RECOMMENDED PRACTICE FOR THE IMPLEMENTATION OF RENEWABLE ENERGY FORECASTING SOLUTIONS

- Part 1: FORECAST SOLUTION SELECTION PROCESS -

2. EDITION

Accepted by the Executive Committee of the International Energy Agency Implementing Agreement in January 2022

Prepared by IEA Wind Task 36 and 51

December 2021

Contents

Preface

This $2^n d$ edition of this recommended practice document is the result of a collaborative work that has been edited and authored by the undersigning authors in alignment with many discussions at project meetings, workshops and personal communication with colleagues, stakeholders and other interested persons throughout the phase 1 (2016-2018) and phase 2 of the IEA Wind Task 36 (2018-2021) as part of workpackage 2.1 and 3.1.
The editors want to thank the Danish EUDP for funding the work under the Grant Number 64018-0515, and everybody that contributed in our meetings, workshops and sessions to the discussions, provided feedback or other input throughout the past 6 years.

IEA Wind Task 36, December 2021

Editors and Authors:
Dr. Corinna Möhrlen (WEPROG, DK) <com@weprog.com>
Dr. John Zack (UL AWS Truepower, USA) <john.zack@ul.com>

Contributing Authors (phase I):
Dr. Jethro Browell (University of Glasgow, UK)
Dr. Jakob W. Messner (MeteoServe Wetterdienst, AT)
Dr. Aidan Tuohy (EPRI, USA)
Dr. Craig Collier (Energy Forecasting Solutions, USA)
Contributing Authors (phase II):
Dr. Jeffrey Lerner (ENFOR, DK)
Mikkel Westenholz (ENFOR, DK)
Dr. Ricardo J. Bessa (INESCTEC, PT)
Dr. Jie Yan (North China Electric Power University, CN)
Supported by:
Operating Agent Dr. Gregor Giebel (Danish Technical Univerity, DTU Wind, Denmark)

Chapter 1

Background and Objectives

1.1 BEFORE YOU START READING

This is the **first part** of a series of four recommended practice documents that address the selection, development and operation of renewable energy forecasting solutions for the optimal integration of weather-dependent variable generation into electric systems. It provides information on the selection and background information necessary to collect and evaluate when developing or renewing a wind and/or solar forecasting solution for the power market. The **second part**, *Design and Execution of Benchmarks and Trials*, of the series deal with benchmarks and trials in order to test or evaluate different forecasting solutions against each other and the fit-for-purpose. The **third part**, *Forecast Solution Evaluation*, which is the current document, provides information and guidelines regarding effective evaluation of forecasts, forecast solutions and benchmarks and trials. The **fourth part**, *Meteorological and Power Data Requirements for real-time forecasting Applications* provides guidance for the selection, deployment and maintenance of meteorological sensors and the quality control of the data produced by those sensors with the objective of maximising the value of the sensor data for real-time wind and solar power production forecasting.

If your main interest is in (2) testing or evaluating different forecasting solutions against each other, (3) verifying the quality of your forecast solution, or (4) setting up meteorological sensors or power measurements for real-time wind or solar power forecasting, please move on to part 2, 3 or 4 of this recommended practice guideline to obtain recommendations on any of these specific issues, respectively.

It is recommended to use the table of contents actively to find the topics that are most relevant for you.

1.2 BACKGROUND

The effectiveness of forecasts in reducing the variability management costs of the variable power generation from wind and solar plants is dependent upon both the accuracy of the forecasts and the ability to effectively use the forecast information in the grid management decision-making process. Therefore, there is considerable motivation for stakeholders to try to obtain high-quality forecasts and effectively use this information as input to operational business processes.

This document is intended to provide guidance to stakeholders who are seeking a forecasting solution that fits their purpose and enables them to work efficient and economically responsible. It provides important input into business processes, for those starting from scratch to build a forecasting solution, consider renewal of your IT infrastructure, require new forecasting products, or need to extend or reduce the amount of vendors engaged. An overview of the decision support tool to help develop structured processes in the design and planning of a new or updated forecasting solution including its associated data communication, can be found in chapter 3 and 4, while chapters 1 and 2 provide background information and initial considerations.

In recent years, carrying out trials or benchmarks seemed to be an industry practice with an easy and straightforward decision process for many. In reality, trials are often expensive for both the end-user and the vendor, are not straightforward, nor entirely conclusive. Benchmarks have little value for commercial vendors, except in their start-up phase, and end-users can often not count on results to indicate the state of the art for their application. Furthermore, if trials and benchmark studies lead to a dissatisfying result, forecasting solutions become increasingly criticized for their value. Providers that may have had the most technically qualified solution at hand, but did not score best at a specific (maybe oversimplified) test, may be deselected. This recommended practices document will therefore focus on the key elements to consider when establishing or updating a forecasting solution to obtain maximum value for a user-specific application. The objective is to provide data communication recommendations (chapter 4) and a decision support tool (chapter 3) to enable the user to establish procedures for an effective selection process.

1.3 OBJECTIVES

This document is intended to serve as guidance and a reference standard for the industry, academia and government for the process of obtaining an optimal wind or solar power forecast solution for their applications and, in particular, for the specification of requirements and the design of effective renewable energy forecasting solutions. These guidelines and best practices are based on years of industry experience and intended to achieve maximum benefit and efficiency for all parties involved.

1.4 DEFINITIONS

In the discussion of the process of obtaining the best possible forecasting solution, there are a number of terms and concepts that are used. Several of the key terms and concepts are defined in the following. Note, these definitions are as general as possible with a focus on forecasting processes in the power industry and may not have such a completely general character to be applied to other areas of business.

- **Request for Information (RFI)**: a RFI is a formal document through which a forecast user or potential user requests information about the state-of-the-art business practices and available commercial products in the preparation or design of a forecast application or solution for a specific target process. By providing information about the target application, a client can ask vendors for their recommendations and experience to solve specific tasks. Such information is useful in the preparation and design of a new system, but also for systems that need to be rebuilt due to changing requirements.

- **Request for Proposal (RFP)**: a RFP is a tender process, where the client prepares a document laying out the system design of a forecasting solution and asking vendors to propose a solution and price quote. Usually, a set of minimum requirements are provided that become part of a contractual agreement for the awarded vendor. Renewable Energy Forecast Benchmark: an exercise conducted to determine the features and quality of a renewable energy forecast, such as wind or solar power. The exercise is normally conducted by an institution or their agent and usually includes multiple participants from industry forecast providers or applied research academics.

- **Renewable Energy Forecast Trial**: an exercise conducted to test the features and quality of a renewable energy forecast solution, such as wind or solar power. This may include one or more participants and is normally conducted by a private company for commercial purposes. A trial is a subset of a Renewable Energy Forecast Benchmark.

Chapter 2

INITIAL CONSIDERATIONS

> ***Key Points***
> *This part provides guidelines for the task of formulating a plan and the justification for a forecasting solution selection process. It intends to assist in finding the necessary information when navigating through the vast jungle of information, opinions and possibilities and ensures that crucial details are being considered.*

2.1 TACKLING THE TASK OF ENGAGING A FORECASTER FOR THE FIRST TIME

The most important consideration, at the start of a search for an optimal forecasting solution, is a clear definition of the desired outcome. A lot of time and resources can be wasted for all parties involved in trials and benchmarks that are (1) not aligned with the requirements of the intended application, and/or planned and conducted by personnel with little or no experience in the forecast solution evaluation and selection process. To avoid this, the recommended practice is to carry out a market analysis in the form of a request for information (RFI) and to establish a requirement list (see also APPENDIX B). In some cases, it can be beneficial to test vendors or solutions prior to implementation. The difficulty with this method lies in the evaluation of tests, especially, when limited time is available for the test and the evaluation of its results. In many cases the test of the vendors do not answer the questions an end-user needs answered, because such tests mostly are simplified in comparison to the real-time application but still require significant resources. For such cases, this guideline provides other methods for an evaluation of different forecast solutions and vendors. The pitfalls and challenges with trials and/or benchmarks are the topic of part 2 of this series of recommended practices. The following table summarises some aspects and provides guidance on where and when such pilot projects, trials or benchmarks may not the best approach for the selection of a forecast solution. The column recommendation in Table provides other methodologies that may be used to evaluate a forecast solution. Additionally, a typical set of questions to be asked to service providers is provided in APPENDIX A**??**.

Table 2.1: Recommendations for initial considerations prior to forecast solution selection for typical end-user scenarios

Scenario	Limitation	Recommendation
Finding best service provider for a large portfolio (> 1000MW) distributed over a large area	Test of entire portfolio is expensive for client and service provider in terms of time and resources. Simplifying test limits reliability of result for entire portfolio.	RFI and RFP, where service providers methods are evaluated and include an incentive scheme in the contract terms to provide more security for performance (see information about incentive schemes in section 3.9.3.3 and Part 3 of this guideline [3]).
Medium sized Portfolio (500MW< X < 1000MW) over limited area	Test of entire portfolio is expensive for client and service provider in terms of time and resources. Simplifying tests limits reliability of result for entire portfolio.	RFP, where service providers methods are evaluated. Building a system that facilities an efficient change of service provider and include an incentive scheme in the contract terms may be more efficient than conducting a trial. .
Finding best service provider for small-sized portfolio (< 500MW)	Test of portfolio requires significant staff resources, a budget and a minimum of 6 months.	Difficult to achieve significance on target variable in comparison to required costs and expenses trial costs makes solution more expensive. Test is possible, but expensive. Cheaper to setup an incentive scheme and a system, where the suppliers may be exchanged relatively easily.
Micro portfolio (< 100MW) or single plants	Cost of a trial with many parties can easily be higher than the cost of a year of a forecasting service. Time for a trial can delay real-time experience by up to a year.	Evaluation of methodologies and setting up the internal system with an incentive scheme and ease of service provider exchange is more beneficial.

Scenario	Limitation	Recommendation
Sale of generation at power market	Best score difficult to define, as sale is dependent on market conditions and a statistical score like RMSE or MAE cannot reflect the best marketing strategy, considering the uncertainty of a forecast and the associated costs	Strategic choice of forecast provider and incentive scheme better than real-time test. Strategic choice may be: choice of vendor in comparison to others that use different, uncorrelated weather forecasts, uncorrelated weather-to-power model, unique forecast methodology, flexibility, expandable, etc. Incentive scheme ensures resources and incentive for continuous performance improvements (3.9.3.3).
Market share of service provider is high	Monopolies in the power market can develop easily in new markets, when "do-what-all-others-do" mentalities start prevailing and mean that forecast errors become correlated among generators.	This situation often leads to increased balancing costs, even though the forecast error might be low in general, the costs for errors may be disproportionately high due to the correlations. Ask about the market share of a provider and do not choose one with a share > 30% as the only provider!
System operation in extreme events	Today, extreme (or rare) events are better forecasted,when considering weather uncertainty.	Statistical approaches relying solely on historic information may not be sufficient. A PoE50 (probability of exceedance of 50%) needs to have equally high probability in every time step above and below. The IEA Task 36 WP 3 has been dealing with uncertainty forecasting and provides recommendations for such situations. See section . Forecasting solution needs to be weather and time dependent, i.e. only physical methodologies (ensemble forecast systems) fulfill such tasks
Critical Ramp forecasts	Critical ramp forecasts are part of an extreme event analysis and require probabilistic methods with time dependency	Consider difference between a ramp forecast and a critical ramp as extreme event analysis that requires time + space dependent prob. methods such as ensemble forecasts. See references for uncertainty forecasts.

Scenario	Limitation	Recommendation
Blind forecasting, i.e. no measurement data available for the park or portfolio	Only useful for portfolios, where small errors are canceled out and indicative regarding performance. Without measurements, forecast accuracy will be non-representative of what accuracy can be achieved by training forecasts with historical data.	Evaluation can only be carried out for day-ahead or long-term forecasts, if measurements are collected throughout the trial. If you have a portfolio > 500MW, a blind test against a running contract can provide an inexpensive way to test the potential of a new provider. For single sites, the benefits of training are so large (>50% of error reduction at times) that blind forecasting is not recommended. It wastes resources for everybody without providing useful results.
Dynamic reserve	Deterministic forecasts cannot solve reserve requirements.	It is necessary to apply probabilistic methods for reserve calculation for variable resources such as wind and solar.

2.2 Purpose and Requirements of a Forecasting Solution

Once the limitations are defined, the next step is to define what objectives the project has. As outlined in Table 3.1, very different forecasting strategies are needed for different application objectives such as the system balance of renewables or selling generated electricity into the power market). In the system balance task, extremes must be considered and risks estimated; mean error scores are not that important. Large errors are most significant, as they could potentially lead to lack of available balancing power. In the case of selling electricity into the power market, it is important to know the uncertainty of the forecast and use a forecast that is uncorrelated to others. The mean error of a forecast is important, but not a priority target, if the target e.g. is to use a forecast that generates low balancing costs. This is not always the same, because errors that lie within the forecast uncertainty are random. Such errors can only be reduced by strategic evaluations and decisions, not by methodology. If the objective is to calculate dynamic reserve requirements, probabilistic forecasts are required and should be part of the requirement list. When choosing a forecast solution, understanding the underlying requirements is key. It is not enough to ask for a specific forecast type without specifying the target objective. For this reason, defining the objective is most important. If there is no knowledge in the organisation regarding the techniques required to achieve the objective, it is recommended to start with a RFI (see section 1.4) from different forecast providers and thereby gain an understanding and overview of the various existing solution and their capabilities.

2.3 Adding Uncertainty Forecasts to Forecasting Solutions

In any power system that is in the transition to carbon neutrality, wind and solar generating resources are part of the solution. In order to integrate larger amounts of these variable energy resources, forecast uncertainty needs to be considered in grid related operational decision-making processes. Future renewable energy systems cannot be economically operated without the consideration of uncertainty in grid management decisions.

In the world meteorological organization's (WMO) guidelines on ensemble prediction [1], the WMO warns about ignoring uncertainty in forecasts, if an end-user receives a deterministic forecast. The WMO argues that *if a forecaster issues a deterministic forecast the underlying uncertainty is still there, and the forecaster has to make a best guess at the likely outcome. Unless the forecaster fully understands the decision that the user is going to make based on the forecast, and the impact of different outcomes, the forecaster's best guess may not be well tuned to the real needs of the user.*

Weather related decision-making hence requires a deeper understanding of weather uncertainty, the way any weather service provider produces uncertainty of weather forecasts, and how such forecasts are to be translated into end-user applications. In [2], a thorough review of uncertainty forecasting techniques, methods and applications has been made. This review will be the basis for the following definitions and recommendations for the selection of forecast solutions in which uncertainty forecasts are to be incorporated. It will describe how to best apply uncertainty forecasts in power system applications and identify potential gaps and pitfalls.

2.4 INFORMATION TABLE FOR SPECIFIC TOPIC TARGETS

Table 2.2 lists a number of topic targets and provides references to specific chapters of this document or other parts of this guideline series where the topic is addressed in detail.

Table 2.2: Information table for specific targets

Target	Information
How to find the best forecast solution	Section 3
Creating a requirements list	Section 3.3, 2.2, 3.2.1, and 3.2.2
Deterministic versus Probabilistic	Section 3.2.2 and 3.9.1.2
Decision support tool and practical guide to forecasting	Figure 3.1
Evaluation of vendors: interviewing or conducting trial?	Section 3.9 and References in section 5

Target	**Information**
Do I need to test reliability and consistency?	Section 3.2.1 and 3.9.2.1
How do I know which forecast solution fits my purpose best ?	Section 2.2 and 3.1 , APPENDIX A
How do I build up sufficient IT infrastructure for a trial?	Chapter 4 and RP Part 2: Trial Execution
Which metrics for what purpose?	RP Part 3: Evaluation of forecasts
Step-by-step guide for trials and benchmarks	RP Part 2: Trial Execution
Are there differences of carrying out a trial or benchmark with deterministic versus probabilistic forecasts?	RP Part 2: Trial Execution
Which requirements are needed meteorological measurements in real-time forecasting applications ?	RP Part 4: Meteorological and Power Data Requirements for real-time forecasting Applications
Which requirements are needed power measurements in real-time forecasting applications	RP Part 4: Meteorological and Power Data Requirements for real-time forecasting Applications

Chapter 3

Decision Support Tool

Practical usage of the Decision Support Tool: *The decision support tool in Figure 3.1 provides a high-level overview of the process for finding the most suitable forecast solution and vendor, respectively. The sections provide guidance in how to use the decision support tool with detailed descriptions and explanations to provide the low-level information for the detailed planning and design of the decision process.*
Note for the efficient usage of the Decision Support Tool: *the numbers in the boxes of Figure 3.1 correspond to the headings in the following sections that provide detailed information about each item.*

From an end-user perspective, it is a non-trivial task to decide which path to follow, when implementing a forecasting solution for a specific application. Whether this is at a system operator, energy management company, a power producer or power trader, there are always multiple stakeholders involved in the decision-making process. A relatively straight forward way to decide to select a specific approach for this process is to use a decision support tool.

Visualisation of the Decision Support Tool
Figure 3.1 shows a decision support tool designed for the high-level decisions of managers and non-technical staff when establishing a business case for a forecasting solution. The high-level thought construct shown in Figure 3.1 is targeted to assist in considering the required resources and involvement of departments and staff for the decision process. The decision tool is constructed to begin with initial considerations to establish a "Forecast System Plan". The tool aims to assist in taking a decision on the major dependencies to the planned item. There are cross-references in the decision tool and referrals to different decision streams depending on the answer at each step of the decision flow.

Starting at the very top, the first major dependency when planning a new or updated forecasting system is the IT infrastructure. The recommended procedure follows different

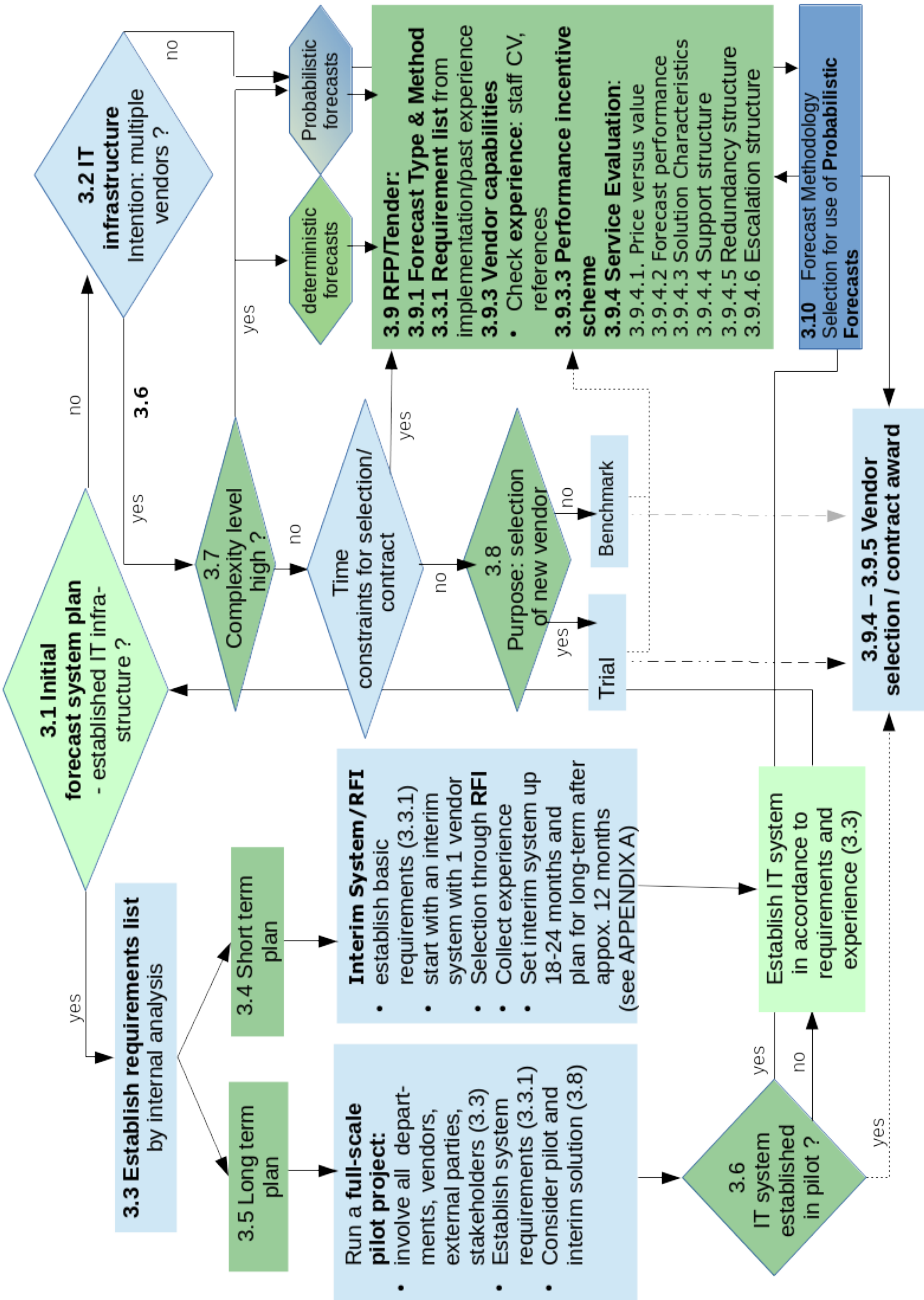

Figure 3.1: Decision Support Tool

paths depending on the status of the IT infrastructure. This is not to be understood that the IT infrastructure has higher priority over the forecasting solution itself. It is rather to sharpen the awareness that if the IT infrastructure is not in place yet or needs to be updated with new technology, the IT needs to be part of the decision process from the very beginning.

The decision support tool in Figure 3.1 provides a high-level overview of the process for finding the most suitable forecast solution and vendor, respectively. The following sections provide guidance in how to use the decision support tool with detailed descriptions and explanation to provide the low-level information for the detailed planning and design of the decision process.

3.1 INITIAL FORECAST SYSTEM PLANNING

The planning of a forecasting system for renewables is a complex task and highly specific to applications and organizations. This guideline therefore focuses solely on the aspects of general planning and management tasks specific to the implementation of wind power or solar power forecasts into an operational environment. Note that the limited information and considerations about forecast technologies or methodologies has the objective to provide guidelines on the impacts of commonly implemented technologies in the implementation and decision process. On the other hand, there is a strong focus on the IT infrastructure as one of the most crucial tasks in the implementation and integration of forecast solutions that are prone to become limiting factors for changes at later stages. For that reason, it is recommended that the IT infrastructure is established or, if already available, evaluated together with the planning of the forecast solution and methodology, in accordance to its ability to develop along with changes in forecast practices, possible statutory changes, etc. Databases are prone to have limitations that prevent changes to incorporate more information or store information differently. Such consideration need to be part of the decision process and the requirement list (see section 3.3).

3.2 IT INFRASTRUCTURE CONSIDERATIONS

The starting point of the tool is the IT infrastructure. If a company has already built an appropriate infrastructure, finding a solution or vendor is more straightforward. The reason for this is that in this case, for example, the forecast provider will need to conform to existing file formats, communication protocols or security constraints. If an IT infrastructure for the forecasting solution is to be established or updated, it needs to closely follow the technical requirements of the solution. In the other case, i.e. no IT infrastructure has been built yet, an internal analysis of the needs are required. In this analysis, it is important to know whether there is a short-term goal with an objective to be reached with time constraints, or whether it is a long-term plan that needs to be satisfied. Usually such differentiation is dependent on the policies for the development of renewable generation in the target country. The important aspects in the IT infrastructure to be considered are:

- database structure
- communication layer
- monitoring and error handling
- data storage and historic data accessibility

In general a forecast system interface, whether in-house or outsourced requires multiple data streams, starting from measured power and weather variables. Usually, there is a connection to the power units SCADA (Supervisory Control and Data Acquisition) system. However, the measurement data needs storage and a data flow to the forecaster needs to be added as an additional internal data flow process.

It needs to be decided, whether there is a need to access other external data sources, such as NWP data, or the forecast data itself.

Dependent on the setup of the forecasting solution, it is necessary to evaluate how fast accessible historic data has to be, for example to carry out internal analysis, external data delivery to vendors, etc.

3.2.1 IT requirements for single versus multiple forecast vendors

IT infrastructure impacts for multiple vendor solution:

- infrastructure more complex
- database requirements are higher due to higher data volumes
- Strategy required for forecast: mixing versus primary/secondary forecast

IT infrastructure impacts for single vendor solution:

- reliability requirement of solution high
- monitoring requirement higher for up-time
- higher requirements for quality control of forecasts
- less data volume than for multiple-vendor solutions
- database structure less complex than for multiple-vendor solutions

3.2.2 IT requirements for deterministic versus probabilistic forecasts

From an IT infrastructure and architectural perspective, deterministic and probabilistic forecasting solutions are quite different. The database requirements are typically higher by a factor of 10 to 100 for the latter. Dependent on the way the probabilistic forecasts are used, they add significant amounts to the storage requirements.
Nevertheless, the available storage and computational resources are changing with changing requirements in industry and hence should not immediately be considered a barrier or limitation for the integration or implementation of new forecasting technologies. However, careful consideration and planning is needed. The advantages and disadvantages of the deterministic versus the probabilistic solution from a IT perspective are similar to single versus multiple providers in section 3.2.1 .

3.3 ESTABLISHMENT OF REQUIREMENT LIST

Establishing a requirement list for a forecasting solution is highly specific to the characteristics of the application and the user's institution, and depends on many factors. Each end-user will have very specific needs. There are however common areas that require consideration and the following recommendation list should be interpreted from that perspective.

Two of the fundamental aspects when establishing a requirements list are:

1. Description of the current situation
   In this process, it is imperative to describe exactly all processes, where forecasting is required and how these processes are interlinked. Here it is essential to get the different departments involved, also the IT department. The more accurate you can describe the situation at hand, (e.g. integration plans, use of forecasts, market situation, statutory aspects, IT restrictions, limitations and methods for data exchange exist, current or future challenges, etc.), the more straightforward it will be to (1) ask questions to the vendors regarding forecasting methodology, but also (2) get clarity of the involved processes enabling forecasting.

2. Engage vendors, stakeholders and independent consultants
   Questions to vendors should be of technical character regarding forecast methodology, but also on available data exchange methodologies, required input data for the models and system support. If you already have a forecast vendor, it is recommended to engage with the forecaster to discuss the current situation and where the forecaster sees limitations and potential for improvements. Often, forecast providers need to adopt their forecasts to a specific need and even though a new technology may be available, it is not used due to current limitations. Other vendors, stakeholders and independent consultants may at any stage be engaged, not only when it comes to establishing a new or renewal of a forecasting system. For new systems, it is recommended to engage different forecast vendors and stakeholders to provide insight from a variety of

experiences. In all cases, it is essential to describe the planned objective and name limitations, if they are already known. The more information that can be shared the better a vendor, stakeholder or consultant can evaluate what is considered the most appropriate solution.

Appendix A contains an additional listing of recommended considerations that are applicable also for RFIs.

3. Description of the envisioned situation
The description of the envisioned situation is most important for the implementation of a solution. Analysis of the current situation, the forecast vendor(s) input and other organizational and statutory requirements should lay the basis for the vision of a new system. It is recommended to put as much detail into this part as possible. The following requirements list assists in defining all aspects for the planning phase of a forecasting system. Recommendation in short: Describe (1) the current situation, (2) engage vendors and stakeholders and (3) describe the envisaged situation in great detail. Ask specific questions that are required to get the highest possible level of detail for the decision process.

***Recommendation Summary**: Describe (1) the current situation, (2) engage vendors and stakeholders and (3) describe the envisioned situation in great detail. Ask specific questions that are required to get the highest possible level of detail for the decision process.*

3.3.1 Requirement List

The following areas are recommended to be considered in the list:

IT infrastructure:

- communication/data exchange with the forecast vendor(s)
- communication/data exchange with the assets (wind/solar parks)
- database and storage implications
- accessibility of data information of internal users
- application interfaces to internal tools (e.g. graphics, models, verification, metering)
- information security policies

Forecast Methodology and Attributes:

- Weather input
- Methodology of weather to power model
- Application/model background for each forecast product
- Forecast time horizons
- Forecast frequency
- Forecast uncertainty

Support and Service:

- service level for each product (e.g. 24/7, business hours etc.)
- system recovery
- failure notifications and reporting
- escalation procedures
- service documentation
- contact list for different services
- staff training

Contracting:

- contract length
- amendment possibilities
- additional work outside contract
- licenses
- confidentiality (NDA)
- insurances
- sub-contracting
- Price table for each product category

Performance and Incentivization:

- verification methods
- verification parameter
- definition of payment structure (boolean or sliding areas)
- expected accuracy for each forecast horizon

3.4 SHORT-TERM SOLUTION

In this case, current requirements should be listed and analysed in accordance with possible time limitations. It is recommended that a short-term solution be sought if the political situation does not seem to be stable to make long-term investments, or a here-and-now issue needs to be solved and experience gained. In such cases, a relatively simple methodology that can be implemented fast and easy is the best way forward. Today, this can be found by carrying out a RFI, where vendors can suggest the best approach to fulfill very specific needs with the lowest level of cost and effort. Due to IT constraints in many organizations, such solutions are sometimes set up with delivery by email. This is not a recommended practice for security and reliability reasons, but can help to fill a gap between a long-term solution and an urgent need.

Despite the shortcomings, interim solutions are recommended as they are valuable in respect to experience with the handling of forecasting data inside an organization. If such solutions are employed while a long-term plan is being developed, it can be of great benefit for the long-term solution. Such solutions should last approximately 18-24 months. Planning for a long-term solution should ideally start after 12 months.

The danger lies in staying with an interim solution, if it has real limitations on security (e.g. email delivery) and reliability, as such limitations may not be problematic for a long time, but reliance on non-redundant systems can cause sudden uncontrollable situations. For this reason, the question about the IT system is raised at the end of the short-term solution, as this is a crucial part in the next step. It is recommended that this should be a priority topic, once practical experience with forecasting has been gained.

3.5 LONG-TERM SOLUTION

Developing a long-term solution can be cumbersome and difficult, as many aspects have to be considered, from policies to governmental plans or corporate strategies. A practical way forward is to conduct a full-scale pilot project, where different solutions are tested and verified over a period of at least one year. The advantage of such a pilot project is that there is the possibility to verify and evaluate different solutions and their fit for purpose over a longer time span.
A pilot project is characterised by:

1. Involvement of all relevant internal and external stakeholders
2. Establishment of system requirements
3. Possible use as interim solution

The disadvantage of a pilot project is that it takes a long time and hence is costly, and it is not certain that it will produce a very clear winning solution for a specific area or task. On the other hand, to find the most appropriate long-term solution needs many considerations, not only technically, but also economically and whether a solution is future compatible. So, the experience of the vendor in adjusting, maintaining and developing a solution with changing needs may be a challenge for some and the business philosophy for others. Such vendor policies can be identified and clarified when carrying out long-term tests. The box therefore feeds into the question about an appropriate IT system. If this has not been established, it is recommended to prioritise the IT before going further.

Optional paths at end of a pilot project:

1. Vendor selection
2. Redefining requirements to start a solution bottom up
3. Carrying out a RFP with the identified requirements.

3.6 GOING FORWARD WITH AN ESTABLISHED IT SYSTEM

In the case an IT system has been established and new vendors or an update of an existing system is the objective for the project, there are various possibilities to move forward. Crucial in this phase is again to set a target and objectives. If the target is to find out, whether there exist forecast vendors on the market that may provide forecasts with other methods or for a lower price, a good way forward may be to carry out a trial or benchmark. Dependent on the structure of the system, or complexity of the system and time constraints, a benchmark/trial or a RFP as alternative are recommended. One crucial criterion when deciding between an RFP or a trial/benchmark is whether the existing IT structure can handle multiple suppliers. If this is not the case, any evaluation against an existing supplier can be cumbersome and at times impossible. The recommended practices guideline part 2 provides details on this topic, which is mostly related to:

- **representative** (including consistency)
- **significant** (including repeatable)
- **relevant** (including fair and transparent)

These are the key points when carrying out a forecast performance comparison.

3.7 COMPLEXITY LEVEL OF THE EXISTING IT SOLUTION

Apart from accuracy or statistical skills of forecasts, there are also other aspects to be considered when choosing a forecast supplier. It has been observed that evaluations based on non-technical skills or skills leading to forecast performance for a specific purpose have been underestimated in their importance. One aspect is the ability to improve, which is fully excluded with a trial/benchmark as the sole decision-making criterion (besides price) for the selection of a vendor. It is often forgotten that long-term experience in a specific area can provide significant advantages. On the other hand, verifying only a small part of a complex system for practical reasons may result in a misleading result (see 3.6 representative, significant and relevant).

The complexity of a system that a forecast solution must adapt to, but also the data flow that complex systems inherit, is seldom easy to simulate in trials and will always disqualify some participants, when it comes to the real system. To conclude, the complexity of a system and the purpose of a forecast within a complex corporate structure are significant aspects to consider in a forecast solution selection.

> ***Recommendation:*** *In case of complex structures and requirements it is best to employ a RFP process in which the core capabilities of potential forecast solutions are evaluated.*

3.8 SELECTION OF A NEW VENDOR VERSUS BENCHMARKING EXISTING VENDOR

If there are no time constraints and the complexity level of the operational system is not too high, or a new system is in the process of being built, a trial or a benchmark exercise can be very useful in order to acquire experience in the building process.

> ***Recommendation:*** *A trial should be conducted in cases in which a new vendor will be selected and a trial can be executed in a manner that yields results that are fair, transparent, representative and significant. A benchmark should be conducted if the initial objective is not to engage a new vendor, but to compare the capabilities of an existing vendor to other vendors or to newer forecasting technology. In both cases the invited vendors should be notified of the purpose of the exercise.*

3.9 RFP EVALUATION CRITERIA FOR A FORECAST SOLUTION

If complexity levels are high and if time constraints do not allow for a lengthy trial or benchmark, the RFP should be compiled with care in order to address all requirements and yet not ask for more than is needed. The most important evaluation criteria for a forecast solution to be defined in a RFP is:

- the type of forecast that is required (e.g., hours-, day-, or week-ahead)
- the methodology that is applied to generate these forecasts
- compliance to requirements

It is recommended that this first step should be vendor independent. And, if this cannot be defined, it is recommended to first conduct an RFI to survey the industry on their capabilities and their recommendations on the forecast type and methodology that should be employed for the specific needs of a user's application. Appendix B contains typical questions for an RFI. Input from specific vendors should only be used after the forecast type and methodology have been defined via a vendor-independent process. At this point, the important vendor-related factors to consider are:

- capabilities (experience)
- support and maintenance services

The following sections describe these considerations in detail.

3.9.1 Forecast Solution Type

Most users will agree that they want to obtain forecasts with the best possible forecast accuracy for their application. A benchmark or a trial has in the past often been viewed as a way to determine which provider is most likely to deliver the best possible forecast performance. In theory, this is a reasonable perspective. In practice, it is not recommended relying solely on results from a trial or benchmark. The following subsections will address a number of key issues associated with the dilemma of finding the best forecasting solution with a simple and low-cost exercise for both the end-user and the forecast provider.

3.9.1.1 Single versus multiple forecast providers

It has been widely documented (e.g. Nielsen et al., 2007, Sanchez, 2008) that a composite of two or more state-of-the-art forecasts will often achieve better performance (accuracy) than any of the individual members of the composite over a statistically meaningful period of time. Indeed, many of the FSPs internally base their approach and services on that concept. There are certainly significant reasons for an end-user to consider the use of multiple FSPs to achieve better forecast accuracy. However, in a practical sense, there are several advantages and disadvantages that should be considered. When building a solution, it is recommended to consider the following aspects: Benefits of using multiple vendors:

1. There are a number of FSPs in todays forecast market that exhibit performance that is close to the state-of-the-art. It may be advantageous for reliability to assemble a set of state-of-the-art forecasts.

2. Higher forecast accuracy can often be achieved by blending forecasts from multiple state-of-the-art FSPs whose forecasts errors have a relatively low correlation.

The benefits of employing multiple forecast vendors also contain inherent challenges for the end-user:

1. Increased internal costs, even if two cheap vendors may be less costly than one high-end forecast vendor, employing multiple vendors increases internal costs significantly due to increased amounts of data and IT processes.

2. Blending algorithms need to be intelligent. Multiple forecasts can be beneficial, but only, if the algorithm is intelligent to only blend/mix, if all forecasts are available and easy to retrain if forecast statistics change. With two forecast vendors, this is relatively easy. If there are more than two, it becomes more complex.

3. Forecast improvements are more complex and difficult to achieve with a multi-provider solution. When improvements are achieved on the vendor side, the blending algorithm becomes inconsistent with those changes, and this can result in worse performance for the composite forecast unless long-term historic data can be delivered to retrain the blending algorithm.

4. It is more difficult to incentivize multi-vendor solutions to achieve continuous performance improvement over time. Although incentive schemes can be a good way to provide resources to the FSP for continuous improvements, this can be counterproductive in a multi-vendor environment because changes to the statistical characteristics of forecasts can have a negative influence on the resulting blended forecast. An end-user needs to be aware of this pitfall, when choosing a multi-vendor solution, and take mitigating measures.

5. Multiple points of failure - with multiple forecast providers, the IT infrastructure needs to contain more logic to deal with one or more data streams when there are, for example, delivery disruptions, timeliness, or quality issues.

3.9.1.2 Deterministic versus Probabilistic

Many forecasting applications need a discrete answer. For that reason, most users have historically employed deterministic forecasts for their applications. Although weather forecasts and hence also power forecasts of variable resources such as wind and solar power, contain inherent uncertainties, probabilistic forecast products have been associated with forecasts not being discrete. The probability of a generic power generation at time x cannot be used in a trading application with the purpose of bidding into the market. As the penetration of variable generation resources increase and digitalization increases, the uncertainty information for decision-making can and is being processed by algorithms, including those who yield a discrete answer for the ultimate decision-making process. Deterministic forecasts by default ignore the underlying uncertainty in the forecasts. By using probabilistic forecasts, this uncertainty can be taken into consideration in the decision processes.

The most common products of uncertainty or probabilistic forecasts are the probability of exceedance (PoE) values, typically given as PoE05, PoE50 and Poe95, quantiles, or percentiles or confidence bands (see Glossary for definitions).

The advantage of probabilistic/uncertainty forecasts in comparison to the deterministic best guesses is the possibility to act upon the probability of an event, rather than being surprised, when the deterministic forecast is wrong. In power markets, for example, a probability of exceedance of 50% (PoE50) is an important parameter for a system operator, because such forecasts prevent the market from skillfully speculating on system imbalance. Extreme ramping, high-speed shut-down risk, unit commitment and dynamic reserve allocation are other examples, where probabilistic forecasts are beneficial or required. In other words, in situations in which there is sufficient forecast uncertainty to have a significant impact on a decision or the costs of a process, probabilistic forecasts provide the necessary information to an end-user to make a decision with a consideration of objective uncertainty information.

Recommendation: *When establishing or updating a forecasting system, the question should not be posed on advantages and disadvantages for deterministic or probabilistic forecast solution, but rather whether a deterministic solution can achieve the objective of the application. Section 3.10 describes uncertainty forecasts and how to select the appropriate probabilistic methodology for specific applications.*
A thorough academic review about probabilistic methodologies can be found in the References Material under Uncertainty Forecast Information in section 5

3.9.1.3 Forecast horizons

The forecast horizons play a major role in the ability to plan using forecasts. Today, there are 5 general classes of forecast horizons widely used in the power industry:

1. Minute-ahead forecasts or nowcasts (0-120min)
2. Hours-ahead forecasts (0-12 hours)
3. Day-ahead forecasts (0-48 hours)
4. Week-ahead forecasts (48-180 hours)
5. Seasonal forecasts (monthly or yearly)

The Minute-ahead forecasts are in literature also sometimes referred to as “ultra-short term forecast” or “nowcast” and are mainly used in areas with high penetration and high complexity in system operation or significant risk for high-speed shut down and extreme events. These forecasts are either based on a statistical extrapolation of power generation measurements or a combination of weather input and high frequency (e.g. 1 minute) measurements of generation. The recommended practice depends on the severity and costs of the target value. For situational awareness, a simple extrapolation of measurements may be sufficient. For extreme events (e.g. ramps, high-speed shut down) the involvement of weather related forecasts in high time resolution is recommended.

Hours-ahead forecasts or sometimes referred to as short-term forecasts correct a day-ahead forecast by using real-time measurements. These forecasts extrapolate from recent real-time power generation data and local area real-time weather observations to obtain a more accurate representation of the current state and the anticipated changes over the next few hours.

There are different methods available, from simple extrapolation of measurements to advanced weather and distance-dependent algorithms. Its recommended to get details of a short-term forecast methodology described by the vendors, as quality and usability can differ strongly with availability of data, quality of measurement data etc.

If the target is e.g. ramp forecasting, system control, a very large fleet or quality issues with measurement data not dealt with by the end-user, simple algorithms are often not capable of providing a good enough picture of the next few hours.

The Day-ahead forecasts are widely-used forecasts for general system operation, trading and short-term planning. Traditionally, they are based on a combination of weather models and statistical models.

The Week-ahead forecasts, sometimes referred to as long-term forecasts, are usually applied in cases where the focus is not on forecast accuracy, but on forecast skill, e.g. in situations, where trends prevail over granularity. These forecasts are most valuable as a blending of a number of different forecasts or from an ensemble predication system, where the small-scale variability is reduced. If this is done, such forecasts can serve to reduce reserve costs and generate more dynamic reserve allocation as well as auctions. The Seasonal forecasts sometimes referred to as ultra-long-term forecasts, predict variations due to seasonal and or climate variability. They may be derived based on climatology, correlation to various climate indices and oscillatory phenomena, climate models, or a combination of these methods. Ensemble methodologies are the most preferable method due to the inherent uncertainty on such time frames. The most simple method is to analyze past measurements.

> ***Recommendation:*** *Key when choosing a methodology is to carefully analyze the accuracy requirements of the task to solve. For trading of futures in a trading environment a simple methodology may be sufficient. Tasks such as grid balancing, grid infrastructure planning or long-term capacity planning however require more advanced methodologies. It is recommended to choose the method according to the need to capture quantities only (simple method) or capture also climatic extremes (advanced method).*

3.9.2 Vendor Capabilities

3.9.2.1 Experience and Reliability

Experience is a key element of a successful vendor and implementation of the forecasting solution. It can usually be evaluated by the selected references that are provided and mea-

sured by conducting interviews with customers of similar type or by asking for information about the vendors background and experience with similar customers. If a vendor is new to the market that may not be possible. In this case, staff resources and the experience of the key staff are a useful indicator of whether the experience level for the minimum requirements is present.
Reliability is often associated with experience, as it implies the reliable implementation and real-time operation of a forecasting service. It is an important aspect and may be derived by requiring examples of similar projects and interviewing references. It can also save a lot of work and resources in comparison to carrying out a trial, if reliability and experience with respect to e.g. complex IT infrastructure, security aspects, reliable delivery and provision of support etc. are a more crucial aspect than specific statistical performance scores.

> ***Recommendation:*** *Ask vendors to describe their experience, provide user references and also the CV of key staff members.*

3.9.2.2 Ability to maintain state-of-the-art performance

The previous section provided an overview of all the considerations for the technical aspects of forecast type and methodology. In order to assure that the forecast vendor can maintain state-of-the-art performance, it is recommended to determine the extent of a provider's ongoing method refinement/development and forecast improvement activities. Recommendation: Evaluate by asking the vendor to provide information about

- research areas and engagement
- references to staff publications of e.g. their methodology, project reports
- references of participation in conferences/workshops
- percent of revenue reinvested into research and development

3.9.2.3 Performance incentive Schemes

A performance incentive scheme is the most effective way to ensure that a forecaster has an incentive to improve forecasts over time and also allocates resources to it. By setting up a performance incentive scheme, the client acknowledges that development requires resources and vendors have not only an economic incentive to allocate resources for further developments, but can also influence their reputation. Incentive schemes do not have to be enormously high, but usually range between 10-30% of the yearly forecast service fee.

A key attribute of an effective performance incentive scheme is that it reflects the importance of the forecast performance parameters that are most critical for a client's application. The evaluation of such forecast parameters should be selected according to:

1. the objective of the forecasting solution

2. the use/application of the forecasts
3. the available input at forecast generation time

The **first objective** in this context is defined as the purpose of the forecast. For example, if a forecast is used for system balance, an evaluation should contain a number of statistical metrics and ensure that there is an understanding of the error sources that the forecaster can improve on. A typical pitfall is to measure performance only with one standard metric, rather than a framework of metrics reflecting the cost or loss of a forecast solution in the context of a user's application. For example, if the mean absolute error (MAE) is chosen to evaluate the performance in system balance, an asymmetry in price for forecast errors will not be taken into account. Also, if e.g. large errors pose exponentially increasing costs, an average metric is unsuitable.

The **second objective** (use or application of forecasts) is defined in the context of where forecasts are used in the organization and where these have impact and influence on internal performance metrics or economic measures. For example, a wind power forecast that a trader uses for trading the generation of a wind farm on a power market has two components: revenue and imbalance costs. The revenue is defined by the market price for each time interval, whereas the cost is defined by the error of the forecast, the individual decision that may have been added to the forecast and the system balance price. When evaluating a forecast in its application context, it is important to choose an evaluation that incentivizes the vendor to tune the forecast to the application. A forecast that is optimized to avoid large errors may create lower revenue. However, if income is evaluated rather than revenue, such a forecast may be superior due to lower imbalance costs. On the other hand, if the end-user makes changes to the forecast along the process chain, the forecast evaluation must not include forecast modifications that are outside the forecast vendors influence.

The **third objective** (available input at forecast generation time) is most important when evaluating short-term forecasts that use real-time measurements. For example, if the forecast is evaluated against a persistence forecast with corrected measurements rather than with the measurements that were available at the time of forecast generation, the evaluation is to the disadvantage of the forecaster. The same applies, if aspects that affect the forecast such as curtailments, dispatch instructions, turbine availability, are not taken out of the evaluation either by excluding periods when these occur or by correcting the measured data to eliminate their impact.

> ***Recommendation:*** *When incentivizing a forecast solution with a performance incentive, the evaluation needs to consider the non-technical constraints in the forecast and the parts that a forecaster does not have influence upon. A fair performance incentive scheme needs to measures the performance of a forecast by blacklisting any measurement data that is incorrect or corrupt, that contains curtailments, dispatch instructions, reduced availability or other reductions outside of the forecasters influence. Evaluation against persistence forecasts also need to be done with the available data at the time of forecast generation in order to not give advantage to persistence.*

Additionally, single standard statistical metric (e.g. MAE or RMSE) alone are not recommended. More details on the purpose and interconnection of statistical metrics for evaluation of incentive schemes can be found in part 3 of this recommended practice and in the references under Evaluation and Metrics.

The structure of performance incentive scheme is an individual process and contractual matter between parties. When establishing the structure of a performance incentive it is recommended to consider that by choosing a maximum and minimum, the maximum value provides budget security to the end-user, also when e.g. changing from a very simple solution to an advanced one with much higher performance. The latter provides security to the forecaster to ensure that the basic costs for generation of forecasts are covered. Adding a sliding structure in between ensures the forecaster always has an incentive to improve, also when it is foreseeable that the maximum may not be achievable.

> ***Recommendation:*** *it is recommended to apply a maximum incentive payment and a maximum penalty or minimum incentive. A sliding change is preferable over a boolean (yes|no) decision for incentive payments, as it always encourages forecast improvement efforts.*

3.9.3 Evaluation of Services

The recommended practice in any evaluation is to consider a number of factors that contribute to the value that a user will obtain from a forecast service. It is not possible to provide a complete list of factors to consider. However, the most important factors that should be addressed are the following elements:

- Price versus value and quality
- Forecast performance
- Solution characteristics
- Speed of delivery
- Support structure

- Redundancy structure

The issues associated with each of these aspects will be addressed in the following subsections in more detail.

3.9.3.1 Price versus Value and Quality

The value of a forecast may or may not be directly measurable. In most cases however, the value can be defined for example in terms of cost savings or obligations and in that way provide an indication of the expected value from a certain solution. Prices are difficult to evaluate. A low price often indicates that not all requirements may be adequately fulfilled in operation or not all contractual items are accepted and left to the negotiations. For these reasons, care has to be taken in the evaluation process. Some services and methods are more expensive than others because of computational efforts, required licenses, database requirements, redundancy to insure reliability and other factors. Unless prices are driven by competition in a overheated market, a service price is normally coupled to the requirements and acceptance of contractual items. Some items such as reliability, customer support or system recovery can have high prices, but can always be negotiated to a different level. In an RFP end-users need to be aware of the relation between cost, value and associated service level to prevent vendors from speculating on negotiable items in the requirement list.

> ***Recommendation:*** *Following a decade of experience in the forecasting industry, the recommended practice on price evaluation is to connect technical and contractual aspects to the price and let vendors provide proposed contractual terms that may be associated with high service costs separately, especially, if a fixed cost price is requested. An example could be the requirement of full system recovery within 2 hours in a 24/7/365 environment. If there is no penalty associated, a vendor may ignore this requirement, which may result in a much lower price. Requesting transparent pricing makes the evaluation process easier and makes sure that negotiable aspects of a service can be clearly compared.*

3.9.3.2 Forecast Performance

Forecast performance evaluation should contain a number of metrics that are representative of the needs of the forecast user. It is recommended that an evaluation framework for the performance evaluation be established. The process of establishing such a framework is addressed in Part 3 of this recommended practice.

3.9.3.3 Solution Characteristics

The solution characteristics of a forecast service also contains much value for an end-user and should get attention in the evaluation. It can be defined in terms of the available graphical tools, ease of IT services for retrieving data or exchanging data in real-time as well as historical data, customer support setup and staff resources connected to the forecasting solution. This can be a key factor for the operational staff of the forecast user to accept and be comfortable with a forecast service, as well as having confidence in the service. Additional work that may be connected, but outside the scope of the operational service, can also be key elements for a well-functioning service. Recommendation: Ask the vendor to describe how the forecast system will be constructed, their vision for communication and support, and to provide examples of forecast graphics (if applicable).

3.9.3.4 Support Structure

Customer service is often under-estimated and in most cases second to an accuracy metric when selecting a vendor. Support can be a costly oversight if, for example, costs are related to a continuously running system or extreme events, where the user needs an effective warning system and related customer service. Support can have a relatively large cost in a service contract and may provide a false impression of service prices, if, for example support is only offered at business hours.

Key elements for the customer support is:

- the responsiveness of the provider, when issues arise
- live support in critical situations

A support structure and its management for operational processes additionally need to bind the following strategic areas together:

1. Customer Support
2. Operations Software and Service
3. IT Infrastructure

The customer support (1) should be handled by a support platform, ideally with different forms for contact, e.g. a telephone hotline and an email ticket system.

End-users should ensure that third-party software used in the operational environment (2) is licensed, renewed in a timely manner and maintained according to the licensing partys recommendations.

The IT infrastructure (3) should ideally be ISO 9001 and ISO 27001 certified in cases, where real-time operation and security is of paramount importance.

> ***Recommendation:*** *Definition of the required support structure should be part of the requirement list for any forecasting solution. For real-time forecasting solutions end-user need to ensure that there is an appropriate support structure in place. Considerations of the real-time environment, the user's resources and which of the forecasting business practices are of significance to the user should be carried out. Especially, where processes are expected to run every day in the year.*

3.9.3.5 Redundancy Structure

Redundancy depends very much on the end-users needs to maintain a frictionless and continuous operation. Forecasting is mostly carried out in real-time, which has an inherit requirement of being functional all the time. While there are many processes and targets for forecasting that may not require large redundancy and permanent up-time, the following recommendation is targeted to those end-users where forecasting is to some extend mission critical. There are a number of different redundancy levels that need consideration and that can be achieved in various ways:

1. Physical delivery of the service IT infrastructure
2. Content of the delivery – Forecasting methods

The delivery of the service (1) is connected to the IT infrastructure. Redundancy measures may be a combination of any of these:

- Delivery from multiple locations to mitigate connectivity failures
- Delivery from multiple hardware/servers to mitigate individual server failure
- Delivery with redundant firewalls to mitigate hardware failure
- Delivery through an ISP using Email, etc.

The redundancy of the forecast content is equally important as the physical delivery of the data, but often neglected. It is recommended to consider any combination of the following redundancy measures for correct forecast content:

- redundant providers of weather input
- redundant/multiple providers of forecast service
- redundant input and mitigation strategy for weather models
- redundant input and mitigation strategy to power conversion models

> ***Recommendation:*** *Define the required redundancy level according to the importance of a permanent functioning service and the impact of delivery failure on other internal critical processes.*

Table 3.1: Recommendation of a three tier escalation structure.

Escalation Level	Forecast service provider coordination	End-user coordination
Level 1: failure to deliver service	Technical Staff	Operations Staff Project manager
Level 2: failure to recover or implement service	Project manager	Project/Department manager
Level 3: failure to solve failure/recovery	General management	General management

3.9.3.6 Escalation Structure

It is recommended for high-level contracts, where forecasting is critical to the end-users processes to get information about escalation structures in case of failure. This is especially important when employing only one forecast provider. Recommendation: An end-user needs to have a description about structure and corresponding responsibilities for their operations staff in order to incorporate such information into own escalation structures in case of emergencies.

Each level of escalation ideally contains the following structured process:

- Formulation of the problem/failure
- Root cause analysis
- Coordination of action plan for troubleshooting inclusive responsibilities
- Coordinated action plan progression
- Escalation to the next level or closure of escalation procedure

3.10 Forecast Methodology Selection for use of Probabilistic Forecasts

Currently, methodologies used to generate probabilistic uncertainty forecasts for the power industry have proven concepts and are integrated in today's business practices. Looking into these applications, it becomes apparent that uncertainty forecasts have found their place in the power industry, but are on the other hand far from being optimally exploited in most applications. As the level of penetration of variable generation resources increases, the value of uncertainty information in operational processes will increase and provide greater incentive to optimize their use in operational processes.

The following definitions and recommendations are intended to assist in the implementation of uncertainty information in the form of probabilistic forecasts into operational processes. While this guide aims to be comprehensive, it is not possible to provide all the details that may be necessary for a first time implementation or for the planning of a fully integrated probabilistic forecast solution. Nevertheless, the information provided is taken from existing documentation, partially coordinated by the IEA Wind Task 36, but also from general publications. This information can be found in in the References Material under Uncertainty Forecast Information 5, especially the reviews on probabilistic methods for the power industry [**?**] and on uncovering wind power forecasting uncertainty origins and development through the whole modelling chain [4].

3.10.1 Definitions of Uncertainty

In order to establish a common language of uncertainty forecasts, the most common definitions of uncertainty are explained. These are:

1. forecast error spread:
   the historically observed deviation of a forecast from its corresponding observation at a specific time. It can also refer to a reference error magnitude provided by an error metric, e.g. variance or standard deviation.

2. confidence interval:
   A confidence interval displays the probability that an observed value will fall between a pair of forecast values around the mean. Confidence intervals measure the degree of uncertainty or certainty in a *sampling method*, not the forecast [1]. They are often constructed using confidence levels of 5%, 95% etc.

3. forecast uncertainty:
   is defined as a possible range of forecast values in the future. In meteorology this range is defined by the uncertainty of the atmospheric development in the future and represented in ensemble forecasts by applying perturbations to initial and boundary conditions and expressing model physics differences.

4. forecast interval:
   determined uncertainty band representing **forecast uncertainty** and containing the respective probability of the real value being contained in the range of forecasted values, which will only be observed in the future.

Forecast intervals are the most common used visualisation for forecast uncertainty. They can be derived from

(a) parametric (e.g. Gaussian distribution)

[1]One of the common misunderstandings is that a **confidence interval** is showing the uncertainty of a forecast. This is not the case. By adding and subtracting for example one standard deviation to the deterministic forecast of wind speed and converting it to wind power, such intervals represent a measure of the deviation to climatology and do not represent current or geographically distributed uncertainty.

(b) non-parametric (e.g. empirical distribution functions, kernel density estimation) representations of uncertainty

(c) a larger number of NWP forecasts in an ensemble forecasting system that represent the forecast uncertainty of the target variable

From these probability density functions (PDFs), quantiles or percentiles[2] can be extracted and higher-order statistics such as skewness and kurtosis can be calculated. This is where the distinction is most pronounced: from a statistical error measure like standard deviation, it is not possible to derive quantiles or percentiles.

For applications like reserve predictions, ramp constraints or optimization tasks for storage applications, this distinction is imperative. Such applications also require that the geographical distribution of the variables are captured by scenarios of ensembles of possible outcomes of a pre-defined value.

3.10.2 Uncertainty Forecasting Methods

Forecast uncertainty for application in the power industry are today based on three main processes and procedures (fig. 3.2):

1. **Statistical methods:**
   This method is based on statistical processing of past (historic) data in order to derive a probability density function of the possible forecasting spread. The advantage of such methods are that they are computationally extremely cheap and simple to apply. The disadvantage is that none of these methods produce a realistic representation of the forecast uncertainty in a spatial and temporal manner. There is also no physical dependency on the forward results, as the spread is based on past climatology. Typically, statistical learning algorithms (e.g., neural networks, machine learning) are used to fit historical time series of weather parameters from a NWP model to their corresponding power generation data. From the fitting process, a PDF can be derived and used forward in time. A newer, more intelligent method is the analogue ensemble method (AnEn) that searches through historical forecasts for those past events that are most similar or "analogous" to the current forecast. The observations with the best fit form the probability distribution of the forecast uncertainty. So far the method is one-dimensional and hence does not take geographical or temporal aspects of uncertainty into account. To be able to benefit from integration of information from geographically distributed time series or from a grid of NWP the methods needs to add a second dimension. Another approach is to use copula theory, which offers a flexible approach to the probabilistic power forecast taking the spatial correlation of the forecast errors into account[**? ?**].

[2]In statistics and the theory of probability, quantiles are cut points dividing the range of a probability distribution into contiguous intervals with equal probabilities. The 100-quantiles are called percentiles.

2. **Spacial-temporal statistical Method:**
With this method, statistically-based scenarios are produced that are a result of statistical generation of scenarios from the probability distributions produced by statistical models based on the copula theory. We define them as scenarios, as the further processing of the approach contains x independent results in contrast to the statistical method, producing a PDF function. Such scenarios are quite similar to the third methods, the physically-based ensembles. However, the uncertainty representation of the statistical scenarios today only capture the spatial variability of the forecast, like ramps. We therefore distinguish them here as scenarios rather than ensembles. Outliers that indicate extreme events, for example above cut-out wind speeds of wind turbines can only be detected with probability characterisation and require an extreme event analysis. This is due to the conversion to power taking place in the first step of the statistical training in the same way as for deterministic forecasts. Extremes in wind power are in that way difficult to detect, because the flat part of the power curve prevents extremes that would be visible in the wind speeds to show up in the power scenarios. The clear advantage of the statistically based scenarios is that they are computationally much cheaper than physical ensembles, as they are built from a deterministic weather forecast. They also generate a much more realistic uncertainty representation than the pure statistical approach, while only being slightly more computationally costly.

3. **Physically based ensemble forecast Method:**
The third type of methodologies, the "physically based ensembles" that have to be sub-divided into 2 types:

   (a) The first type ensemble is generated by perturbing a deterministic NWP forecast model's initial conditions. Often ensemble prediction systems (EPS) are found to be "under-dispersive", i.e. the uncertainty spread under-estimates the true uncertainty of the target variables (i.e. the ensemble spread is too narrow meaning it is "too confident" relative to the observed outcomes). This can have many reasons, some often found reasons being that:
      (a) the ensemble is not targeted to the variable of interest of the end-user
      (b) the time or spatial resolution is too coarse to capture the small scale phenomena of the target variable
      (c) insufficient information is extracted or used in the conversion to wind power to represent a realistic uncertainty. Mostly such deficiencies can be mitigated by calibration methods ((see e.g. [2**?**]).

   (b) The second type can be considered a post-processing of a set of NWP ensemble members. The ensemble members are a set of deterministic NWP forecasts produced by perturbing the initial or boundary conditions (i.e. input data for a specific forecast) and/or the formulation of model physics. The perturbations of the model physics can be in the form of alternative sub-models (e.g. for radiative processes or water phase changes associated with clouds and precipitation) within a single NWP model (referred to as a "multi-scheme" approach) or a set of different NWP models (referred to as a "multi-model" approach. The meteorological variable output from each ensemble member is converted in a subsequent phase into power with a curve fitting method (see e.g. [2]). The NWP ensemble is configured to represent the physical uncertainty of the weather ahead of time rather than uncertainty as a function of past experience. In practice, this means that the NWP ensembles, especially the multi-scheme approach, can produce outliers, because they are event driven and also represent NWP model uncertainty. This means that they can represent extreme events, even those with return periods of 50 years or more. This is a clear distinction from statistical methods, because even long time-series of historic data contain too few extreme events to have impact in learning algorithms.

3.10.3 Training Tools for ensemble forecasting

An example of a training tool is the Ensemble Prediction System (EPS) Training course created by the Meteorological Service of Canada. This course has three objectives:

(i) introduce participants to ensemble forecasting

(ii) provide basic training on EPS for operational forecasters

(iii) move away from the deterministic paradigm towards a probabilistic paradigm.

The training tool is available for download at: (`http://collaboration.cmc.ec.gc.ca/cmc/ensemble/Formation-Training/Read-me.html`

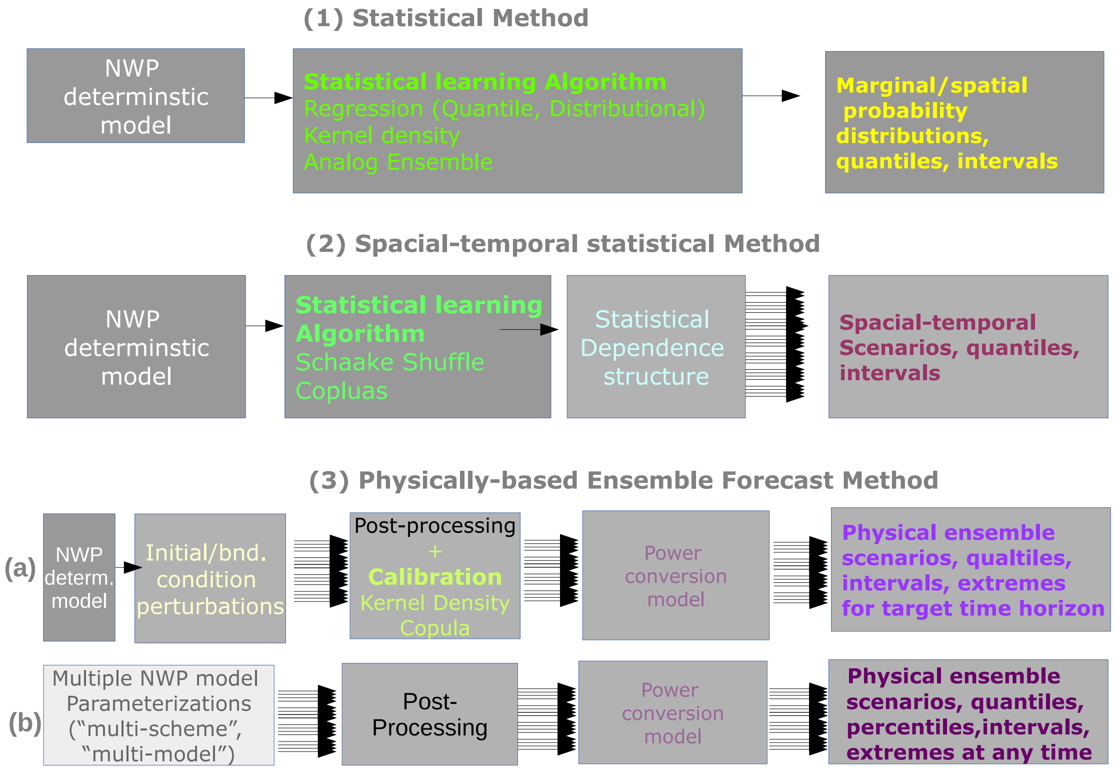

Figure 3.2: Standard methods of uncertainty forecast generation to be used in wind power and PV forecasting. The black arrows indicate whether the so-called ensemble members stem from a statistical procedure or are individual scenarios.

Recommendation: *when selecting an uncertainty (probabilistic) forecast method for a specific application, it is important to know, whether or not a specific method is suitable for the application or not. There are 3 major branches of uncertainty generating forecasting methods:*

1. *Statistical methods of probabilistic forecasts*
2. *Statistically-based ensemble scenarios*
3. *Physically based ensemble forecasts*

We have provided some basic guidance and a graph (fig. 3.2) summarising these methods in order to differentiate between the methods, showed the spatial and temporal dependencies of some methods and emphasised that the statistical methods are not suitable for applications that have such dependencies to the uncertainty measure of interest. These are e.g. applications that deal with extremes that may not happen frequently or where the uncertainty estimate is required in each hour of the forecasts rather than over a forecast period of a day or a week.
More information about probabilistic methodologies can be found in the References Material under Uncertainty Forecast Information, especially in a review on probabilistic methods for the power industry [6].

3.10.4 Applications of Uncertainty Forecasts in the Energy Industry

Typical applications in the energy industry, where it is recommended to use uncertainty forecasts, are:

1. **Balancing/trading of wind/solar power:**
   For balancing and trading applications the optimal bid/schedule, from the expected value decision paradigm, consists in a quantile calculated from the forecasted imbalance costs [7] or a percentile calculated from an ensemble forecasting system [9**?**]. The calibration of uncertainty is a critical requirement for the end-user and has a non-marginal economic impact. Moreover, in electricity markets with high integration levels of wind/solar power, the combination of extreme forecast errors and high imbalance prices is critical and demands for risk modelling techniques and uncertainty forecasts with high accuracy in detecting extreme events (e.g., cut-out wind speed, ramps) ([2]). If the portfolio includes also energy storage units, the temporal dependency of forecast uncertainty is a primary requirement [10]. For this use case, the end-user should request ensemble forecasts from physically based methods (see 3.10.2).

2. **Dynamic reserve and ramping reserve requirements:**
   The use of uncertainty forecasts for setting the power system reserve requirements is probably the most well-accepted business case for the energy industry. A critical requirement is minimum deviation from perfect calibration to avoid under- and over-estimation of the risk (i.e., loss of load probability, probability of curtailing renewable energy) [11]. Another criteria in the design of dynamic reserve allocation are the boundaries that need to be defined. The following aspects are crucial boundaries in this respect:

   - **Use the correct type of ensemble data input**
     Physical NWP ensemble: e.g. multi-scheme approach
     Deterministic reserves do not provide uncertainty
     It is the weather uncertainty that generates the errors

   - **Clear definition of the forecast objective**
     Which types of errors are critical
     How to handle outliers
     What type of reserve fits to the end-users objective:
     typical scenarios are: static, security or dynamic/economic

   - **Definition of the time scales that needs to be forecasted**
     Required ramping capabilities

- **Forecast uncertainty required for all weather dependent sources & sinks**
  The uncertainty term should ideally be built upon load+wind+solar
- **Definition of a noise term to handle the non-local imbalances**
  imbalances from interconnections (small system <-> large system)

Allocating reserve dynamically requires probabilistic forecasts and the value for the system operator is well defined. Yet, the following challenges also need to be addressed, when implementing probabilistic forecasts for dynamic reserve requirements and allocation:

(i) communication and visualisation of forecast uncertainty and extreme events in TSO dispatch centers

(ii) training of human operators to understand and exploit the probabilistic information, i.e. move from a deterministic/ real-time paradigm to probabilistic/predictive operation paradigm.

An example of a dynamic reserve visualisation tool is illustrated and described in Appendix C.

3. **Extreme event warning such as high-speed shut down warnings:**
   For risk indices, it is imperative that there exists a well-justified and transparent underlying computation of the conditions that may lead to a shut-down event that may impact system security, which should be provided as early in the evolution of the event as feasible. It is generally accepted that a planned scheduled shut-down at a slightly lower wind speed extends the lifetime of the gearbox system in wind turbines. Therefore, one could argue that there is modest economic loss by executing controlled shutdowns to reduce the ramp-rate in a power system.

   The value of such alert systems is gained with early detection of extreme events. This can for example be accomplished by introducing a gradual artificial transition from full generation to no generation at 22.5 m/s. The starting point of such an index will be discussed below. A simple argument for 22.5 m/s is that 2 m/s is the typical forecast accuracy at such high wind speeds.

   A "high-speed wind event" can be defined as active, if the hub height wind speed is above 24.5m/s, while there is no event, if the wind speed is below 22.5m/s. Table 3.2 shows how such an index may be defined.

   The required low level forecast information to raise alerts can be generated in a typical 6-hourly cycle, although it may be coupled with a short-term forecast on a shorter frequency dependent on the importance of critical ramps for system security. One of the major challenges for such an alarm system is in fact the strategy of dissemination of the warning information to the user in the control room. If a critical event is discovered about 5 days in advance, the question is how often a warning should be issued, also in order to avoid too many false alarms or forecast misses. Threshold values for alert

Table 3.2: Definitions of a high-speed shutdown index for a control area with a high penetration level of wind power and a wind resource with a high variability and wind speeds often exceeding 25 m/s.

wind speed in 100m	index value
0 - 22.5 m/s	0.00%
22.5 - 24.5 m/s	0 -> 100%
24.5 m/s	100.00%

generation therefore has to be a function of lead time, time of the day and day of the week.

The more alerts there are generated, the less serious they are taken and the higher the likelihood that a critical event is overlooked. Nevertheless, there are periods where events should create alertness, even though they may not result in a sufficient strong concurrent shutdown. Typical examples could be:

- An alert at a 6-day horizon issued on a Thursday valid for Tuesday morning following a long holiday weekend may be desirable even if the likelihood is low.
- An alert to cause attention on a change of expected ramp rate 6 hours ahead, even though there has already been raised an alert for the event from previous forecasts

The objective for such an alert must always be to avoid costly actions to be initiated, if there is a critical ramp rate in the forecast far enough away that an economic solution can be prepared.

As briefly discussed below under *situational awareness*, if a major fraction of the power generation is wind dependent, it would be considered best practice, if the operator is aware of the risk of high-speed shutdown, even if the likelihood is low, but still justifiable. The same applies to the ramp rate caused by a fast moving low pressure system, where the wind speeds at the center of the system may be below the cut-in level. Both event types can simultaneously amplify the ramp down rate and call therefore for a ramp rate based consideration instead of an isolated high-speed shutdown consideration.

4. **Situational awareness:**
For system operators, but also wind farm operators or trader, information from uncertainty forecasts can be integrated at two levels:

   (a) *Visualization and cognition*: provision of alarms and early warnings to human operators about predefined events with impact in the frequency control tasks, e.g.

large ramps, wind turbines tripping, large forecast errors. With this information, the human operator can use his/her experience or operating practice to derive a set of control actions (e.g., change current dispatch, activate reserve) that mitigate the effects of renewable energy uncertainty and variability in the system's frequency.

(b) *Technical evaluation of network constraints*: uncertainty forecasts can be integrated in a power flow module, available in commercial energy management systems (EMS), to detect voltage and congestion problems with a certain probability threshold [12]. With this information the human operator can plan preventive actions in advance, e.g. change the market dispatch, define a cape for market offers in a specific network area/node.

The following requirements should be requested by the end-user for the forecasting provider:

(a) high accuracy in detecting extreme events related to RES uncertainty and variability

(b) capacity to capture the temporal and spatial dependency of forecast errors

5. **Flexibility management in smart power grids:**
The deployment of smart grid technology enables the control of distributed energy resources (DER), e.g. storage and demand response, which flexibility can contribute to increase the RES hosting capacity while maintaining the standard quality of supply levels. The combination of forecasting systems and optimal power flow tools can be used by transmission and distribution system operators to pre-book flexibility for the next hours in order to handle the technical constraints of their electrical network [13].

Presently, distribution system operators are starting to explore RES forecasts in the following use cases: a) forecast grid operating conditions for the next hours; b) improved scheduling and technical assessment of transformer maintenance plans; c) contract and activate flexibility from DER to solve technical problems.

In all these cases, a primary requirement is the need to have a spatial-temporal representation of forecast uncertainty, where the temporal component is only relevant, if inter-temporal constraints are required (e.g., operation of storage devices, control of capacitor banks and on load tap changers).

Finally, a current topic of interest is the coordination between the transmission and distribution systems. Different frameworks for information management and exchange are under discussion [14]. It is clear that uncertainty forecasts can be used to provide future information about nodal consumption/injection in the interface between the two networks. For example, the FP7 European Project evolvDSO developed the concept of flexibility maps, where RES forecasts are used to quantify the operating point and flexibility range in the TSO-DSO interface [15]. This paves the way to combine information about forecast uncertainty and flexibility, as proposed in [16].

Recommendation:
The transition of the energy systems towards a CO_2-free power generation with large-scale integration of renewables on a global basis also requires a restructuring of the power system operation processes. The variable generating units driven by wind and solar resources call for a more dynamic and weather-driven structure for the operating practice. Probabilistic forecasts can support that dynamic structure and provide the possibility to deal with the uncertainties associated with the non-linear attributes of weather event development as well as extremes that can affect the power system and cause large-scale blackouts.
No forecasting solution today should be designed without the uncertainty of weather-driven energy resources in mind. At present, the primary cases of the integration of uncertainty forecasts into the operational processes of energy systems are for the following application types:

1. Balancing/trading of wind/solar power
2. Dynamic reserve and ramping reserve requirements
3. Extreme event warning such as high-speed shut down warnings
4. Situational awareness
5. Flexibility management in smart power grids

The basics of these methodologies have been described in this section. Detailed implementation information about the described probabilistic methodologies can be found in the References Material under Uncertainty Forecast Information, especially in a review on probabilistic methods for the power industry [2, 4, 17, 18].

3.10.5 Visualisation of forecast uncertainty

Many users have found that the visualisation of uncertainty forecasts is a difficult issue. This is especially true for the inexperienced user. While an expert immediately can see the difference between a chart generated with a statistical approach and an ensemble approach as defined in section 3.10.2, a beginner often finds it difficult to differentiate between the results of these two approaches.

The following subsections provide a general overview of alternative approaches for the graphical visualization of uncertainty forecasts.

1. "**Fan Chart**"

   The "fan chart" is a common way of visualising a set of *forecast intervals* that are aggregated in one plot. Fan chart visualizations as shown in Figure 3.3 may however provide misleading information to a decision-maker. For example, if the decision-maker interprets each one of the quantiles as a possible evolution of wind power production in time, the user needs to be sure that the visualization tool uses the data that is expected in order to interpret the information correct.

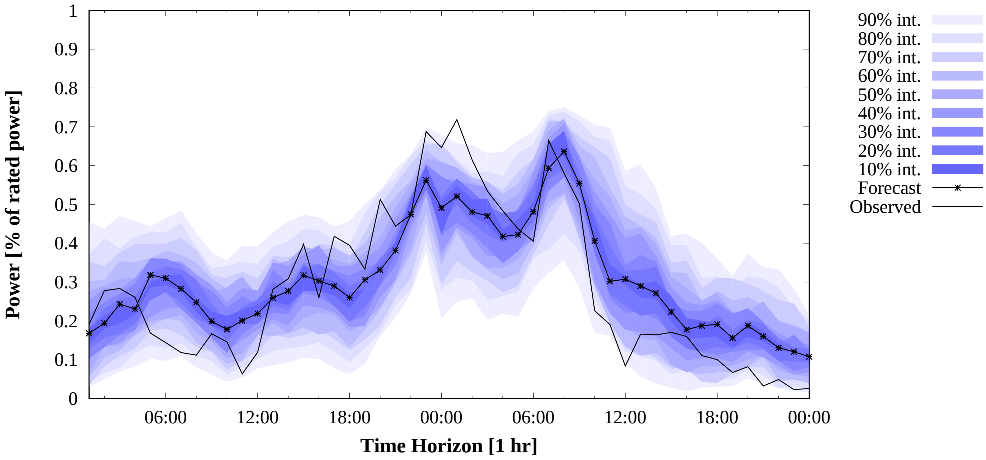

Figure 3.3: Example of a "Fan chart" of wind power production at a single wind farm built from marginal forecast intervals of a statistical method.

Differentiation of forecast methods used in the fan chart:

- **statitical method**:
  A fan chart generated with a statistical method visualizes the "marginal forecast interval", meaning each interval is only confined to separated forecast lead-times and does not have information about the joint probability distribution across the full set of lead times, or in other words, these intervals are not modeling the inter-temporal dependency structure of forecast uncertainty. These intervals are different for each lead-time. Figure 3.3 shows an example of a fan chart where the intervals were generated with a statistical model. The lead-time dependence is visible through the relatively equal intervals in size over the entire forecast. In this example, the observations (black solid line) are covered, except for a short period around midnight of the first day.
  In that hour there is a probability of around $\alpha = 90\%$ (limited by quantiles 95% and 5%) that the observed value is within approximately $P_{t+k}^{\tau^L} = 0.18$ and $P_{t+k}^{\tau^H} = 0.65$. This is the typical interpretation. Looking at the observations, another way to interpret is that there is a 5% likelihood that the observations are within $P_{t+k}^{\tau^L} = 0.63$ and $P_{t+k}^{\tau^H} = 0.65$.
- **Ensemble Method**:
  In Figure 3.4 we also see forecast intervals for the same wind farm and day. This time, the intervals were formed of 300 wind speeds in 4 different heights by a 75-member multi-scheme NWP-based ensemble prediction system (MSEPS).

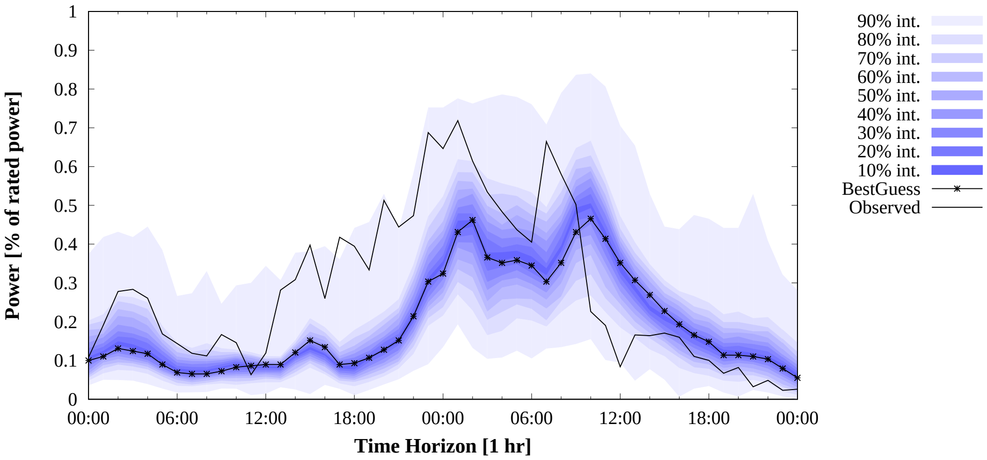

Figure 3.4: Example of a "Fan chart" of wind power forecasts at the same time and wind farm as in 3.3, but built by a 75-member multi-scheme NWP ensemble system (MSEPS).

These intervals look very different from the statistically generated intervals. Even though the 90% probability is within approximately $P^{\tau^L}_{t+k} = 0.21$ and $P^{\tau^H}_{t+k} = 0.75$, the 5% probability that the observations is found within the upper quantile has an interval size of 0.25 (range $P^{\tau^L}_{t+k} = 0.50$ and $P^{\tau^H}_{t+k} = 0.75$). That means the interval size is larger by a factor of 10. Compared to the statistical method, this result indicates that the current weather development contains a low probability for a high uncertainty range towards increased production.

Especially the physical based multi-scheme approach that provides the uncertainty in each time step quantifies the uncertainty with the knowledge of current meteorological conditions and different physical approaches to compute the future development, rather than comparing the situation with past data.

Any application that may be subject to extreme events that may not have happened within the last months or years, should use uncertainty forecasts from this method and make sure that this information is evident in the visualisation of the forecasts.

2. **"Spaghetti Plot"**

Figure 3.5 shows the same wind farm, forecast days and method as in Figure 3.4, but as individual forecasts in a so-called spaghetti-plot where each of the 300 wind power forecasts are one line. In this way, it becomes apparent, how individual ensemble forecast "members" can generate outliers.

In comparison to the lead-time dependent approach, the physical approach forms a large outer quantile band and a more condensed inner part, indicating that many of the 75 forecasts are aligned in their atmospheric development, while there are a small number of forecasts that result in higher power generation. The difference here is that

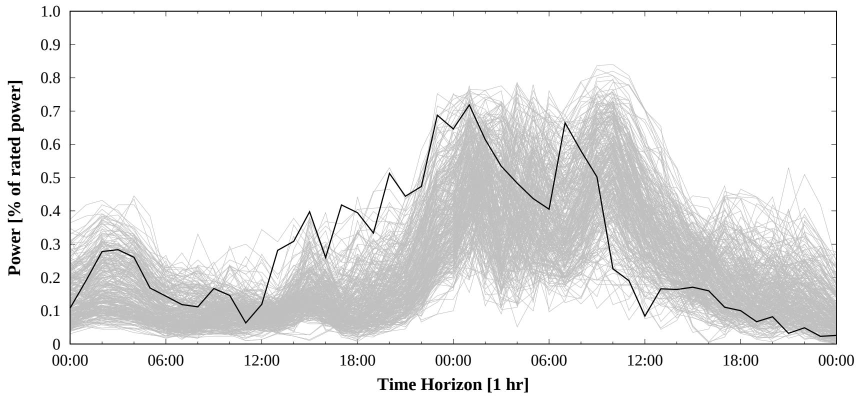

Figure 3.5: Example of a spaghetti plot of 300 wind power forecasts at the same time and wind farm and method as in 3.4.

the intervals are a result of the NWP ensembles reproducing the physical uncertainty of the current atmospheric processes that generate the power and are fully independent of the lead-time. Here, a large spread can be generated based on a very low likelihood or probability, also if such events have not been observed before.

An operator or trader has a number of ways to interpret such a forecast. Two likely scenarios could be:

(a) ignoring the outer interval and acting upon the highest probability ranges

(b) verifying the system upon issues or the market price that could arise, if the low probability of high generation would become reality

Whether the operator or trader acts upon such a forecast depends on their business practices. Nevertheless, it shows that the information contained in the forecast intervals have a direct practical application.

Take-away from the Visualisation of Uncertainty:
The different results illustrate that the successful interpretation of such information depends on an understanding of the the algorithm used to generate the uncertainty estimates. The major difference here is that one method is based on current atmospheric conditions (NWP ensemble) and the other relies on an historical dataset of the atmospheric conditions. With the historical method, the intervals of extremes are usually smaller and less pronounced unless there are long time series available that contain a significant number of such extremes to impact the spread in given weather conditions.

Chapter 4

DATA COMMUNICATION

Key Points

This section provides recommendations for forecast data-related terminology, data description and data formats and exchange protocols

- The **terminology section** (4.1) provides definitions for terms commonly used in the description and exchange of data between forecast providers and users
- The **description section** (4.2) provides a specification of the mandatory and optional types of data required to train and operate a forecasting system
- The **exchange section** (4.3) provides recommended standards for data formats and exchange protocols. The standards are presented for two levels of users:

  Level 1: basic data format and data exchange for groups with limited IT knowledge and/or experience

  Level 2: detailed description of more sophisticated formats and exchange protocols that enable groups with more extensive IT knowledge, experience and resources to achieve higher level of data exchange robustness and efficiency.

Currently, there exists no best practices or standard for (1) definitions of the various inputs that are used to configure and operate a renewable energy forecasting system, (2) data formats and (3) data exchange protocols. Forecast suppliers and consumers use different terminology and can end up spending many hours on unnecessary communication. This is a problem which ultimately comes at a cost to the supplier, energy forecast purchaser and overall cost of operating renewable energy projects. Similarly, there is no standard or recommended best practice for the format of the data used by the forecasting systems and the methods for delivering this data. This also creates additional delays and inefficiencies in the forecast setup process.

Two user groups are targeted in this recommendation. These are referred to as Level 1 and Level 2 users in this document:

Level 1 users: this group typically has limited IT resources or experience. Input documents are geared towards manual input of forecast specifications.

Level 2 users: this user group will have a deeper IT knowledge or experience than Level 1 users. Input file format examples and exchange methods presented here may be programmatically adopted for real-time use.

Once adherence to the data exchange standard is attained, the benefits are numerous and tangible. For the supplier of renewable energy forecasts this is:

1. More efficient onboarding Level 1 consumers (i.e., with less experience using forecasts or less IT expertise) standard templates are followed; for more advanced, Level 2 users, the onboarding process can be mostly automated.

2. Back-and-forth communication time is minimised - Online references to standard documentation reduces communication blockages between forecast supplier and consumer.

3. Greater automation of adding/removing renewable power plants to forecast engine. Adhering to a standard reduces (doesnt eliminate) the need for customised software development

For the renewable energy forecast consumer, some benefits of adhering to the data exchange interface include:

- A much more efficient process to benchmark different forecast providers

- Easier to add, remove, or switch forecast providers

- Quicker turnaround time in adding or removing forecast projects to asset portfolio

- No need to develop new processes for different weather-impacted renewable technologies

This recommended practice can be applied to many types of renewable generation entities. The focus of this specification is forecasting of individual renewable projects. An aggregate or area-level forecast is not specifically addressed in this document, as these configurations are less common. However, aggregations and area forecasts may be treated like a single project or be specifically coded by a unique ID (e.g., Wind Region 01). Data field definitions are also provided in the hopes of promoting a standard definition for these fields. However, we recognise that there are many factors that make data definition standards more challenging and beyond the scope of this recommendation. For example:

- Industry-specific standards several industries are involved in the Renewable Energy industry and each has its own data definitions for similar fields. This includes OEM (turbine manufacturers), independent engineers (consultants), SCADA software companies, renewable plant developers, utilities, and TSO or ISOs.
- Geographic location terminology and translation from one language to another.

Different standardisation bodies governing different industries also can present challenges, but for renewable energy forecasting, the International Electrotechnical Commission (IEC) is the generally accepted organisation that establishes, promotes, and updates data definition standards.

4.1 Terminology

For clarification, several terms are defined below that appear repeatedly in this section.

Renewable Energy Forecast Customer/Consumer: an institution or corporation that requires a forecast of power from a renewable energy generation facility with a look-ahead time of minutes to days.

Renewable Energy Forecast Provider: an institution or corporation that delivers renewable energy forecasts with a look-ahead time of minutes to days. In most cases, the provider is a company whos business includes selling forecasts to customers/consumers.

Renewable Energy Forecast Trial: an exercise conducted to test the features and quality of a renewable energy forecast such as wind or solar power. This may include one or more participants and is normally conducted by a private company for commercial purposes. A trial is a subset of a Renewable Energy Forecast Benchmark.

Renewable Energy Forecast Benchmark: an exercise conducted to determine the features and quality of a renewable energy forecast, such as wind or solar power. The exercise is normally conducted by an institution or their agent and multiple participants, including private industry forecast providers or applied research academics.

Online measurements: These are observations used for tuning a renewable energy forecast system and adjusting intra-day renewable energy forecasts. Measurements are usually power or energy, since that is the target variable of interest to the consumer. However, other weather variables might be included with online measurements. Online measurements are also referred to as real-time measurements and are transferred between forecast customer and provider on a regular basis.

Offline measurement: These are observations used for tuning a renewable energy forecast system. As opposed to online, offline observations are historical and dont directly impact short term (< 12 hours) forecast horizons. Measurements are usually power or energy since that is the target variable of interest to the consumer. Other weather variables might be used for energy forecast training, especially for a newly operational renewable energy plant.

4.2 Data Description

This standard interface is defined on two levels. Ideally, renewable energy forecast customers and renewable energy forecast providers should comply with both level 1 and level 2 of the standard, but only complying with level 1 can also provide significant efficiency gains during the setup of a forecasting system. The two levels are:
Level 1: A high-level description of the information and data required to carry out a successful trial and operation of a specific forecast solution. This level of standardisation provides a common terminology that will enable the renewable forecast customer to prepare and organise data facilitating an efficient system configuration process.

Level 2: A detailed specification of both the format and method, which should be used to exchange data between the renewable forecasting provider and the renewable energy forecasting customer. This level of standardisation enables an efficient, repeatable and scalable configuration process applicable to trials as well as operational forecast systems. Compliance with level 2 facilitates renewable energy forecast customers to efficiently carry out trials/benchmarks as well as enabling renewable energy forecast providers to participate in trials/benchmarks efficiently and at low costs.
Online/real-time measurements are suited for both intraday and day-ahead forecasting whereas offline measurements are best for day-ahead forecasting only.

Mandatory and optional data
The metadata tables and definitions below specify some data to be mandatory in order to setup a meaningful forecasting system. Other data is considered optional as those data may improve forecast accuracy, take into account a future operating state of the renewable energy plant, or might be less common requirements of the forecast consumer. All renewable energy forecast consumers should be able to provide the mandatory data and all forecast providers should be able to process mandatory data, whereas optional data depends on specifics to each forecast installation.

4.2.1 LEVEL 1 Data description

Table 4.1 provides an overview of the different data types required by a forecasting system. This data needs to be available to the forecast provider for both training and operating a forecasting system. Table 4.2 provides an overview of the different types of meta data, which describes the attributes of the data types listed in Table 4.1. Tables 4.3 to Table 4.7 contain the data field and definitions that a forecast solution will require configuring an operational forecast.

Table 4.1: List of the different types of input and output data needed in a forecast setup

Data	Type of Data	Description of the Type of Data
Master Data	Site information	A specification/description of the site(s). A description can contain one or more sites. A site can be an aggregate of multiple sites. All sites in the same description must have similar data structure as specified in the associated meta data descriptions. If the data structures are not similar, then the sites need to be split up into multiple Sites and multiple meta data descriptions.
Online Data	Measurements	Observational data from a site which will be used as input for training models produced by the forecast system.
	Future Availability	The data about expected future availability of the site(s) due to maintenance, curtailment or other planned schedules. Used as input to the forecast.
	Forecasts	The output data (results) produced by the forecast system.

It is important to note that Measurements data should be made available both as historical data (also referred to as Offline Data) for training of models and as operational or real-time data (also referred to as Online Data) for operational forecasting. If available, the forecast customer should provide a minimum of 3 months of historical Measurements, but ideally 1-2 years of historical data to capture both seasonal and inter-annual variability.

Metadata, also referred to as Master Data, has a broad definition but generally refers to information that describes the forecast configuration or the data itself. In most cases, it should not change often. The different types of metadata needed for renewable energy forecast include information about the sites, the measurements, and the forecast configuration. This is detailed in Table 4.2 .

The metadata about the renewable energy site (or power plant) itself is often the first information a forecast supplier will need to initially set up a forecast installation and is, therefore, essential to be accurate and from the forecast consumer. Table 4.3 details the renewable energy site metadata.

Table 4.2: List of different types of meta data needed in a forecast setup

Type of meta data	Description of the meta data
Site specification	This is a description of the renewable energy power plant characteristics. Most of the characteristics dont change often with time.
Measurement specification	This is a description of the attributes of the observational data sent to the forecasting system. Measurement meta data may be separated into realtime (online) and historical (offline) measurements because these can often be described differently or represent different parameters.
Forecast Time Series specification	This is a description of the forecast system product which is the time series output.
Scheduled Availability specification	This is a description of the forecasted or scheduled availability at the power plant.
Forecast system specification	A description of the necessary inputs and outputs that tells the forecasting system how to model the target forecast variable(s). This includes forecast system and output attributes such as units, variables, timing, and temporal resolution.

Table 4.3: Specification of the data required for describing a renewable energy site

Sites:
The sites description can contain data about one or more site(s). A site can be comprised of an aggregate of sites or, in the case of wind, an aggregate of individual turbines. For each site the following data needs to be filled out.

Description	Mandatory /optional	Wind/ PV/Both	Type	Data field
Plant Name ID	Unique ID (name) used for identifying the site(s)	Mandatory	Both	String
Generation Type	Either Wind or Solar	Mandatory	Both	String
Latitude	Latitude coordinate of Plant Name in decimal degrees.	Mandatory	Both	Float
Longitude	Latitude coordinate of Plant Name in decimal degrees.	Mandatory	Both	Float
Capacity	Capacity of the site (often also referred to as the rated power of the site) for which the forecast should not exceed (kW)	Mandatory	Both	String
Hub height	The average height of the wind turbine hubs (meters)	Mandatory	Wind	Float

Description	Mandatory /optional	Wind/ PV/Both	Type	Data field
Number of turbines	Number of turbines that comprise wind farm	Mandatory	Wind	Integer
Wind turbine make and model	Turbine manufacturer and model name	Mandatory	Wind	String
Turbine power curve*	Default power curve table of wind speeds and corresponding power capacity factor. May be turbine manufacturers specification. Normalized by rated capacity in the range [0, 1]	Optional	Wind	Float
Solar Technology	Description of the PV technology. Fixed-tilt, single axis or dual axis are most common.	Mandatory	PV	String
Minimum panel orientation angle	The minimum orientation angle of the PV panels in degrees from north (0 to 359, where east is 90ř and west is 270ř). If the system is single axis tracking or fixed tilt, then minimum and maximum orientation should be the same.	Mandatory	PV	Integer
Maximum panel orientation angle	The maximum orientation angle of the PV panels in degrees from north (0 to 359, where east is 90ř and west is 270ř). If the system is single axis tracking or fixed tilt, then minimum and maximum orientation should be the same.	Mandatory	PV	Integer
Minimum panel inclination angle	The minimum angle of the PV panels in degrees from horizontal (-90 - +90). If the system is fixed tilt, then minimum and maximum inclination should be the same.	Mandatory	PV	Integer
Maximum panel inclination angle	The maximum angle of the PV panels in degrees from horizontal (-90 - +90). If the system is fixed tilt, then minimum and maximum inclination should be the same.	Mandatory	PV	Integer

Description	Mandatory /optional	Wind/ PV/Both	Type	Data field
Panel tested capacity	The total solar panel capacity for the site (kW) based on standard test conditions (1000W/m^2) at panel temperature of 25řC	Optional	PV	Float
Panel temperature sensitivity	The temperature sensitivity of the PV panels (%/řC)	Optional	PV	Float
Inverter capacity	The capacity (kW) of the inverters	Optional	PV	Float
Inverter efficiency	The inverter efficiency at 95% load	Optional	PV	Float

* Turbine power curve table is often appended or delivered separately.

Measurement data for the forecast site is often provided prior to the configuration of the forecast system to calibrate the forecast model and thus reduce forecast error. If the renewable energy site has been in operations, then this would likely include power observations since that is typically the target forecast variable. However, for new renewable energy sites, a history of wind speed or irradiance is often provided to the forecast supplier which may help reduce forecast error until a suitable history of power observations is obtained.

Table 4.4 details the specific fields that describe the measurement data required for renewable energy forecast model training. This table should be filled out more than once if the historical measurement data differs in any way from the online (realtime) data being sent to the Forecast Provider. Differences may arise due to the type of observation (e.g., SCADA power versus settlement power observations, wind speed from a met tower versus nacelle anemometer average wind speed).

Table 4.4: Specification of the data required for describing the forecast system input measurements

Measurements:
The Measurements should be delivered for each site and contain the information described below. All values must be available with the same granularity, e.g. every 5 minutes and with a fixed update frequency.

Data field	**Description**	**Mandatory /optional**	**Wind/ PV/Both**	**Type**
TIME SERIES FIELDS				
Plant Name ID	Unique ID (name) used for identifying the site(s)	Mandatory	Both	String
StartTime	Date and time stamp indicating the start of the period for which the measurements are observed.	Mandatory	Both	String
EndTime	Date and time stamp indicating the end of the period for which the measurements are observed.	Mandatory	Both	String
Power	The power production (kW) when the measurement was observed	Mandatory	Both	Float
Available capacity	The observed available capacity (kW) of the site due to a reduction in available generators. If wind turbines, solar panels or inverters are not available (due to maintenance, break downs or similar) the capacity of the site is temporarily reduced.	Optional	Both	Float
Limitation level	The limitation (kW) of the site due to curtailment, set point level, do not exceed limitations or down regulation. This includes non-scheduled changes by grid operator.	Optional	Both	Float
Wind speed	Wind speed (m/s) from a representative instrument. For example, a mean of the turbine nacelles, a meteorological tower anemometer or LIDAR instrument).	Optional	Both	Float
Wind direction	Wind direction measured in degrees from north (0-359ř). East = 90ř, South= 180ř, West = 270ř, North = 0ř.	Optional	Wind	Float
Temperature	Air temperature (degrees Celsius)	Optional	Both	Float

Data field	**Description**	**Mandatory /optional**	**Wind/ PV/Both**	**Type**
Pressure	Atmospheric air pressure (hectopascals, hPa)	Optional	Both	Float
Relative Humidity	Relative humidity of the air (%)	Optional	Both	Float
Precipitation	The amount of rain or snow that has fallen on the ground (millimeters, mm)	Optional	Both	Float
Global Horizontal Irradiance	The total short-wave radiation from the sky falling onto a horizontal surface (W/m^2)	Optional	PV	Float
Global tilted irradiance	The total short-wave radiation from the sky falling onto a tilted surface (W/m^2)	Optional	PV	Float
Direct solar irradiance	The short-wave radiation that has not experienced scattering in the atmosphere (W/m^2). The radition comes from the disc of the sun.	Optional	PV	Float
Diffuse irradiance	The short-wave radiation from light scattered by the atmosphere excluding from the disc of the sun (W/m^2)	Optional	PV	Float
META DATA				
Time zone	The time zone of the timestamp in IANA Time Zone (TZ) database format (e.g, Europe/Barcelona)	Mandatory	Both	String
Time interval label	Describes what time the measurement point represents. Can be instantaneous, period beginning average (leading), or period ending average (trailing)	Mandatory	Both	String
Power measurement type	This field is a text description of the power measurement field. It can be, for example: substation meter, SCADA power, active power, potential power, settlement power.	Optional	Both	String
Wind speed measurement type	Specify if the wind measurement for the site is from turbine nacelle, average of nacelle, met mast or other.	Optional	Both	String
Wind speed measurement height	The height of the wind speed measurement in meters.	Optional	Both	Float

Most forecast suppliers have the ability to incorporate scheduled changes to the renewable plants availability on the forecasted output. This comes in the form of reduced capacity owing to reduction in available units (e.g., turbines or inverters) or due to a generating limit of the power plant (e.g., curtailment or transmission limit).). The important distinction between an outage and limitation is that an outage is a proportional reduction in the plants capacity for all wind or solar irradiation conditions. The limitation is a maximum capped output (e.g., set point) of the plant based on the available capacity. This information needs to be described as it will routinely be sent from the forecast consumer to the forecast supplier. Table 4.5 details this information.

Table 4.5: Specification of the data required for describing the future availability and curtailments

Scheduled Availability: Future availability and curtailments for each site, should contain the information described below.				
Data field	**Description**	**Mandatory /optional**	**Wind/ PV/Both**	**Type**
Plant Name ID	Unique ID (name) used for identifying the site(s)	Mandatory	Both	String
StartTime	Date and time stamp indicating the start of the period for which the measurements are observed.	Mandatory	Both	String
EndTime	Date and time stamp indicating the end of the period for which the measurements are observed.	Mandatory	Both	String
Outage level	The expected available capacity (kW) of the site. If wind turbines, solar panels or inverters are not available (due to maintenance, break downs or similar) the Capacity of the site is temporarily reduced to available power capacity.	Optional	Both	Float
Limitation level	The expected available capacity (kW) of the site due to a limiting factor such as curtailment, setpoint instruction from grid operator or temporary limit on the maximum allowable production.	Optional	Both	Float
Reason of unavailability	Editable text that gives a reason for the reduction in available capacity (e.g., Maintenance, plant limitation). Often entered by plant manager or remote operations center.	Optional	Both	Float

The forecast deliverable is a point time series generated by the forecast software system. This product has characteristics that will vary depending on the consumers needs. Table **??**

contains a description of the forecast file metadata.

Table 4.6: Forecast time series specification metadata

Forecast Time Series:
The attributes of the output forecast time series are described below.

Data field	**Description**	**Mandatory /optional**	**Wind/ PV/Both**	**Type**
Plant name ID	Unique ID (name) used for identifying the site(s)	Mandatory	Both	String
StartTime	Date and time indicating the beginning of the forecast interval	Mandatory	Both	String
EndTime	Date and time indicating the ending of the forecast interval	Mandatory	Both	String
Power	The power production forecast (kW) for the period	Mandatory	Both	Float
Power quantiles	Probabilistic power production forecast corresponding to a specific quantile level	Optional	Both	Float
Wind speed	Wind speed forecast (m/s)	Optional	Both	Float
Wind direction	Wind direction forecast in degrees from north (0-359ř). East = 90ř, South= 180ř, West = 270ř, North = 0ř.	Optional	Wind	Float
Temperature	Air temperature forecast (degrees Celsius)	Optional	Both	Float
Pressure	Atmospheric air pressure forecast (hectopascals, hPa)	Optional	Both	Float
Relative Humidity	Relative humidity of the air forecast (%)	Optional	Both	Float
Precipitation	Forecast of the amount of rain or snow that has fallen on the ground (millimeters, mm)	Optional	Both	Float
Global Horizontal Irradiance	The forecast total short-wave radiation from the sky falling onto a horizontal surface (W/m^2)	Optional	PV	Float
Global tilted irradiance	The forecast total short-wave radiation from the sky falling onto a tilted surface (W/m^2)	Optional	PV	Float

Data field	Description	Mandatory /optional	Wind/ PV/Both	Type
Direct solar irradiance	The forecast short-wave radiation that has not experienced scattering in the atmosphere (W/m^2). The radition comes from the disc of the sun.	Optional	PV	Float
Diffuse irradiance	The forecast short-wave radiation from light scattered by the atmosphere excluding from the disc of the sun (W/m^2)	Optional	PV	Float
Event Forecast	Forecast value of the custom-defined power forecast event (e.g., ramp rate probability, %)	Optional	Both	Float

The forecast deliverable is the product of many configuration parameters within a forecast software system. Not all forecast software systems have similar built-in features, but Table 4.7 highlight some of the salient details that are important to a forecast system specification regardless of software system implementation details.

Table 4.7: Specification of the data required for describing the Forecast System configuration

System specification: This specification describes general aspects (meta data) of the forecast system				
Data field	**Description**	**Mandatory /optional**	**Wind/ PV/Both**	**Type**
Plant name ID	Unique ID (name) used for identifying the site(s)	Mandatory	Both	String
Power unit	Unit of power quantities (MW, KWh)	Mandatory	Both	String
Time zone	The time zone of the timestamp in IANA Time Zone database format (e.g, Europe/Barcelona)	Mandatory	Both	String
Daylight Savings Time flag	Flag to indicate whether daylight savings time applies to forecast file (True or False)	Mandatory	Both	String
Time stamp format	Format of the date and time stamp (e.g., yyyy-MM-ddTHH:mm:ss).	Mandatory	Both	String
Forecast interval label	Describes what the time of forecast point represents. Can be instantaneous, period beginning average (leading), or period ending average (trailing)	Mandatory	Both	String

Data field	Description	Mandatory /optional	Wind/ PV/Both	Type
Issue time of day	The time of day that a forecast is issued specified in HH:MM format, e.g. 00:30. For forecast runs issued multiple times within one day (e.g. hourly), this specifies the first issue time of day.	Mandatory	Both	String
Forecast update frequency	Define how often the forecast time series is updated (in minutes)	Mandatory	Both	Integer
Forecast interval length	The length of time (in minutes) each forecast point represents	Mandatory	Both	Integer
Measurement delay	The expected time delay from when a value is measured until it is available to the forecasting system in minutes	Mandatory	Both	Integer
Forecast maximum horizon	Horizon (or maximum look-ahead) of the forecast in hours	Mandatory	Both	Integer
Forecast quantiles	Quantile of the forecast distribution given to the nearest integer. Specify a single or list of quantiles (e.g., P10, P25, P50, P75, P90, P99)	Optional	Both	String
Forecast weather variable units	Units corresponding to weather forecast variables	Optional	Both	String
Event forecast	Name and description of custom forecast variable	Optional	Both	String
Event forecast units	Units of custom forecast event	Both	String	

4.3 Data Format and Exchange

4.3.1 LEVEL 1 Data Format and Exchange

Two main considerations in recommending a suitable data format for Level 1 users of forecasts is ease of use for the forecast client and, for the forecast provider, the ability to programmatically read in the necessary metadata and time series input files. The Comma Separate Value (CSV)format satisfies these conditions and is also an acceptable format for Level 2 users. While Level 2 users can utilize high-level programming languages to generate and process CSV files, Level 1 users can still interact with CSV format through Microsoft Excel or other ASCII-text editors. Another advantage of CSV for Level 1 users is that they can shift to become a Level 2 users should experienced IT resources be procured. It can be done incrementally by keeping the same CSV format or shifting to JSON or XML as described below.

For Level 1 users that have less IT experience or very limited IT resources on hand, it is recommended that data transfer between forecast consumer and forecast provider be done via *SSH File Transfer Protocol (SFTP)* which is a secure and reliable standard of sharing data. Forecast providers typically will host an SFTP server and issue a unique login credential to the forecast consumer. The forecast consumer can choose among several SFTP applications common in both the Windows and Linux operating system environments. The SFTP application should have the functionality to create batch job configurations such that online measurements can be automatically uploaded between forecast consumer and provider.

Command line SFTP works out-of-the-box with Linux operating system installations. Software applications such as Filezilla that support SFTP can also be installed on a server running Linux. Many file transfer applications built for Windows operating system have SFTP functionality. This includes Filezilla and WinSCP.

Most cloud storage commercial systems (e.g., OneDrive, GoogleDrive, Dropbox, AWS) now include SFTP. As API's become more user-friendly and accessible for people without computer programming experience, this recommendation might have to be revised as REST API (along with SFTP) are the Level 2 recommended data exchange methods between forecast provider and consumer.

4.3.2 LEVEL 2 - Data Format and Exchange

Level 2 data exchange is for both providers and consumers of renewable energy forecasts that wish to programmatically exchange data. Thus, the most widely used and extensible tools and formats were selected to allow for more seamless integration. The following three data formats are the most commonly used in the exchange of renewable energy forecasting data and the measurements that feed into forecasting systems:

1. CSV (Comma Separated Value)
2. JSON (JavaScript Object Notation)
3. XML (eXtensible Markup Language)

Each format comes with its own advantages and weaknesses, but all are in ASCII, human-readable form. Examples using representative data are useful for illustrating how metadata, measurement, and forecast data are organized and may be copied as a template. CSV-format files can be used for both Level 1 and Level 2 users as it has the distinct advantage of being opened and converted in the widely-used Microsoft Excel application. However, for Level 2 users that want to automate processes or configure many forecasts, JSON and XML are much more efficient formats.

Both JSON and XML formats are accompanied by a schema whose main purpose is to enforce consistency and data validity. They also serve as human readable documentation for the forecast system metadata, measurements, and forecast files.

Two widely used modes of data exchange are recommended for Level 2 users in this best practice. They are:

- Secure File Transfer Protocol (SFTP), and
- Application Programming Interface (API) that is RESTful

One of the main advantages of programmatically generating metadata and time series measurement and forecast files is the wide number of applications that can be used to exchange this data from forecast provider to forecast consumer and vice-versa. Many commonly used programming languages such as Python, Javascript, R, and Ruby have packages and libraries that make parsing and interacting with JSON and XML formats easier. Additionally, and often overlooked, is that internal applications can rely on the same data exchange methods further standardizing code that has to be developed and maintained.

In recommending a data exchange standard, there are several important issues that have been considered including:

- International support and usage
- Upfront, transitional and integration resource costs (financial, human)
- Extensibility
- IT Security
- Ease of use

International support and usage can not be overstated. If a method of data exchange becomes obsolete or doesnt have a very large user base, it will not adapt to evolving communication and security standards. Additionally, the number of people familiar with the exchange method is smaller thus putting operational support of automated processes more at risk in case of a disruption in data flows.

The **upfront, transitional and integration costs** all have to do with how much an organization must invest to build, transition, or support the methods of data transfer. If the exchange method is open source and works across operating systems, this is a huge benefit to the organization. If the data exchange methods can be integrated into existing software (e.g., using a simple URL to make requests), this lowers the integration and development costs. Transitional costs associated with adopting the standard or best practice will be a key consideration on whether an organization chooses to incorporate a new data exchange method. This touches upon all the important considerations listed above.

Extensibility is a key issue in choosing an exchange method as society goes through an energy transition away from fossil fuels and towards an energy system with greater electrification, distributed generation and load, and faster internet. Will what works today for sending data back and forth be around in 10 years? This is why we recommend not one data exchange method, but two, since its difficult to predict how computers, electronic devices and communications will change over time. RESTful APIs are quickly becoming the international standard in data communications as it is not constrained to one format (like SOAP is with XML) and doesnt have to be http-based although that is the primary protocol in use today with RESTful APIs.

IT security is crucial in the energy industry as malicious malware usage and cyber attack incidents have grown in number and scale every year. Both SFTP and RESTful API supports secure standard protocols for data sharing. Secure shell in the case of SFTP and HTTPS using TLS encryption as one example in RESTful APIs. Although these protocols dont eliminate security risks entirely, they reduce the risks of cyber attacks.

Both SFTP and RESTful APIs are supported by most software applications and are **easy to use** since they can be invoked from the most commonly used scripting languages. Ease of use may be the primary factor in deciding whether to adopt a new method to transfer data for the purpose of renewable energy forecasting. A forecast provider can develop a web application to accept any of the recommended formats. There are many tools and applications which then allow the forecast consumer to verify or view the metadata, measurements and forecasts in a web browser. A good example of this can be seen in the US Department of Energy Solar Forecast Arbiter (SFA) project (Hansen et al., 2019). This project developed an open-source RESTful API that uses JSON formatted messages. Forecast site metadata, measurements, and forecast time series are exchanged through POST and GET commands. Once the data is uploaded via the API, a dashboard has been built that allows the forecast provider and consumer to visualize, download, and create verification reports.

Chapter 5

FINAL AND CONCLUDING REMARKS

While every forecasting solution contains customized processes and practices, there are a number of attributes and components that all forecasting solutions have in common. For any industry it is important to establish standards and standardise practices in order to streamline processes, but also ensure security of supply with a healthy competition structure.

This document provides an overview of state of the art practices that have been carefully collected by experts in the area and reviewed by professionals and experts in an appropriate number of countries with significant experience in renewable energy forecasting. The recommendations are to encourage both end-users and forecast service providers to bring focus to areas of practice that are common to all solutions. The document will be updated as the industry moves towards new technologies and processes.

The key element of this recommended practice is to provide basic elements of decision support and thereby encourage end-users to analyse their own situation and use this analysis to design and request a forecasting solution that fits their own purpose rather than applying a "doing what everybody else is doing" strategy.

This document is also intended to serve forecast service providers new to the market or those wanting to evolve to a new level of service and support as a guideline to state of the art practices that should be incorporated into business processes.

REFERENCE MATERIAL

NOTE: The following selected reference material is a collection of references that have been published at the IEA Wind Task 36 webpage in relation to this recommended practice : https://www.ieawindforecasting.dk/Publications

Dissemination Material of the first Edition:

IEA Wind Task 36: Recommended Practices Guideline for the Implementation of Wind Power Forecasting Solutions Part 1-3. Online access: https://www.ieawindforecasting.dk/Publications/RecommendedPractice

C. Möhrlen, J. Zack, J. Lerner, A. Tuohy, J. Browell, J. W. Messner, C. Collier, G. Giebel, Recommended Practices for the Implementation of Wind Power Forecasting Solutions Part 1: Forecast Solution Selection Process, Proc. 17th Int. Workshop on Large-Scale Integration of Wind Power into Power Systems,ăStockholm, Sweden, October 2018. Online Access: ăhttp://download.weprog.com/wiw18-133_recommended-practice_selection-process.pdf

C. Möhrlen, C. Collier , J. Zack , J. Lerner , Can Benchmarks and Trials Help Develop new Operational Tools for Balancing Wind Power?, Proc. of 16th International Workshop on the Large-Scale Integration of Wind Power into Power Systems, Paper WIW-292, Berlin, Germany, 2017. Online access: http://download.weprog.com/WIW2017-292_moehrlen_et-al_v1.pdf Evaluation and Metrics

IEA Wind Task 36: Recommended Practices Guideline for the Implementation of Wind Power Forecasting Solutions Part 3: Evaluation of forecast solutions. Online access: https://www.ieawindforecasting.dk/Publications/RecommendedPractice

C. Möhrlen, C. Collier , J. Zack , J. Lerner , Recommended Practices for the Implementation of Wind Power Forecasting Solutions Part 2&3: Designing and executing forecasting benchmarks and trials and evaluation of forecast solutions, Proc. of 16th International Workshop on the Large-Scale Integration of Wind Power into Power Systems, Paper WIW-160, Berlin, Germany, 2017. Online access: http://download.weprog.com/wiw18-160_recommended-practice_benchmark-evaluation.pdf

Anemos.Plus Project DELIVERABLE D-1.3, Towards the definition of a standardised evaluation protocol for probabilistic wind power forecasts. Online available: http://www.anemos-plus.eu/images/pubs/deliverables/aplus.deliverable_d1.3-protocol_v1.5.pdf http://www.anemos-plus.eu/images/pubs/deliverables/aplus.deliverable_d1.3-protocol_v1.5.pdf

Gensler, A. and Sick, B. and Vogt, S. (2016). A Review of Deterministic Error Scores and Normalization Techniques for Power Forecasting Algorithms. 10.1109/SSCI.2016.7849848. Online access: https://ieeexplore.ieee.org/document/7849848

Jensen, T., Fowler, T., Brown, B. Lazo, J., Haupt S.E. (2016), Metrics for evaluation of solar energy forecasts, NCAR Technical Note NCAR/TN-527+STR. Online available: http://opensky.ucar.edu/islandora/object/technotes:538 Nielsen, H.A., Nielsen, T.S., Madsen, H., San Isidro Pindado, M.J., Marti, I.: Optimal combination of wind power forecasts, Wind Energy 10(5), pp. 471-482, 2007. Online: https://onlinelibrary.wiley.com/doi/abs/10.1002/we.237

Frías Paredes, L., Stoffels, N., Statistical analysis of wind power and prediction errors for selected test areas, EU 7th Framework project Safewind, Deliverable Dp-7.1. Statistical analysis of wind power and prediction errors for selected test areas. Online available: http://www.safewind.eu/images/Articles/Deliverables/swind.deliverable_dp-7.1_statistical_analysis_v1.6.pdf http://www.safewind.eu/images/Articles/Deliverables/swind.deliverable_dp-7.1_statistical_analysis_v1.6.pdf

Sánchez, I.: Adaptive combination of forecasts with application to wind energy. International Journal of Forecasting 24(4), pp. 679693, 2008. Online: https://doi.org/10.1016/j.ijforecast.2008.08.008

Uncertainty Forecast Information

Yan, J; Möhrlen, C.; Göçmen, T.; Kelly, M.; Wessel, A.; Giebel, G. Uncovering wind power forecasting uncertainty origins and development through the whole modelling chain. Submitted to Sustainable and Renewable Energy Reviews, Sept. 2021.

Möhrlen, C.; Bessa, R.J.; Fleischhut, N.; Decision-Making Experiment under Wind Power Forecast Uncertainty. Submitted to Meteorological Applications, Aug. 2021.

S. E. Haupt, M. Garcia Casado, M. Davidson, J. Dobschinski, P. Du, M. Lange, T. Miller, C. Möhrlen, A. Motley, R. Pestana, and J. Zack. The use of probabilistic forecasts: Applying them in theory and practice.IEEE Power and Energy Magazine, 17(6):4657, 2019.

Bessa, R.J.; Möhrlen, C.; Fundel, V.; Siefert, M.; Browell, J.; Haglund El Gaidi, S.; Hodge, B.-M.; Cali, U.; Kariniotakis, G. Towards Improved Understanding of the Applicability of Uncertainty Forecasts in the Electric Power Industry. Energies 2017, 10, 1402.
Online access: `https://www.mdpi.com/1996-1073/10/9/1400`

Dobschinski, J., Bessa, R., Du, P., Geisler, K., Haupt, S.-E., Lange, M., Möhrlen, C., Nakafuji, D., Rodriguez, M. d.l.T., Uncertainty Forecasting in a Nutshell: Prediction Models Designed to Prevent Significant Errors, IEEE Power and Energy Magazine, vol. 15, no. 6, pp. 40-49, Nov.-Dec. 2017. doi: 10.1109/ MPE.2017.2729100.

C. Möhrlen and J.U. J/orgensen, Chapter 3: The Role of Ensemble Forecasting in Integrating Renewables into Power Systems: From Theory to Real-Time Applications, Integration of Large-Scale Renewable Energy into Bulk Power Systems - From Planning to Operation, Editors: Du, Pengwei, Baldick, Ross, Tuohy, Aidan (Eds.), pp 79-134.

Möhrlen, C., Bessa, R., Giebel, G., Jørgensen, J.U., Uncertainty Forecasting Practices for the Next Generation Power System, Proc. 16th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants,Germany, of 16th International Workshop on the Integration of Solar Power into Power Systems, 2017. Online available: `www.ieawindforecasting.dk/publications`

Related Data Standards and Projects

European Network of Transmission System Operators for Electricity (ENTSO-E), Weather Process and Energy Prognosis Implementation Guide:
`https://www.entsoe.eu/Documents/EDI/Library/cim_based/Weather_IG_V1r2.pdf`

European Network of Transmission System Operators for Electricity (ENTSO-E), Common Information Model, `https://www.entsoe.eu/digital/common-information-model/cim-for-energy-markets/`

C. W. Hansen et al., "The Solar Forecast Arbiter: An Open Source Evaluation Framework for Solar Forecasting," 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), 2019, pp. 2452-2457, doi: 10.1109/PVSC40753.2019.8980713

US Department of Energy Solar Forecast Arbiter Project - https://solarforecastarbiter.org

IEA Task 43 Work Package 4 - Digital Wind Resource Assessment Data Standard - https://www.ieawindtask43.org/work-package-4-digital-wra

Presentations:

Möhrlen, C., Collier, C. ,Zack , J., Lerner, J.A., Can Benchmarks and Trials Help Develop new Operational Tools for Balancing Wind Power?, Proc. of 16th International Workshop on the Integration of Solar Power into Power Systems, Paper WIW-126, Berlin, Germany, 2017. Online access: `www.ieawindforecasting.dk/publications`

RECOMMENDED PRACTICES FOR THE IMPLEMENTATION OF WIND POWER FORECASTING SOLUTIONS
Corinna Möhrlen, John Zack, Jeff Lerner, Aidan Tuohy,ăJethro Browell, Jakob W. Messner, Craig Collier, Gregor Giebel
Part 1: FORECAST SOLUTION SELECTION PROCESS
Part 2 and 3: DESIGNING AND EXECUTING FORECASTING BENCHMARKS AND TRIALS AND EVALUATION OF FORECAST SOLUTIONS

Möhrlen, C., Zack, J., Lerner, J.A., Tuohy, A., Browell, J., Messner, J.W., Collier, C., Giebel, G. RECOMMENDED PRACTICES FOR THE IMPLEMENTATION OF WIND POWER FORECASTING SOLUTIONS - Part 1: FORECAST SOLUTION SELECTION PROCESS and Part 2 and 3: DESIGNING AND EXECUTING FORECASTING BENCHMARKS AND TRIALS AND EVALUATION OF FORECAST SOLUTIONS, Proc. of 17th International Workshop on the Integration of Solar Power into Power Systems, Paper SIW-126, Berlin, Germany, 2018.
Online access: `https://www.ieawindforecasting.dk/publications`
Training Tools:
Canadian Meteorological Center's "Ensemble Prediction System (EPS) Training course" The training tool is available for download at: `(http://collaboration.cmc.ec.gc.ca/cmc/ensemble/Formation-Training/Read-me.html`

GLOSSARY AND ABBREVIATIONS

Ensemble Forecasting:
Ensemble forecasts are sets of different forecast scenarios, which provide an objective way of evaluating the range of possibilities and probabilities in a (weather or weather related) forecast.

Probabilistic Forecast:
General description of defining the uncertainty of a forecast with objective methods. These can be ensemble forecasts, probability of exceedance forecasts, or other forms of measures of uncertainty derived by statistical models.

Quantile:
A quantile is the value below which the observations/forecasts fall with a certain probability when divided into equal-sized, adjacent, subgroups.

Quartile:
quantiles that divide the distribution into four equal parts.

Percentile:
Percentiles are quantiles where this probability is given as a percentage (0-100) rather than a number between 0 and 1.

Decile:
Quantiles that divide a distribution into 10 equal parts.

Median:
the 2nd quantile, 50th percentile or 5th decile, i.e. the value, where the distribution has equally many values above and below that value.

Abbreviations

The following abbreviations are used in this document:

FSP	Forecast service provider
NWP	Numerical Weather Prediction
EPS	Ensemble Prediction System
NDA	Non-disclosure Agreement
RFI	Request for Information
RFP	Request for Proposals
TSO	Transmission system operators
ISO	Independent system operator

Bibliography

[1] Gill, J. and Rubiera, J. and Martin, C. and Cacic, I. and Mylne, K. and Dehui, C. and Jiafeng, G. and xu, T. and Yamaguchi, M. and Foamouhoue, A.K. and Poolman, E. and Guiney, J., Guidelines on communicating forecast uncertainty, Edited by Haleh Kootval, World Meteorological Organization, Tech, Report WMO/TD No. 4122, 2008.

[2] Bessa, R.J.; Möhrlen, C.; Fundel, V.; Siefert, M.; Browell, J.; Haglund El Gaidi, S.; Hodge, B.-M.; Cali, U.; Kariniotakis, G. Towards Improved Understanding of the Applicability of Uncertainty Forecasts in the Electric Power Industry., Energies, 10, 1402. https://doi.org/10.3390/en10091402, 2017.

[3] IEA Wind Task 36, Recommended Practice on Renewable Energy Forecast Solution Selection Part 3: Forecast Solution Evaluation, Edited by Möhrlen C. and Zack J.W., International Energy Agency Technical Cooperation Programme Wind, `https://iea-wind.org/task-36/task-36-publications/recommended-practice/`, 2019.

[4] Yan, J. and Möhrlen, C. and Göçmen, T. and Kelly, M. and Wessel, A. and Giebel, G., Uncovering wind power forecasting uncertainty origins and development through the wholemodelling chain, submitted to Sustainable and Renewable Energy Reviews, September 2021.

[5] Sperati, S., Alessandrini, S. and Delle Monache, L., Gridded probabilistic weather forecasts with an analog ensemble. Q.J.R. Meteorol. Soc., 143: 2874-2885. https://doi.org/10.1002/qj.3137, 2017.

[6] Bessa RJ, Miranda V, Botterud A, Wang J, 'Good or bad wind power forecasts: a relative concept, Wind Energy, 14(5), 625636. doi:10.1002/we.444, 2010.

[7] J. B. Bremnes, Probabilistic wind power forecasts using local quantile regression, Wind Energy, vol. 7, no. 1, pp. 4754, 2004.

[8] Möhrlen, C., Pahlow, M. and Jørgensen, J.U. Untersuchung verschiedener Handelsstrategien für Wind- und Solarenergie unter Berücksichtigung der EEG 2012 Novellierung., Z. Energiewirtsch, 36, 925, https://doi.org/10.1007/s12398-011-0071-z, 2012.

[9] Möhrlen, C., Pahlow, M. and Jørgensen, J.U., Investigation of various trading strategies for wind and solar power developed for the new EEG 2012 rules, Authors translation of Z. Energiewirtsch, 36, 925, http://download.weprog.com/WEPROG_Trading_strategies_EEG2012_ZEFE_71-2012-01_en.pdf, 2012.

[10] P. Haessig, B. Multon, H. B. Ahmed, S. Lascaud, and P. Bondon, Energy storage sizing for wind power: impact of the autocorrelation of day-ahead forecast errors, Wind Energy, vol. 18, no. 1, pp. 4357, January 2015.

[11] R. J. Bessa, M. A. Matos, I. C. Costa, L. Bremermann, I. G. Franchin, R. Pestana, N. Machado, H.-P. Waldl, and C. Wichmann, Reserve setting and steady-state security assessment using wind power uncertainty forecast: A case study, IEEE Transactions on Sustainable Energy, vol. 3, no. 4, pp. 827836, 2012.

[12] J. Usaola, Probabilistic load flow in systems with wind generation, IET Generation, Transmission & Distribution, vol. 3, no. 12, pp. 10311041, December 2009.

[13] T. Soares, R. J. Bessa, P. Pinson and H. Morais, "Active Distribution Grid Management Based on Robust AC Optimal Power Flow," in IEEE Transactions on Smart Grid, vol. 9, no. 6, pp. 6229-6241, Nov. 2018, doi: 10.1109/TSG.2017.2707065, 2018.

[14] G. de Jong, O. Franz, P. Hermans, and M. Lallemand, TSO-DSO data management report, Joint Report (ENTSO-E, CEDEC, GEODE, EURELECTRIC and EDSO), Tech. Rep., 2016.

[15] J. Silva, J. Sumaili, R. J. Bessa, L. Seca, M. Matos, V. Miranda, The challenges of estimating the impact of distributed energy resources flexibility on the TSO/DSO boundary node operating points, Computers & Operations Research, Volume 96, Pages 294-304, ISSN 0305-0548, https://doi.org/10.1016/j.cor.2017.06.004, 2018.

[16] M. A. Bucher, S. Delikaraoglou, K. Heussen, P. Pinson, and G. Andersson, On quantification of flexibility in power systems, in IEEE Eindhoven PowerTech, Eindhoven, pp. 16, 2015.

[17] Würth, I.; Valldecabres, L.; Simon, E.; Möhrlen, C.; Uzunoğlu, B.; Gilbert, C.; Giebel, G.; Schlipf, D.; Kaifel, A. Minute-Scale Forecasting of Wind PowerResults from the Collaborative Workshop of IEA Wind Task 32 and 36. Energies 2019, 12, 712. https://doi.org/10.3390/en12040712, 2019.

[18] S. E. Haupt et al., "The Use of Probabilistic Forecasts: Applying Them in Theory and Practice," in IEEE Power and Energy Magazine, vol. 17, no. 6, pp. 46-57, Nov.-Dec. 2019, doi: 10.1109/MPE.2019.2932639, 2019.

Appendix A

CLARIFICATION QUESTIONS FOR FORECAST SOLUTIONS

In order to define the objectives and possible solutions for a forecasting system, it is recommended to follow an overall structure: 1. Describe your situation In this process, it is imperative to describe exactly those processes, where you need forecasting in the future. Here it is essential to get the different departments involved, especially the IT department. The more accurate you can describe the situation you need to solve with forecasting (e.g. which IT restrictions, limitations and methods for data exchange exist, current or future challenges, etc.), the more straight forward it will be to (1) ask questions to the vendors regarding forecasting methodology, but also (2) get clarity of the involved processes enabling forecasting.

Ask Questions to the vendors

The questions to the vendors should be of technical character regarding forecast methodology, but also on available data exchange methodologies, required input data for the models and system support.

TYPICAL QUESTIONS FOR PART 1

- Processes: Which processes require forecasting
- Data
  - How will the data flow internally be solved: data storage, data exchange, data availability ?
  - Which data do we collect that may assist the forecaster to improve accuracy

- Data Formats:
  - Which formats are required for applications, data exchange and storage ?
- Applications
  - Who/which department will use the forecasts, are new applications required to make use of the forecasts ?
- Education
  - Is it required to train staff in how to use forecasts ?
- Policies
  - Are there policies, political or legal restrictions to be aware of when exchanging data with a forecaster ?

TYPICAL QUESTIONS FOR PART 2

The following are typical questions to get some overview of what is state-of-the-art in forecasting for renewables and what products are available on the market for a specific purpose.

- Describe the methodology you will use when generating forecast for (wind|solar|)
- How many years of experience do you have in this specific area or related areas
- Required data fields for the forecasting model for the trial
- Time scales and IT requirements for the data for the forecasting model
- Required data for vendor's model, if adopted and used live
- Applicable charges for a trial with vendor
- Vendors forecast model forecast horizons

Appendix B

TYPICAL RFI QUESTIONS PRIOR TO OR IN AN RFP

- **Methodology**
  - What unique services can you provide that may address our needs ?
  - What input weather data is used
  - What methodology is used for power generation for the long-term (>1 days ahead) and short-term forecasting (0...24h).
  - Can uncertainty forecasts or probability bands be provided ?1 If yes, which methodology is being used.
  - What are the minimum requirements for wind farm site data?
  - Can a Graphical User Interface be provided to visualise forecasts ? If yes, please describe it in detail (e.g. platform dependence, user management, in-house installation or web-based).
- **Service Level**
  - What kind of service level does the provider offer (ticket system, personal support, call center, online support, etc.)
  - What kind of service level is recommended for the specific service.
  - Does the provider have outage recovery guarantee
- **Contract and Pricing**
  - What are restrictions and preferences on the pricing structure of your service (e.g. price per park, per MW, per parameter, per time increment)?
  - What restrictions/preferences does the provider have in responding to RFPs ?
- **Experience**

- Can the vendor provide minimum of 3 examples of your work that is applicable to our needs (e.g. forecast accuracy, references, methodology)?
- Does the company have significant market shares in the market/area of business
- Additionally, can your company supply products or information that you consider relevant for us when setting out an RFP ?

Appendix C

Application Examples for Use of Probabilistic Uncertainty Forecasts

C.0.1 Example of the Graphical Visualization of an Operational Dynamic Reserve Prediction System at a System Operator

Figure C.1 shows an example of the graphical visualization of an operational dynamic reserve prediction system at a system operator, where operators requested to have various intervals in order to evaluate which of the intervals was economically or from a system security aspect the better choice in a given situation.

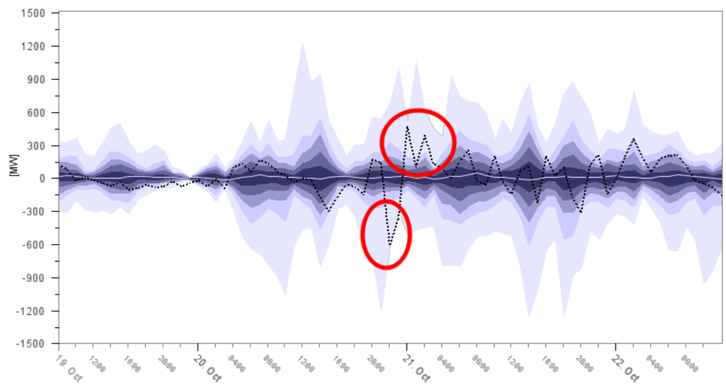

Figure C.1: Example of the graphical visualisation an operational dynamic reserve prediction at a system operator.

The reserve requirement is built with a NWP ensemble approach where the ensemble spread is related and calibrated to the expected forecast error of wind power, demand and an estimated cross-border exchange requirement. The mean of the computed reserve requirement is scaled to zero and the possible positive and negative requirement intervals are plotted in form of 4 percentiles up and down, respectively.

The red circles indicate areas, where the requirements would have been higher than what e.g. a P20-P80 interval would have covered, if this was the uncertainty range the operators would have requested. It also illustrates why the operators wanted to be "aware" of such outliers, even if they may not have pre-allocated according to the outer ranges or boundaries.

C.0.2 High-Speed shut down warning system

In a typical area where high-speed shut down is a challenge for the grid security, the development of low pressure systems are frequent and the variability of the wind resources are relatively high. Thus, an alert system concerning high-speed shutdown of wind power must be established based on probabilities computed from a probabilistic prediction system that can take the spatial and temporal scales into consideration in order to capture the temporal evolution and spatial scale of such low pressure systems that contain wind speeds leading to large scale shut-down of wind farms.

This can for example be provided by a physical approach based on a NWP ensemble that ideally contains all extreme values inherent in the approach without the requirement of statistical training. Alternative solutions may exist from statistical approaches (see **??** by employing an extreme event analysis to a statistical ensemble of type 2. This is due to the requirement that such forecasts must be able to provide probabilities of extreme events, where each "forecast member" provides a valid and consistent scenario of the event. The probabilities need to be suitable solutions for a decision process. They can be computed for very critical and less critical events, dependent on the end-users requirements.

Figure C.2 shows an example of a real-time setup of such a high speed shut down warning system. The example exhibits 2 events. The first graph shows the risk index in probability space of a high-speed shutdown event to occur. The second graph shows the wind power forecast with uncertainties inclusive the observations (black dotted line) of what happened. From the upper graph, the operator can directly read out the following:

- Case 1 at 26. January:
  - 10% probability of 50% shutdown
  - 8% probability of 90% shutdown
  - 90% probability of 5% shutdown

- Case 2 on 31. January:
  - 10% probability of 50% shutdown
  - 15% probability of 90% shutdown
  - 90% probability of 10% shutdown

The reality is shown by the observations in the lower graph of figure C.2, where it can be seen that the first case's peak value was 35% high-speed shut-down and the second case exhibited a peak value of 45% of high-speed shut-down.

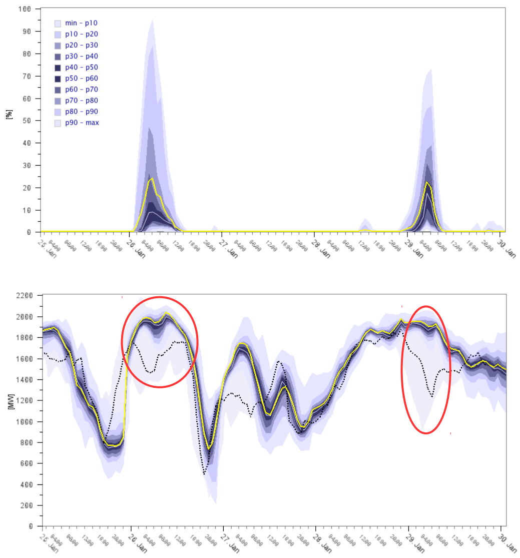

Figure C.2: Example of a high-speed shut-down example, where within 5 days 2 extreme events showed up in the risk index of the system (upper graph), showing the probability of occurrence in terms of probability ranges as percentiles P10...P90 of a high speed-speed shutdown. The second graph shows the 5-day wind power forecast inclusive uncertainty intervals as percentile bands P10...P90 and the observations (black dotted line). The red circles indicate the time frame in which the alarms were relevant.

Practical experience from evaluating high-speed shutdown events and discussing the alert system with the operators, showed that it is absolutely crucial that the operators understand the alerts and are capable of checking and verifying themselves in a graphical way, what they may receive as written alert. Therefore, the impact of a false alarm needs to be evaluated, decided upon and documented in the design phase, so that the operators have a clear reference system to relate an alert to. Technically, the frequency of the alert generation should be adjusted to:

a lead time of the alert

b change of severity level since previous alert

c initial and valid week day and time of the day

d severity of the event computed from a ramp-rate perspective and actions required

e the need and possibility to call back and/or revert actions

The strategy of issuing an alert should include (1) issuing of every alert according to a simple scheme and (2) reduction of the amount of alerts to a level that prevents that critical alerts are not accidentally overlooked.

It was also found that the Use of sliding interval from 23-25m/s was an important introduction into the design to ensure that tje warning is issued **before** the event.