e-HIGHWAY 2050 Modular Development Plan of the Pan-European Transmission System 2050			
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Start date	1st of September 2012	**Duration**	40 months
WP 3	**Technology portfolio to meet the 2050 scenarios**		
D3.1	**Technology assessment from 2030 to 2050**		

Annex to D3.1 - Technology Assessment Report

Generation Technologies: Wind energy

Revision	**Organisation**	**Date**
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Checked by	E. Peirano (Technofi)	29-08-2014
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Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

Document information

General purpose

This document is an annex of deliverable **D3.1** focusing on the technology assessment (technical and economic performances) of generation, storage, transmission and demand-side technologies. It deals with wind energy technologies on the time horizon set by the e-Highway2050 project, i.e. from today until 2050 time horizon.

The present document is complemented by an attached Excel file providing the data compiled according to the methodology described in the in the next sections.

NB: the present document and the attached data (Excel sheet) has been written by EWEA and validated by WP3 leader. The data has however been supplemented with a data set (rated power of wind turbine, operating hours and costs) provided by VGB Power Tech. VGB Power Tech has provided data for thermal generation technologies and some renewable generation technologies. The wind power data of VGB Power Tech has been derived under a set of hypotheses that can be found in the file report_generation_VGB.doc. For applications in the project, the data of EWEA should be used.

Change log

Revision	Date	Changes description	Authors
V1.0	29.04.2013	Creation of the document	I. Pineda
V1.1	02.07.2014	Preparation of D3.1. Insertion of VGB data in Excel sheet.	E. Peirano
V2.0	29.08.2014	Integration of final version in D3.1	E. Peirano

Table of contents

1 Technology performance characteristics

1.1 Variables selected

In the following a list of variables is listed for each data type (Technology performance characteristics, Technology readiness and maturity, etc.). The definition of each variable is given together with the unit (mean) of quantification (quantitative or qualitative).

1.1.1 Rated Power - Average wind turbine rated power in megawatts [MW]. Computation: total installed capacity / total number of wind turbines.

1.1.2 Diameter - Typical diameter of a wind turbine rotor in meters [m].

1.1.3 Cut-in speed - Wind speed expressed in [m/s] at which rotor blades of the wind turbine are able to start rotate and therefore produce electricity.

1.1.4 Cut-out speed – Wind speed expressed in [m/s] at which rotor blades of the wind turbine are stopped in order to avoid mechanical problem. Hence no electricity is generated above this speed.

1.1.5 Drive train configuration - Market share of commercially available drive train configurations. Geared box drive. Percentage [%].

1.1.6 Generator type – Market share of commercially available conversion type generator according to IEC 61400-27 classification. Percentage [%]

1.1.7 Availability – Percentage of time the technology produces electrical energy when primary resource is available. Percentage [%]. Computation: Availability = MTBF/(MTBF +MTTR)[1].

1.1.8 Capacity factors – Percentage of its nameplate capacity that a turbine installed in a particular location will deliver over the course of a year. Percentage [%]. Computation: Capacity Factor in region (i) = Normalised wind energy production in region (i) / Installed Capacity in region (i), where i= (Northern, Central, Southern Europe)

1.2 Underlying assumptions

The overall expectation of the wind energy industry is to build bigger, lighter and more cost-effective wind turbines. Also, there is an increasing trend of wind turbine designs suitable for offshore operation and low wind speed sites.

Total capacity installed in 2012 has been taken from EWEA statistics (1). Forecast figures for 2020-2050 were computed based on expected capacity installation from EWEA (2) as well as the number of wind turbines. The resulting average rated power and its forecast are in line with figures reported by the European Commission in (3). Also, wind turbine rated power estimation is in line with industry expectation of evolution of turbines with bigger rotor diameters (variable 1.1.2).

Bigger rotor diameters are expected to contribute significantly to the exploitation of offshore wind and low wind speed onshore sites. This trend will become apparent as the best onshore sites are taken, thus leaving lower speed sites for exploitation. The correlation of rotor diameter and rated power reported in (3) is kept in the figures reported in the data sheet.

$$D = 44.1 * \ln(P_n) + 56.5,$$

where, D is the rotor diameter expressed in [m] and P_n is the rated power in [MW].

As a reference, the largest commercial wind turbine is the 8MW Vestas V164 with a 164m diameter (Source). Several wind turbine manufacturers already have prototypes for up scaling wind turbines (3) (5) (Source: http://vestas.com/en/products_and_services/offshore#!v164-development).

[1] Mean Time Between Failures (MTBF): average interval of time between 2 successive failures. Mean Time to Repair (MTTR): average interval of time between the instant when a failure occurred and the instant when the turbine is operational.

Low wind speed onshore sites and offshore wind exploitation trends will also have an impact on the design parameters of cut-in and cut-out speeds. According to main manufacturers as Vestas, Enercon or Siemens, cut-in speed can be considered around 3.5 m/s whereas cut-out speed is generally at 25 m/s (3) in the aim to avoid damage to wind turbine components. Projections up to 2050 reflect improvements in pitch and blade design (variables 2.1.1, 2.1.2 and 2.1.3) as well as improvements in storm control for offshore wind farms (variable 8.1.2)

Similarly, increasing turbine sizes will put interest in systems that reduce weight and costs. This interest, together with increasingly demanding grid codes and cost reductions in power electronics, will drive the evolution of drive trains and conversion systems (variables 1.1.4 and 1.1.5). The overall trend is that industry will progressively move to lighter, easy-to-maintain and more reliable systems with less moving parts systems. Gearless drive trains and full power converters technologies will become more popular. Market shares of geared versus gearless systems as well as Doubly-Fed Induction Generators (DFIG) are reported in specialized industry publications. Baseline figures for 2012 and short-term projections to 2015 are taken from (6). Projections to 2020 and 2030 are from (3) and 2040 and 2050 are EWEA expectation based on these trends.

Evolution of drive trains and conversion systems will have a direct consequence in wind turbine reliability. Historical information show that the most frequent failures from wind turbines (short downtime, less severe) occur on electric and electronic components while the most severe (large downtime, less frequent), occur on drive train components (7).

In this sense, there is an important relationship between the Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR). Intuitively, tracking each of them would be ideal for assessing the technology performance in the coming decades. However, the relationship between MTBF and MTTR could be captured by Availability (variable 1.1.6). Availability of wind turbines is generally reported to be high, above 97% (8). The general assumption in this report is that this level will not deteriorate in the future. A brief description on the limitations of this variable is given in section 1.4

Finally, the main factor determining wind energy technology performance is its capacity factor. As this variable is highly dependent on local wind conditions, it has been split in three regions representing northern, central and southern Europe. The underlying assumption was to help a better representation of the electricity grid needs in the future where large regional flows are expected to occur (9)

Normalized wind energy production was calculated according to Directive 2009/28/EC (10). Baseline data on wind power installed capacity and electricity production from 2011 per country was sourced from Eurostat (11) and (12). Expected future capacity installations of wind power (onshore and offshore) 2020-2050 are EWEA forecast (2). Capacity factors per region are the average of countries as per table below:

Northern Europe	Central Europe	Southern Europe
Belgium	Austria	Bulgaria
Denmark	Czech Republic	Greece
Estonia	France	Italy
Finland	Hungary	Portugal
Germany	Luxembourg	Spain
Ireland	Romania	
Latvia		
Lithuania		
Netherlands		
Poland		
Sweden		
United Kingdom		

1.3 Methodology for data gathering

Data gathering is a combination of own (EWEA) and others' (experts) expertise. Knowledge is formalized in public articles and industry specialized publications. See bibliography for a complete list of references.

1.4 Conclusions on robustness of the produced data

Quality of source: 4 (in a scale 1 to 5, 5 being the best). Existence of a possible bias: None.

All the variables selected are widely documented in by industry experts, government and academia institutions. Computations performed were done by highly qualified industry experts.

Confidence level on the nature of data is 4 to 5.

Confidence level on the time horizon is 4.

The variable related to technology reliability (1.1.6. Availability) could be subject to further scrutiny. It was selected as compromise of practicality between availability of data, objectivity and level of detail necessary for this assessment and further work packages. In this sense, it is worth to note that there is limited up to date, publicly available information on specific reliability measures of wind turbines. To our knowledge, mature markets (Germany and possibly Denmark) are the most advanced ones where measuring reliability of individual wind farms is performed but processing and characterization of this data at European level would require a significant amount of time and effort. Furthermore, forecasting reliability data to 2050 and assessing offshore wind technologies separately poses increased complexities, such as further assumptions on site distance and access feasibility. The latter becomes increasingly important for MTTR at offshore sites. For the purpose of this assessment, we opted to omit this exercise. Finally, data from U.S.A. (13) has not been included in the assessment but could be incorporated in further discussions with partners if deemed relevant.

2 Technology readiness and maturity

2.1 Variables selected:

2.1.1 Aerodynamics, aero-elasticity and aero-acoustics - [TRL]

2.1.2 Electrical generators, power electronics and control - [TRL]

2.1.3 Loads, safety and reliability - [TRL]

2.1.4 Materials, structural design and composites - [TRL]

2.1.5 Material characterization and LCA - [TRL]

2.2 Underlying assumptions

The variables from this category represent the main areas of innovation in wind turbine design. R&D activities of the entire wind industry span over different categories, including resource assessment, grid integration, manufacturing, logistics, O&M and HS&E. For the purpose of this assessment, the list of main innovations shown above, do not cover all of the aforementioned areas but only the expectation of R&D breakthrough developments in wind turbine design. The baseline considered is the R&D priorities up to 2030 from the European Wind Energy Technology Platform, TP Wind (14). Projection to 2050 keeps same priorities but with a higher level of development as it expectation is that these priorities are broad enough to reflect changes on R&D. Developments are qualified according to the Technology Readiness Level scale, cf. Figure 1.

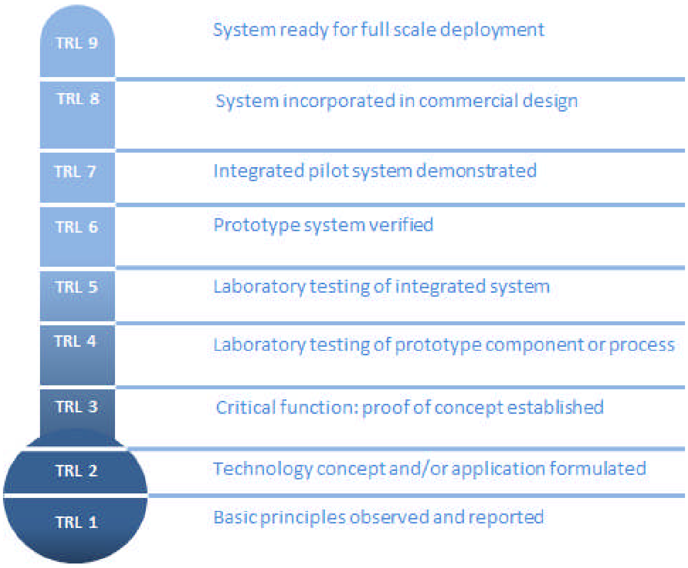

Figure 1 : TRL scale.

Innovations on aerodynamics, aero-elasticity and aero-acoustics areas reflect the efforts for upscaling wind turbines. Larger wind turbines require developments on characterization of aerodynamic behavior and aero-elasticity stability of rotors. Also, developments are expected in new rotor concepts for offshore with higher tip speed ratios than those used onshore and development of aerodynamic control devices for very large rotor blades.

Similarly, larger wind turbines require important development of power electronics for high voltage levels; improvement of power converters in terms of partial load efficiencies as a function of rotor loading; development of new generator designs for achieving light-weight, low-speed maintenance-free and controllable generators, for example by incorporating super conducting wiring; and development of 'integral adaptive control' to incorporate varying external conditions from both individual wind turbines and wind farm.

Regarding loads, safety and reliability areas, the development of methodologies for reducing uncertainty in safety design factors and the development of floating foundations are expected to make cost breakthroughs in offshore wind turbine design.

Finally, almost all the previous innovations are underpinned by materials, structural design and composites breakthroughs. Mainly, development of alternatives to steel towers, like the use of special concretes; use of fibre-reinforced composites and coatings for blades construction; thermoplastics and high-temperature superconductors for electrical gear. All of these developments are expected to have a strong focus on life cycle characterization so construction materials can be fully recyclable while keeping mechanical properties.

2.3 Methodology for data collection

Data collection was based on others' expertise. Knowledge is formalized in public articles and industry specialized publications. See bibliography for a complete list of references

2.4 Conclusions on robustness of the produced data

Quality of source: 5. Existence of a possible bias: None.

All the variables selected are widely documented by industry experts, government and academia institutions.

Confidence level on the nature of data is 5.

Confidence level on the time horizon is 5.

Nevertheless, it is worth to note that R&D activities of the entire wind industry span over different categories and their impact can also be reflected in the other variables such as cost and to overcome implementation and market constraints (variables 3.1.1, 4.1.1, 4.1.2 and 6.1.1).

3 Possible implementation constraints

3.1 Variables selected:

3.1.1 Permitting lead time – Lead time for obtaining permitting (before start of any construction work) in [months].

3.2 Underlying assumptions

The main constraints for deployment of wind power are considered to be regulatory related. These could be political, social or environmental constraints. Technology, economic and supply chain potential issues are treated with variables 1.1.1 to 2.1.4, 4.1.1, 4.1.2 and 6.1.1 in this assessment. To this end, we recommend using "permitting lead time" as the main variable to measure possible implementation constraints. Permitting procedures reflect intrinsically the multiple aspects that any type of infrastructure project or technology faces for its deployment, ranging from environmental regulations, social acceptability and land use, to infrastructure availability and red tape procedures efficiency (15). The rule of thumb is, the longer the permitting lasts, the more implementation constraints the technology faces.

Industry expectation is that regulatory constraints are progressively overcome in the future. This will be reflected by administrative and permitting procedures to be standardised, streamlined and centralised in a single national body. Improvements on spatial planning are also expected to accelerate offshore wind power (16).

3.3 Methodology for data collection

Data collection was based on others' expertise. Knowledge is formalised in public articles and European research projects. See bibliography for a complete list of references

3.4 Conclusions on robustness of the produced data

Quality of source: 4.

Existence of a possible bias: Yes.

Possible bias towards positive evolution of permitting procedures in favour of wind power technology.

Confidence level on the nature of data is 4 to 5.

The main source of information is taken from a public funded project coordinated by EWEA (15).

Confidence level on the time horizon is 3.

4 Costs

4.1 Variables selected:

4.1.1 CAPEX – Capital investment in Euros per kW installed [€ /kW].

4.1.2 OPEX – Operational costs in Euros per kWh produced [€ /kWh].

4.1.3 Lifetime – Economic useful lifetime of typical wind turbines in [years].

4.2 Underlying assumptions

Costs variables are based on EWEA calculations of LCOE of wind power as reported in (17). Calculations are calibrated with published data from reports (3) (6) and (18). Baseline data from 2012 includes historical learning rates from 1984 to2011 of 14% for onshore wind as reported in (18). This means, a cost reduction of 14% has occurred every time the installed capacity has doubled. CAPEX and OPEX forecast 2020 to 2050 reflect insights from industry experts and EWEA expectation of capacity installations to 2050 (2). Accordingly, costs variables for onshore wind assume a higher future learning rate of 17%. For offshore wind an historical learning rate of 7% is assumed up to 2020 and a higher future value of 16% for 2020 to 2050. Computation of future CAPEX and OPEX are calculated according to European Commission's methodology reported in (19) with the formulas below:

$$CAPEX_{future} = CAPEX_{present}\left(\frac{P_{future}}{P_{present}}\right)^{\frac{\ln(1-LR)}{ln2}}$$

$$OPEX_{future} = OPEX_{present}\left(\frac{P_{future}}{P_{present}}\right)^{\frac{\ln(1-LR)}{ln2}}$$

Furthermore, in order to reflect differences in cost from offshore installations close to and far from shore, scale factors reported in annex B, table B2 of the report (20) were used. Accordingly, far-from-shore CAPEX costs are 1.15 greater than those of close-from-shore installations (total cost scale factor at 93.8 km distance, ibid) and far-from-shore OPEX costs are 1.26 greater than those of close-from-shore installations (average of installation scale factors at 93.8 km distance, ibid). Distance to shore value for 2012 is sourced from real up to date installations as reported by EWEA in (21). Projections to 2050 follow an increasing trend up to 93.8 km in line with cost assumptions.

Lifetime assumption is based on European Commission report (19).

4.3 Methodology for data collection

Data collection is a combination of EWEA's and others' expertise. Knowledge is formalised generally in public articles, but insights and industry expertise availability are limited in the public domain. In some occasions, access to this information poses commercial and strategic risks for companies. EWEA has engaged with some of its members to confirm costs and other variable assumptions for this assessment. It also engages with external organisations such as academia, government and non-profit organisations to cross-check our information. EWEA also pays for specialised market research and consultancy services to collect information on costs.

4.4 Conclusions on robustness of the produced data

Quality of source: 4. Existence of a possible bias: Yes.

Possible bias on future expectation of cost reduction may be reflected in the data. Further scrutiny of generation costs for all technologies could be foreseen and ranges could be established according to economic boundaries from WP1.

Nevertheless, there is enough confidence that variables selected are sufficiently documented for the end purpose of the overall project. Computations performed were done by highly qualified industry experts.

Confidence level on the nature of data is 4 to 5.

Confidence level on the time horizon is 3 to 4.

5 Environmental impact and public acceptance

5.1 Variables selected

5.1.1 Energy payback time – total amount of time that it takes for a typical wind turbine to offset the amount of energy used for its construction and decommission on a life cycle basis [months].

5.1.2 Social Acceptance – Social acceptance in percentage based on Eurobarometer surveys [%].

5.1.3 Recyclability – Percentage of materials that can be recycled [%].

5.1.4 Contribution to local economy – Number of direct and indirect Full Time Employment jobs created [FTE].

5.2 Underlying assumptions

The main impact that wind power technologies have to the environment is the amount of CO_2 emissions they save throughout their lifetime. This is well known and widely accepted. However, detailed figures depend not only on the type of fuel used for generating electricity, but also on other more complex interactions, such as the decabornisation rate assumed for a variety of other industries necessary for its deployment, such as transport, construction, etc. We assume that an estimation of CO_2 emissions savings to 2050 is a very wide exercise in the context of this assessment, especially considering all the possible macro-economic scenarios and decarbonisation paths.

An alternative variable to show the evolution of environmental impacts of the technology is the life cycle energy use or the energy payback time. To this end, energy payback time can be easier related with variables already reported in this assessment, such as capacity factor (1.1.7) and life time (4.1.3). We used figures from Vestas V90-3 MW wind turbine Life Cycle Assessment (22) and it is assumed an improvement trend to 2050 in line with technology readiness and maturity variables (2.1.1 to 2.1.5).

Other variables relevant for measuring the environmental impacts of wind technologies are those related to health & safety and public perception. We assumed that the former is reflected in the permitting procedures of variable 3.1, which normally involve comprehensive environmental impact assessments including visual impacts, noise generation, shadow casting, flickering, etc., while the latter can be measured by social surveys measuring social acceptance of the technology. Deliverable D1.2 from WP1 already documents public perception as one of the boundary conditions for the project using Eurobarometer survey results. Also, social acceptance is not exclusively related to visual perception but also to the value that a technology or an industry brings to the local and wider economy. Hence, we proposed to include variables related to job creation and GDP contribution. Estimation of such variables are based on EWEA report Green Growth (23).

Finally, an increasing area of interest regarding RES environmental impacts is the sustainability of the materials they use. We propose to use a “Recyclability” variable to measure the amount of materials that can be recycled from a wind turbine when dismantled.

5.3 Methodology for data collection

Data collection is combination of EWEA’s and others’ expertise. Knowledge is formalised in public articles and industry specialised publications. See bibliography for a complete list of references.

5.4 Conclusions on robustness of the produced data

Quality of source: 4.

Existence of a possible bias: None.

Exclusion of CO_2 offset time variable could be subject to further reconsideration once overall assumptions for all generation technologies are established. Quick calculations with available data from Vestas report (22) showing 5.23 g CO_2/kWh (offshore) and 4.64 g CO_2/kWh (onshore), suggest that it could be feasible to establish a base line value. If we consider that the European Commission estimates that coal, gas and oil emitted on average 696 g CO_2/kWh in 2010 (23) and wind power displaces a mix of these technologies then, a 3 MW turbine has a CO_2 payback ratio of 133 (offshore) and 150 (onshore). However, this number highly on the assumptions made about turbine size, location of installation and level of CO_2 intensity in year study. In order to make comparisons between technologies, a set of standard assumptions may be required.

Confidence level on the nature of data is 4 to 5.

Confidence level on the time horizon is 3 to 4.

6 Supply chain issues

6.1 Variables selected

6.1.1 Project lead time - Total time for project completion in [years]. Computation: Total time for project completion in [months] - Permitting time [months].

6.1.2 Risk of shortage of materials - [high/medium/low].

6.2 Underlying assumptions

Modern manufacturing of wind turbines requires input of several raw materials, which are traditionally used in many other industries. Deployment of wind power to the levels expected by the industry creates increasing interest on the availability of materials for manufacturing components and support infrastructure. For example EWEA estimates are that the wind energy sector is currently using 13% of the glass fiber consumption and 22% of the carbon fiber consumption in Europe. By 2020 these numbers are expected to increase to 35% and 58% respectively, keeping the wind energy industry among the top users of these materials. Numbers beyond 2020 are uncertain and dependent on R&D technology progresses, manufacturing techniques and recyclability potential, some of which are covered in this report. However, while the use of some materials can be related to some variables, others are more complex to predict.

To this end, and for the purpose of this assessment, it is proposed to use the project lead time as a variable that measures not only the availability of materials but also other supply chain issues necessary for wind power deployment, such as availability of ports infrastructure and vessels. The rule of the thumb is, the longer the project lead time is, the more supply chain issues the technology faces.

Data is based on EWEA reports (15) and UK Crown State report (25).

6.3 Methodology for data collection

Data collection is combination of EWEA's and others' expertise. Knowledge is formalised in public articles and industry specialised publications. See bibliography for a complete list of references.

6.4 Conclusions on robustness of the produced data

Quality of source: 3.

Existence of a possible bias: None.

Confidence level on the nature of data is 4.

Confidence level on the time horizon is 3 to 4.

7 Dynamic performance of technology

7.1 Variables selected

7.1.1 Strom Control operation - [TRL].

7.1.2 Active power control - [TRL].

7.1.3 Ramp rate control- [TRL].

7.1.4 Frequency control - [TRL].

7.1.5 Voltage control - [TRL].

7.1.6 Harmonics control - [TRL].

7.2 Underlying Assumptions

Overall assumption is that wind turbines performance capabilities progressively evolve in line with grid code requirements and grid support service opportunities. With current technology, wind power plants can be designed to meet power industry expectations such as riding through voltage dips, supplying reactive power to the system, controlling terminal voltage, participating in system operation with output and ramp rate control, and providing SCADA information (27).

Variables selected are qualified according to the TRL scale, cf. Figure 1, and they comprise improved control performance under storm and other extreme weather, capability to control active power output either by capping its maximum output level or fixing it to a lower set point level. In parallel with active power control, the wind turbine can be controlled so as to limit the rate at which output power can increase, so a ramp rate capability could be defined over a period of time (e.g. one, ten minutes, etc.) as long as the wind resource is available.

Also, reactive power control at steady-state as well as increasing reactive power range provision, even at zero active power delivery, are capabilities that are gaining interest in grid codes (28). Generally, these are specified at the point of connection (POC) and will differ in transmission and distributions systems. However, external sources of reactive power can also be STACOMs, static var compensators (SVC) and other FACTS-based or voltage source converter (VSC)-based technologies, all of which are also assessed in WP3 (cf. Annexes related to the assessment of active transmission technologies).

Finally, not only the capability to stay connected and ride through power system faults is expected as standard performance capability, but also the provision of post-fault voltage support strategies such as (fast) reactive current injection, reactive current injection negative sequence. The delivery of this capability will be in line with evolution of generator configurations in the future.

7.3 Methodology for data collection

Data collection is combination of EWEA's and others' expertise. Knowledge is formalised in public articles, network codes and industry specialised publications. See bibliography for a complete list of references

7.4 Conclusions on robustness of the produced data

Quality of source: 4.

Existence of a possible bias: None.

Confidence level on the nature of data is 4.

Confidence level on the time horizon is 4 to 5.

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