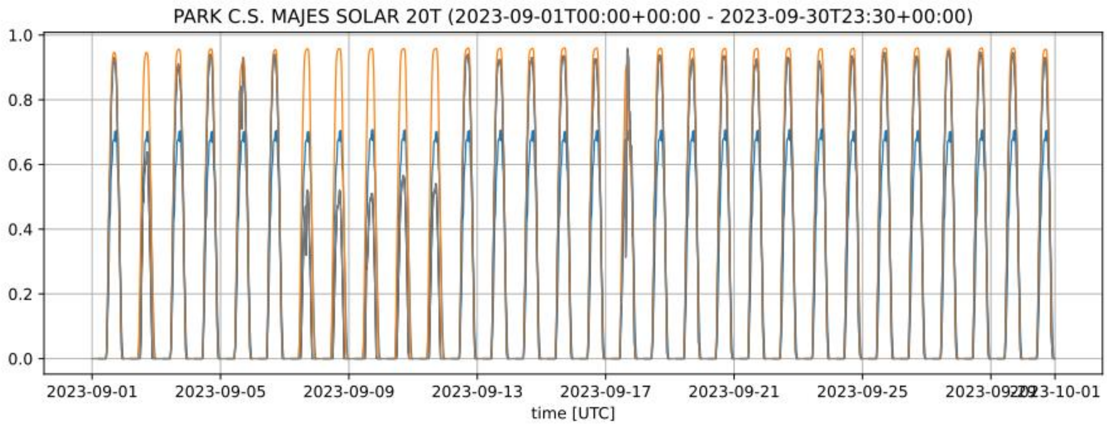


FIGURE 13. Scatter plot of predicted (horizontal axis) vs. measured (vertical axis) power for Tacna during the total period of the pilot, showing day-ahead predictions by emsys (orange) the plant operator (blue).



Another source of errors are outages which were not communicated to the forecast providers. **FIGURE 14** shows an example for the park Majes during September 2023. A part of the farm was obviously shut down from 2nd to 7th of September, leading to errors in the forecasting. In contrast, the operators' forecast is clearly too low during the entire period.

FIGURE 14. Solar power time series for Majes for September 2023, showing measured power (grey) and day-ahead predictions by emsys (orange) and the plant operator (blue).

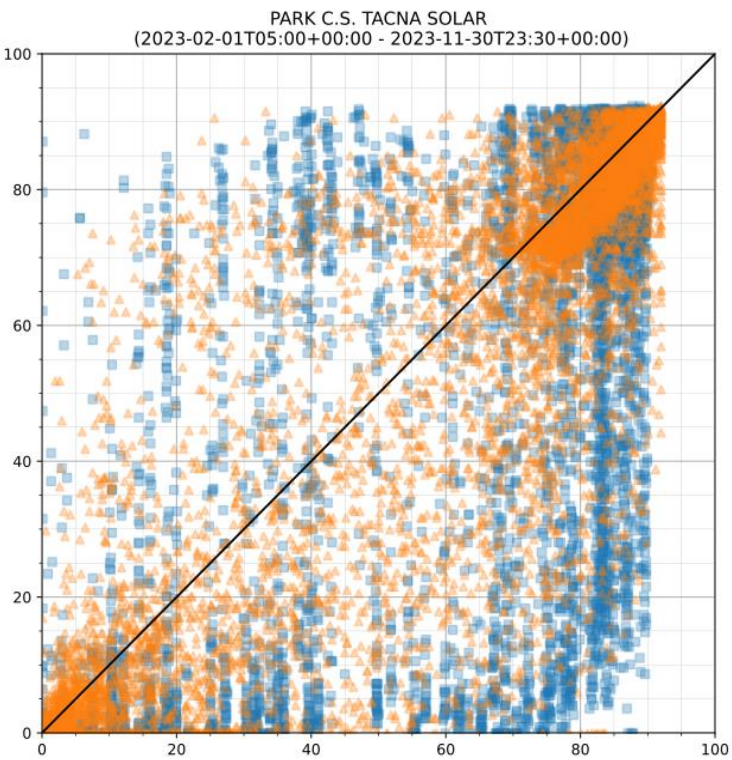
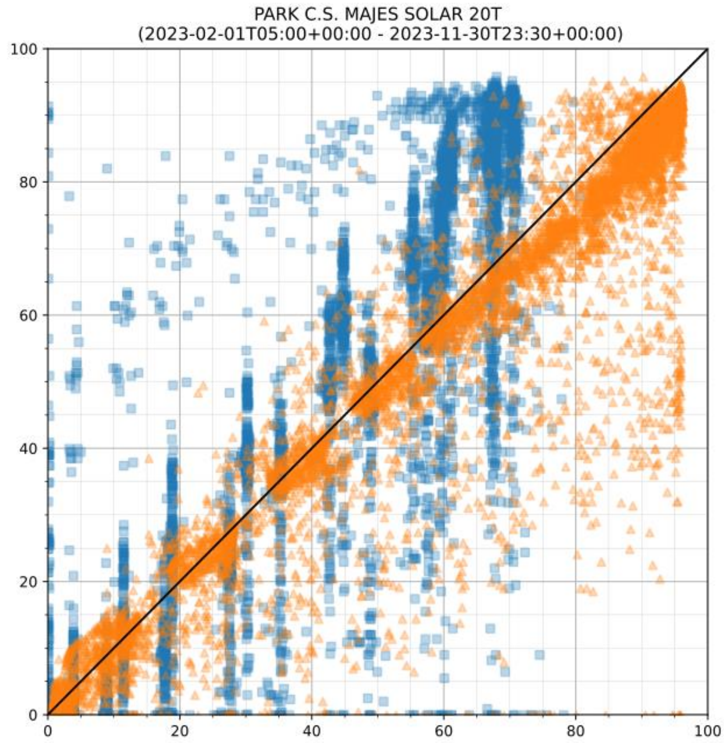


FIGURE 15. Scatter plot of predicted (horizontal axis) vs. measured (vertical axis) power for Majes during the total period of the pilot showing day-ahead predictions by emsys (orange) and the plant operator (blue).



3.5 Accuracy of solar power forecasts at aggregated levels

Similar to wind power, the forecast performance for solar power is significantly better on an aggregated level (all parks) compared to individual park level. The RMSE values for the forecasted total aggregation are given in **TABLE 6**. A comparison with the operators' forecasts is not possible, as these are only available on park level. The day-ahead RMSE is below 5%, MAE approximately 2%, and bias below +1%.

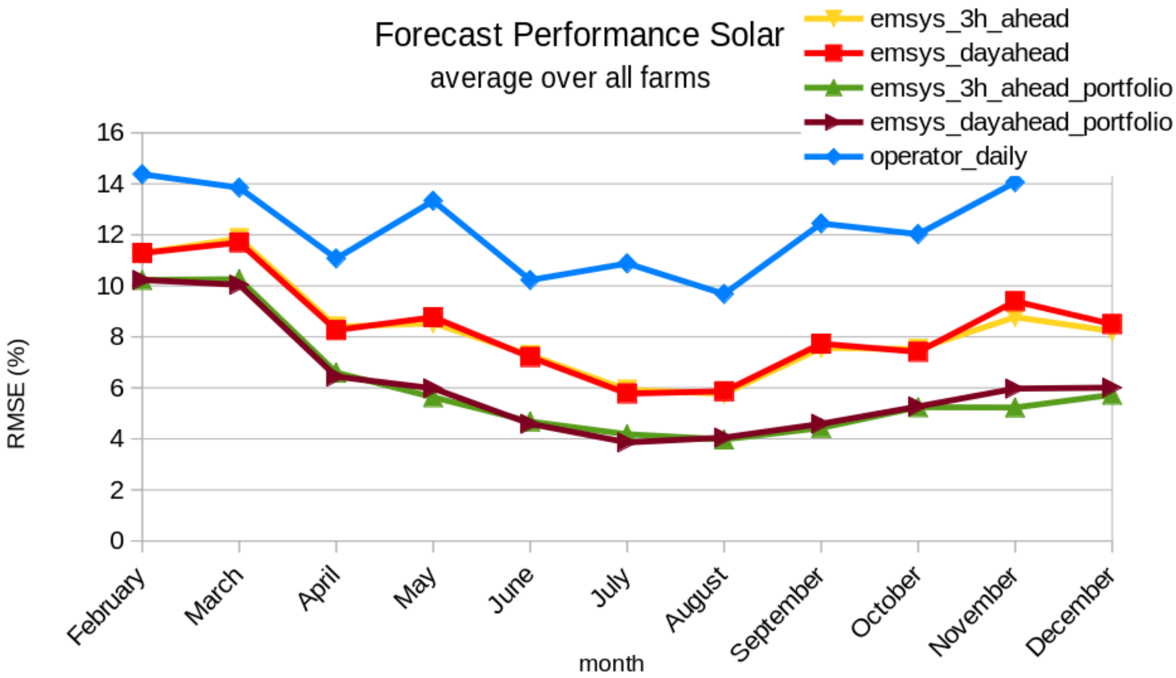
TABLE 6. Forecast performance in terms of RMSE [in % of installed capacity] for the aggregated solar parks. Evaluated period: 2023-02-01 until 2023-12-31.

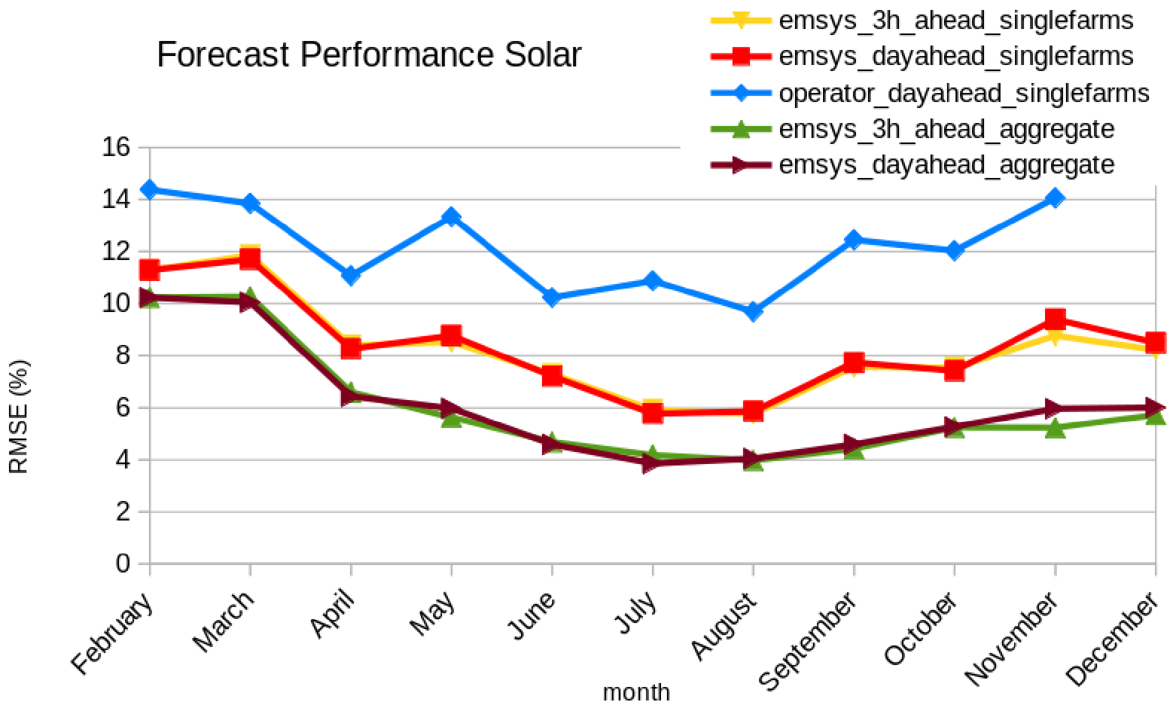
FORECAST AGGREGATION	EMSYS DAY-AHEAD	EMSYS 3 HOUR-AHEAD	EMSYS 1 H-AHEAD
Total	4.73%	5.27%	5.27%

Here as well, the solar forecast performance is subject to slight variations during the period of evaluation as can be seen in **FIGURE 16**. These are mostly seasonally fluctuations, corresponding to the varying solar inclination angle and more diurnal clouds (from the inland of Peru) in the period between December and April. Sometimes also technical issues, i.e. non-reported outages or gaps in the measurements can lead to higher errors. Especially the higher error level in February and March can be attributed to the inception phase of the pilot.

Generally, in all months, the forecasts provided by the centralised system outperform the operators' forecasts when comparing the average of the single farm forecast performances.

FIGURE 16. Monthly solar power forecast performance in terms of RMSE [in % of installed capacity] averaged over all PV farms and for the total aggregate (only emsys). Evaluated period: 2023-02-01 - 2023-12-31.





3.6 Solar eclipse in Peru on 14th of October 2023

Forecast service providers usually also provide weather reports to inform the user about special meteorological conditions or other events likely to affect power forecasts. A month ahead of time, emsys sent a report to COES on an upcoming solar eclipse on 14th of October 2023 between 6 pm and 9 pm in Peru. With the report issued a month ahead of the event, there were not yet reliable weather predictions available. Therefore, the report forecasted the possible impact on the solar power production in Peru based on the difference between a clear sky scenario with and without eclipse. Parting from the maximum solar production volume, the report can be interpreted as the worst-case scenario concerning the difference with and without solar eclipse.

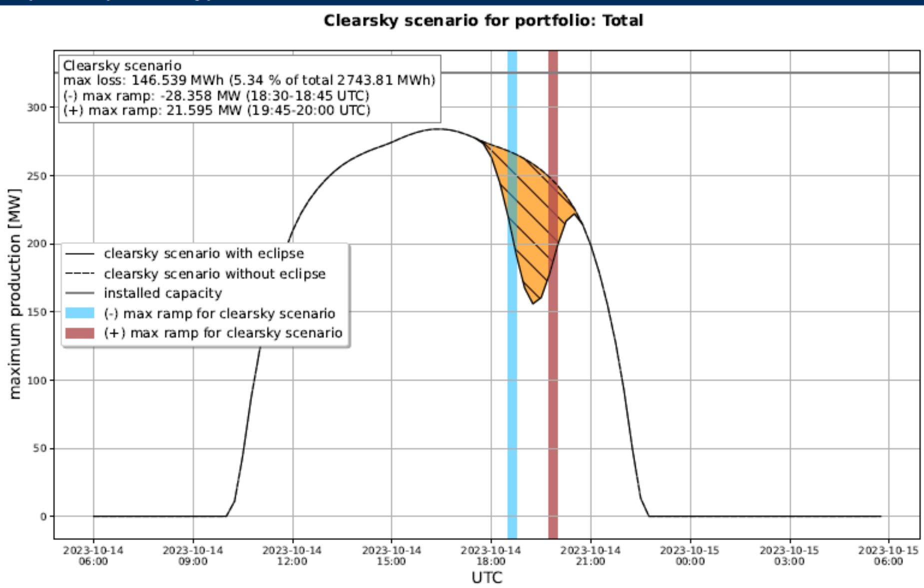
In this scenario, the maximum production loss on this day for the entire solar power portfolio in Peru would amount to almost 147 MWh, equivalent to 5.34% of the total solar power production on this day. The steepest downward ramp was predicted to occur between 6:30 pm and 6:45 pm with -28.4 MW, while towards the end of the eclipse the largest upward ramp was expected to happen between 7:45 pm and 8 pm (21.6 MW). The maximum difference in solar power production would occur at 7:15 pm with 160 MW in comparison to 265 MW without solar eclipse.

FIGURE 17. First alert issued on the upcoming solar eclipse (Source: emsys)

Summary Table of portfolio impacts

Portfolio	max loss [MWh]	max down ramp (clearsky)	max up ramp (clearsky)
Total	146.539	-28.358 MW (18:30-18:45 UTC)	21.595 MW (19:45-20:00 UTC)
COES	146.539	-28.358 MW (18:30-18:45 UTC)	21.595 MW (19:45-20:00 UTC)

Portfolio impacts of eclipse in clearsky predictions



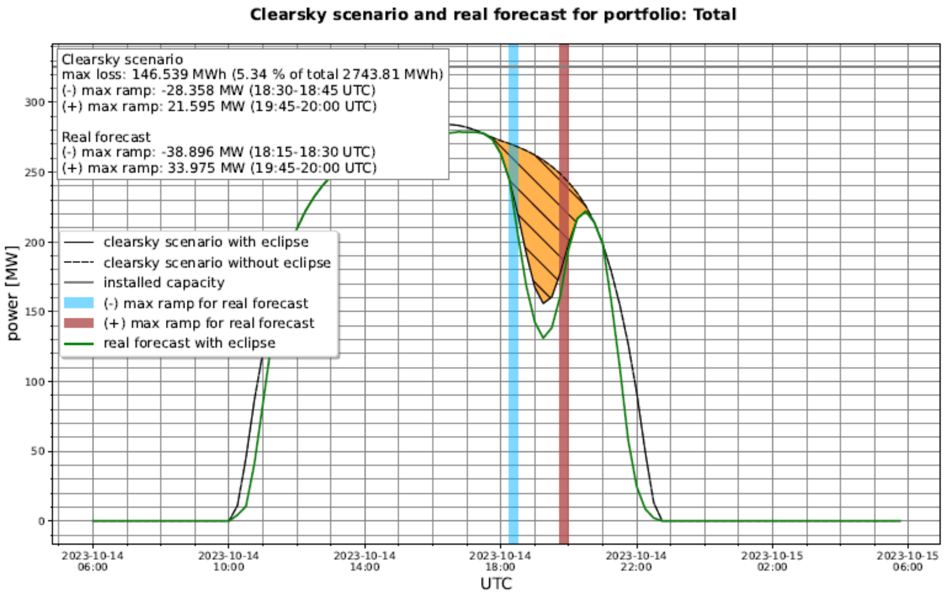
Four days ahead of the event, an updated solar eclipse report based on available weather predictions for the day was provided.

FIGURE 18. Updated alert on the solar eclipse (Source: emsys)

Summary Table of portfolio impacts

Portfolio	max loss [MWh]	max down ramp (clearsky)	max up ramp (clearsky)	max down ramp (real forecast)	max up ramp (real forecast)
Total	146.539	-28.358 MW (18:30-18:45 UTC)	21.595 MW (19:45-20:00 UTC)	-38.896 MW (18:15-18:30 UTC)	33.975 MW (19:45-20:00 UTC)
COES	146.539	-28.358 MW (18:30-18:45 UTC)	21.595 MW (19:45-20:00 UTC)	-38.896 MW (18:15-18:30 UTC)	33.975 MW (19:45-20:00 UTC)

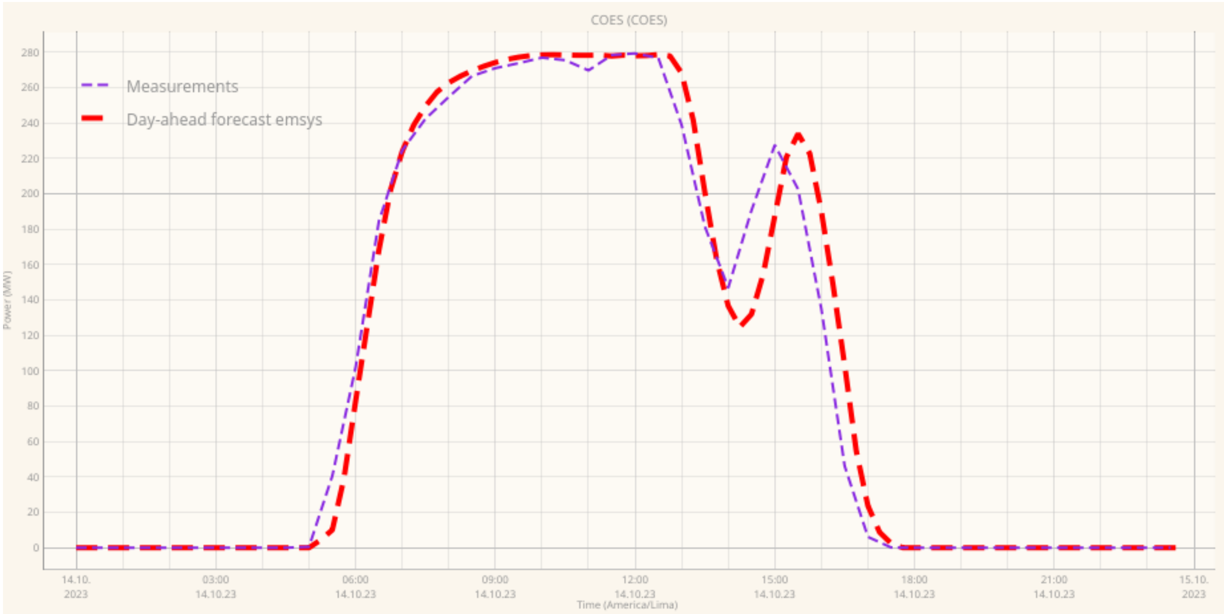
Portfolio impacts of eclipse in power prediction



As can be observed, the updated weather-model based production forecast for the solar eclipse is even lower than in the previous report. This is due to the training of the predictions based on historic measurements and predictions. Here, this hardly has an impact on the predictions when production levels are high, but it does correct the forecasts downwards at low to medium power production levels of the parks. Consequently, the maximum down ramp and up ramp increase to -38.896 MW and 33.975 MW respectively.

The following **FIGURE 19** created after the solar eclipse shows the forecast and actual measurement data of the solar power portfolio in Peru.

FIGURE 19. Forecasted and actual impact of solar eclipse on solar power production in Peru



As can be observed, system-wide solar power production dropped from 280 MW to around 155 MW due to the solar eclipse. Since the solar parks are not distributed across Peru but concentrated in the South of the country, the complete loss of production affected this area. The time-shift between production (blue line) and forecast (red line) is due to the 30-minute resolution. This stresses the importance of working with a higher resolution (15 minutes) as recommended in the previous report on how to improve Peru´s power forecasting system[5].

By contrast, several solar plant operators did not consider the impact of the solar eclipse in their forecast. This is illustrated by the following charts which show the forecasts provided by the operators of Majes Solar and Intipampa. For Majes Solar, the chart shows in addition that the forecast underestimated production throughout the day.

[5] The Executive Summary of the report is available for download under the following link: https://www.get-transform.eu/wp-content/uploads/2023/11/GET.transform-Improving-vRE-Forecasting-Peru-ExecSum.pdf

FIGURE 20. Plant operators not incorporating the solar eclipse in their production forecast

The solar eclipse is another example that underlines the value of having a centralised forecast provider. Centralised forecast providers offer this service and can predict the impact of special events like the solar eclipse on the production of the entire solar power portfolio in Peru. Operators in Peru did not consider the special event in their delivered forecasts.

3.7 Potential of using live data for short-term forecasts

As mentioned in **section 2.4**, a backcast was computed to demonstrate the potential of using real-time production data to adjust the short-term forecast. Although at least partly real-time data was provided and used to adjust the forecast, it came with a large delay (45 minutes to 3 hours), causing the short-term forecast to be less accurate than possible. The recalculated forecasts simulated the availability of real-time data without any delay.

The forecasts have been recalculated for the period June 1st 2023 - November 30th 2023. This period was chosen as it contained the full set of wind parks and sufficient calibration with historical measurement data (Punta Lomitas was added in April 2023 and calibrated by the end of May). Real-time data for December 2023 was not available at the time of the backcast.

In **FIGURE 21** and **FIGURE 22** the recalculated wind and solar power forecasts are compared with the original forecasts in terms of RMSE for the 1 hour-ahead and 3 hours-ahead horizons. The benefit of using real-time production data with as little delay as possible is obvious, the error level is significantly reduced for both wind and solar power forecasts, but more significantly for wind (due to reasons outlined above).

On a single wind park level, the RMSE is reduced by 5-15% for the 3 hours-ahead forecast and even by 20-40% for the 1 hour-ahead forecast. On aggregated wind levels, the increase in performance is 11-16% for 3 hours-ahead and 29-36% for 1 hour-ahead. Compared to the base forecast without any use of live data, the improvement would have been even more significant.

For most of the solar parks, the improvement in the 3 hour-ahead forecasts is hardly detectable, for Panamericana it is even negative. In the 1 hour-ahead forecasts a clear improvement for some of the parks can be observed (e.g. Moquegua by 10%, Repartición by 28%, Tacna by 12%). The forecasts for the other parks were slightly improved or remained at the same level (Panamericana). On an aggregated level, the increase in performance is 0.4% for 3 hours-ahead and 7% for 1 hour-ahead.

FIGURE 21. Forecast performance in terms of RMSE [in % of installed capacity] for the individual wind parks and aggregations. Delivered forecasts vs. re-calculated forecasts using live data without delay. Evaluated period: 2023-02-01 until 2023-12-31.

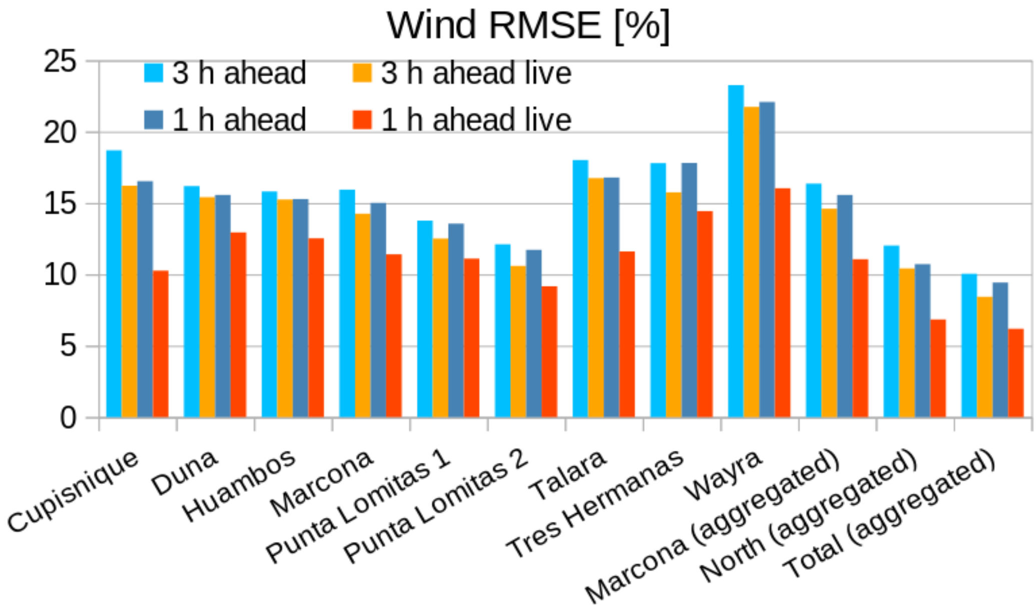


FIGURE 22. Forecast performance in terms of RMSE [in % of installed capacity] for the individual wind parks and aggregations. Delivered forecasts vs. recalculated forecasts using live data without delay. Evaluated period: 2023-06-01 until 2023-11-30.

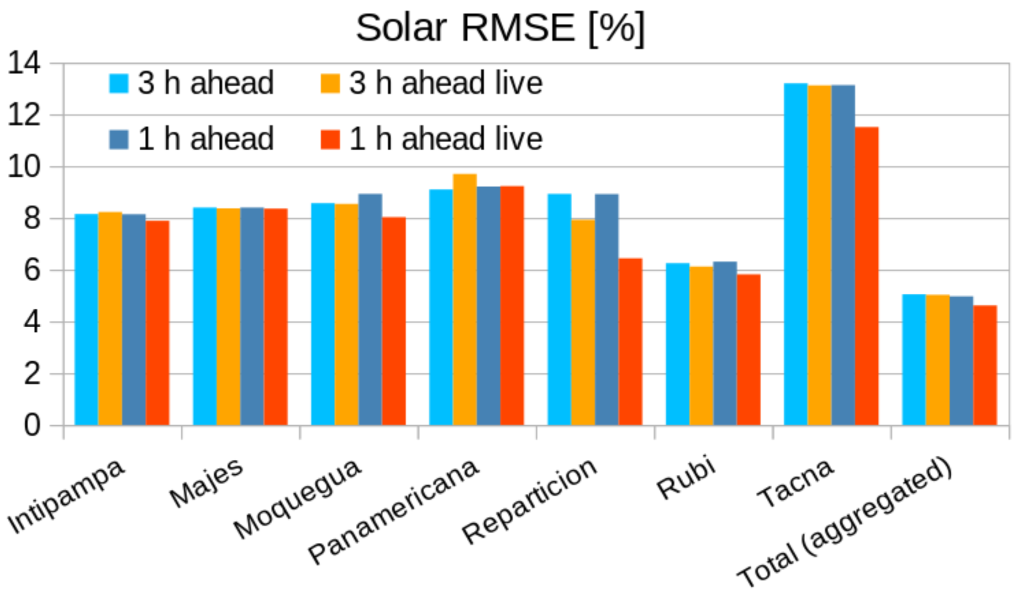
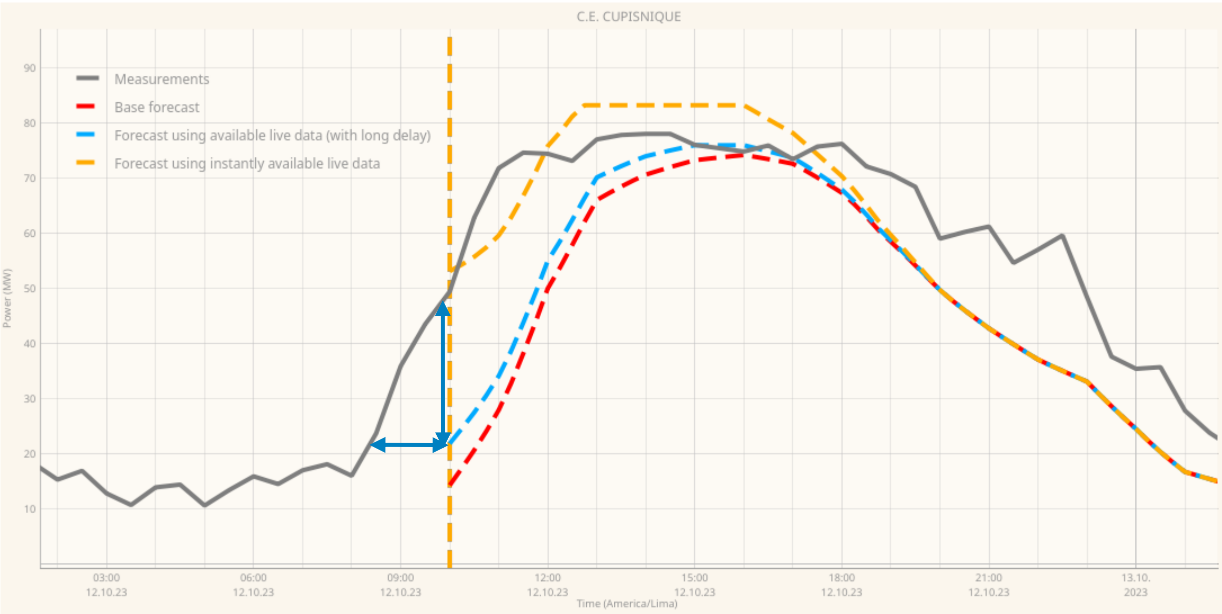


FIGURE 23 exemplifies the benefit of using real-time data with as little delay as possible for a typical day with a strong diurnal wind ramp in the morning. The base forecast which solely relies on weather data is shown in the red line, the forecast processing delayed measurement data in blue and the forecast using real-time data without delay in orange.

FIGURE 23. Measured and predicted time series of wind power for wind park Cupisnique on 2023-10-12. Black: measurements, red: base forecast (not using any live data), blue: forecast using available live data (with delay), orange: forecast using live data without delay.



The ramp is considered in the base forecast (not using any real-time data from the power plant) but the weather models predicted the ramp to start later than it actually occurred in reality. This caused a significant forecast error for a few hours.

The short-term forecast using delayed real-time data reduces the forecast error only slightly, due to the steep increase in production from 22 MW to 50 MW during the delayed data transmission.

By contrast, the orange forecast using instantaneously transmitted real-time measurements considers real-time measurements without delay. Consequently, this forecast is informed about the increase in production and corrects the short-term forecast accordingly. As a draw-back the maximum was slightly over-forecasted, but overall, the error was largely reduced.

The simulated short-term forecasts show that COES could greatly benefit from using improved short-term forecasts, which are currently hampered by the delay in transfer of real-time production data. Second, the tremendous improvement of the 1 hour-ahead forecasts in comparison to the 3 hour-ahead forecast shows the importance to adjust operational processes accordingly. The reduction of the 3-hour lead-time in scheduling Peru´s generation fleet would allow the use of more accurate short-term forecasts, thus decreasing imbalances and the need of costly short-term redispatch of generators.

4 COES´ experiences with centralised power forecasts

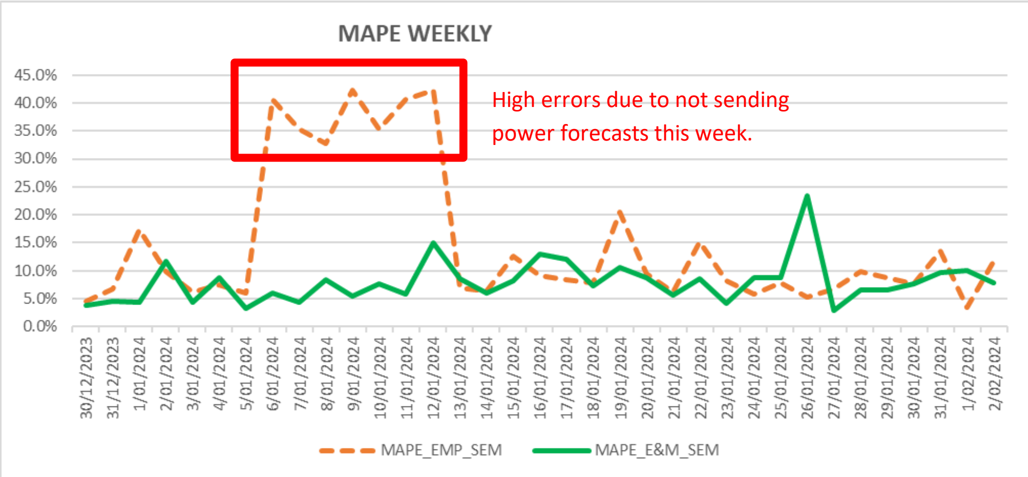
The Peruvian regulation allows COES to use the "information presented by the generators and/or the best information available"[6]. As a result, and given the higher accuracy, COES could start to use the predictions provided by the centralised system for all of the 9 wind parks (672 MW) and 7 solar parks (285 MW) during the forecasting pilot project. The forecasts were used for planning the week-ahead, intraday, redispatch and real-time dispatching processes.

Following the pilot project, COES defined the following advantages of receiving centralised forecasts from a professional service provider:

1) Centralised forecasts have multiple advantages, such as the permanent delivery of updated and good quality forecasts, as currently the delivery of forecasts by plant operators is partly irregular and of low quality. **FIGURE 4** shows the forecast error for a solar park whose operator was not sending power forecasts for various consecutive days in January 2024.

[6] Procedimiento Técnico del COES N°01, Programación de la operación de corto plazo: menciona en el numeral 6.1.3 que el COES elabora el programa de operación utilizando la información presentada por sus Integrantes y/o la mejor información disponible,

FIGURE 24: High errors in the evaluation of the plant operator´s forecast due to not providing a forecast for an entire week. Source: COES



Source: COES, 2024, document about the external service for the vRE forecasting

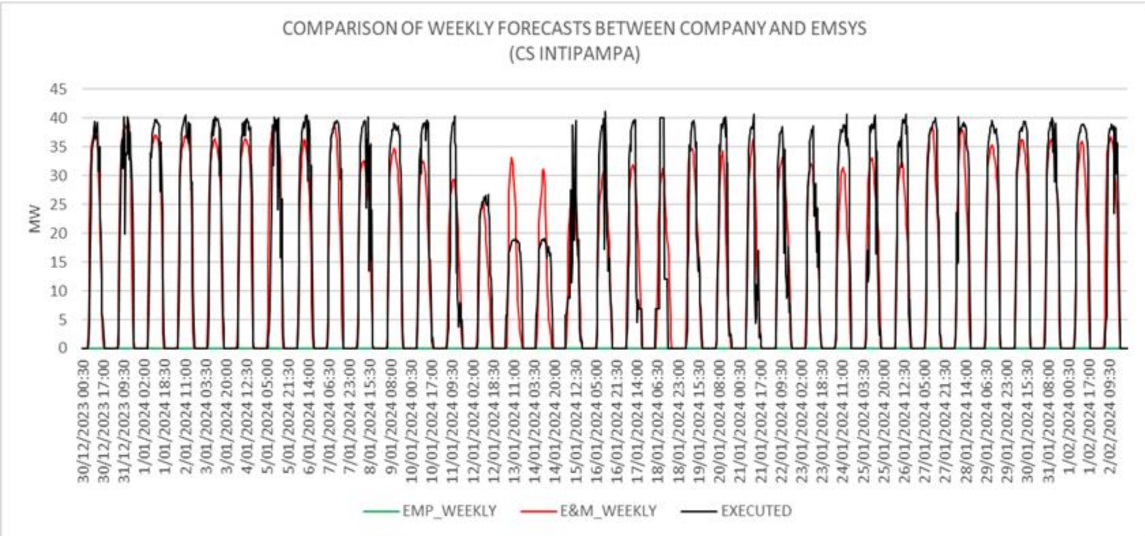
2) The forecasting service ensures high quality forecasts for a horizon of several days ahead due to the use of meteorological models, state-of-the-art technology and qualified staff.

3) The forecasting provider has largely eliminated the calls and e-mails to plant operators to request their forecasts, which, in many cases, take a long time to be answered because they must be referred to the company's specialist.

4) The forecasting provider provides a monthly assessment of the quality of their forecasts, giving appropriate feedback and as well using them for the improvement of the forecasting model.

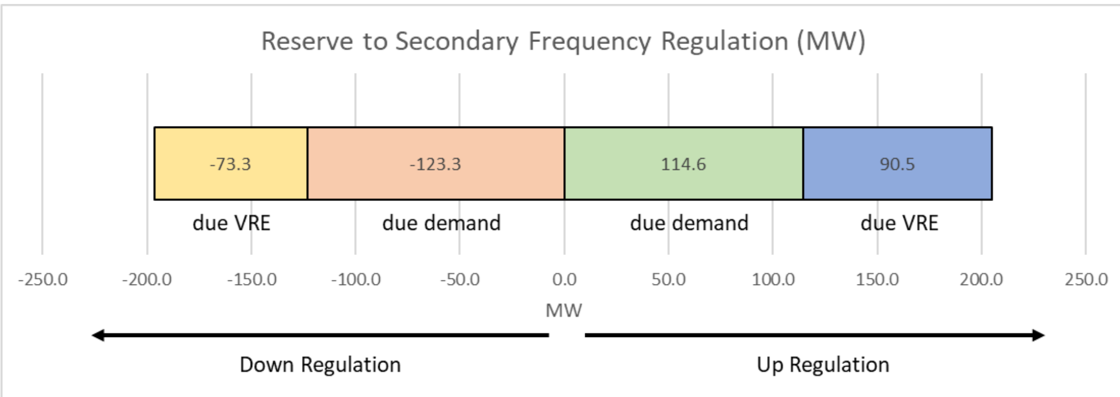
5) The forecast provider allows forecasting well in advance (in accordance with COES´ weekly programming) the deficit of solar generation either due to cloudy skies or solar eclipses. The following figure shows, for example, the case of the solar park Intipampa in which a drop in production was predicted well in advance between January 12 and 14, 2024:

FIGURE 25: Comparison of weekly forecasts provided by plant operators and emsys. Source: COES



6) The demand for balancing energy is closely related to forecast errors. Having access to better generation forecasts for solar and wind power plants could reduce the need for secondary frequency regulation. For example, on average, the allocation of positive and negative secondary frequency reserve is composed as follows:

FIGURE 26: Need for balancing energy in Peru due to deviations in demand and due to forecasting errors of vRE production. Source: COES



Source: COES, 2024, document about the external service for the vRE forecasting

As can be seen, according to COES´ calculation 90.5 MW (44%) of the positive secondary reserve is due to the forecast errors of solar and wind power plants. Likewise, 73.3 MW (37%) of the negative secondary reserve magnitude is also due to the forecast errors of solar and wind power plants. This illustrates the cost-saving potential for balancing energy if more accurate forecasts are available.

5 Conclusion

As the share of variable renewable energy (vRE) increases in the interconnected electricity system, accurate forecasts of wind and solar PV power generation are becoming essential to maintaining system stability and minimizing balancing costs.

Based on the recommendations from the previous study on improving the vRE Forecasting Framework in Peru, COES in continued partnership with GET.transform, decided to pilot a centralised forecasting system for solar PV and wind power plants. The international service provider energy & meteo system was commissioned to pilot the forecasting system.

The forecasting pilot project allowed to test for eleven months the performance of centralised solar and wind power forecasts from an external service provider in comparison to the predictions supplied by individual generators. Currently, generators are required to supply forecasting information under a decentralised forecasting system. However, there are no incentives or penalties tied to the quality of the data or for failing to submit forecasts.

The analysis of forecast data reinforced international findings: centralised forecasts are generally more reliable, consistent, and accurate than decentralized forecasts from individual operators. This provides COES with better tools for programming, dispatching, and re-dispatching Peru’s power generation fleet. Nevertheless, higher accuracy in the short-term forecast could have been achieved if the delays in transferring real-time production data to the forecasting system were reduced.

Several specific situations during the pilot project are detailed in this document. For instance, ahead of a solar eclipse, an early alert was issued, allowing COES to prepare well in advance for the event, which significantly impacted solar power production. Another example highlighted the flexibility of the centralised forecasting system, which swiftly integrated additional power plants, such as the wind parks Punta Lomitas I & II.

While Peru is still in the early stages of its energy transition, with wind and solar power contributing modestly to the national electricity supply, this is expected to change significantly in the coming years. The pilot demonstrates that centralized power forecasting can effectively accommodate the dynamic growth of wind and solar power plants, delivering more accurate and consistent results. Based on the insights gained from this pilot, COES has decided to adopt centralized power forecasts to improve the integration of solar and wind energy into Peru's power system.

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