SCHOOL OF HUMAN SCIENCES & TECHNOLOGY

Stream Processing and Real-Time Analytics

ANALYZING STREAMING DATA FOR BETTER DECISION MAKING

HOW WINDY WILLOW USES WIND GENERATION AND PRICE STREAMING APIs TO MAKE DATA-DRIVEN DECISIONS ON SELLING WIND POWER AND MAINTAINING WIND TURBINES

Group C

Allison Black

Dennis Pedersen

Eleonora Jimenez

Georgy Eremin

Leonard Valencia

Rayan Alghamdi

Submitted on 14 January 2021

Table of Contents

1 Introduction **3**

2 Executive Summary **4**

3 Turning Wind Power into Electricity **5**

How is electricity measured? 6
How much electricity can a wind turbine create? 6

4 Business Case **7**

Big Players in Combining Wind Power and Streaming Data: AWS & Vestas 8
Power Purchase Agreements (PPAs) 10

5 Problem **10**

Problems with PPAs 11
Maintenance Costs 12

6 Technology Solution & Architecture **12**

7 Benefits of Using Streaming Data (Business Results) **16**

Business Decisions 16
Maintenance Decisions 17

8 The Future **17**

9 References **19**

1 Introduction

Along with climate change comes a change in the means with which the world sources its power. Last June, Spain closed seven coal-fired stations from A Coruña to Córdoba, halving the country's coal capacity. With less reliance on fossil fuels, more opportunities for renewable energy are appearing. Today we will focus on wind: a cost-effective[i], renewable energy source.

Wind power capacity is increasing rapidly, as more wind turbines are being installed all over the globe, both onshore and offshore (see figure 1). An increased capacity means that wind power now accounts for a higher percentage of consumers' electricity needs. This is good news for the climate, for consumers, for wind farms and for the people who are benefitting from the jobs created by this industry.

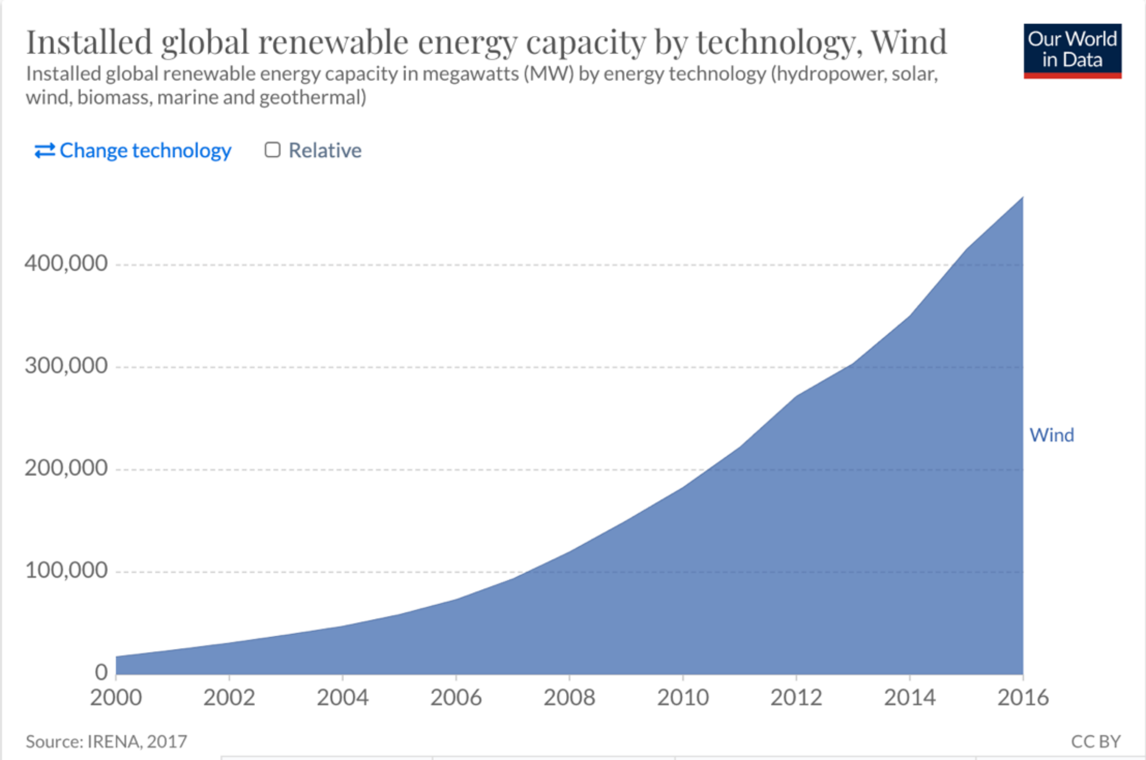

Figure 1: Installed global renewable energy capacity by technology. Source: ourworldindata.org

We will present our research and business case from the point of view of Windy Willow, a mock-up wind farm, and we will explain how this wind farm captures wind and turns it into profit by analyzing streaming APIs to make data-driven decisions. This report will cover background information on how wind turns into electricity, how the wind power industry works, and how Windy Willow's business case fits into this industry. The objective of this report is to give a technical solution to the business problem:

Wind farms are missing out on potential revenue for two main reasons:

1. *Signing Power Purchase Agreements (PPAs)*

2. *Expensive maintenance costs*

The first point deals with a common but complex agreement between the seller of wind power electricity (in our case, Windy Willow) and a purchaser. Although PPAs are currently trending as part of a standard business plan for wind projects, these contracts generally give more control to the purchaser than to the wind farm. These agreements are long-term, lasting 10-20 years, locking a wind farm into an agreement that might not be in their best interest. Although such an agreement can provide start-up funding and/or long-term security for a wind farm, there is also a way that wind farms, big or small, can achieve better business results without the need of a PPA.

Secondly, due to the high cost of maintaining wind turbines for a wind farm, profit margins can drastically shrink. The maintenance of a wind turbine can be quite expensive, and therefore operations and maintenance must play a major role in the business strategy of a wind farm. Operations and maintenance costs average between €35,000 and €40,000 per megawatt during the first 10 years of a wind turbine's operations.[ii] However, costs can vary widely depending on the turbine's age and location as well as the operations and maintenance strategy.

Windy Willow will exemplify how wind farms can increase revenue by maintaining control over their turbines and business decisions and reduce costs effectively maintaining their turbines in an efficient and effective way. After explaining the technical architecture of our solution, we will explain the benefits of using streaming data and finally reveal the business results. This report will give an example of how wind farms like Windy Willow can independently run their business in a more profitable way by using streaming data.

2 Executive Summary

Windy Willow is a mock-up wind farm in Spain that sells electricity to the marketplace as well as to customers who wish to buy directly from the wind farm in bulk amounts.

- **Problem:**

Wind farms like Windy Willow are missing out on potential revenue for two main reasons:

1. Signing Power Purchase Agreements (PPAs)
2. Expensive maintenance costs

- **Solution:**

  Instead of signing a PPA, Windy Willow can use streaming data to make decisions in real-time about when and to whom to sell their electricity. Streaming data will also allow for up-to-date decisions on maintenance, thereby lowering costs and increasing profits.

- **Benefits of Using Streaming Data:**

  1. By understanding the power of streaming data, wind farm operators are able to obtain information that will allow them to maintain control over all of the electricity generated on the farm. Rather than get stuck in a long-term PPA with only one purchaser, wind farms can decide whom they want to sell their electricity. More buyers mean more opportunities for Windy Willow.
  2. Data-driven business decisions are at the heart of any successful business. In the wind power industry, more data, better data, and faster data are all keys to run a smoothly operating wind farm while making important decisions such as, "Do we call the insurance?", or "Do we shut down the turbines?", or "Should we sell or store our electricity?"
  3. Windy Willow relies on streaming data in order to make maintenance decisions before a problem becomes too big (and too expensive). The streaming architecture provides an event trigger alert well before the wind operator would notice something was wrong. As soon as the wind farm operator sees the "Shutdown" signal, she can take action and avoid major problems with the wind turbines.

- **The Future:** Windy Willow's technical solution has been created so that it is easily scalable. In the future, when there will be so much data that a layering in processing is needed, Windy Willow will need to use a product like Apache Kafka. With more sensors on wind turbines, this extra data will give more accurate information on operations and maintenance.

3 Turning Wind Power into Electricity

When sunlight heats the earth, it also heats the atmosphere. As hot air rises, cooler air rushes in to fill its place — thus creating wind. For more than 2,000 years people have captured this energy with windmills and used it to do useful things, such as grind grain or pump water. By the late 19th century, windmills were also being used to produce electricity, mostly in rural areas.[iii]

How is electricity measured?

Watts are a measurement of power, describing the rate at which electricity is being used at a specific moment. [iv] For example, a 20-watt light bulb draws 20 watts of electricity at any moment when turned on. Watt-hours are a measurement of energy, describing the total amount of electricity used over time. Watt-hours are a combination of how fast the electricity is used (watts) and the length of time it is used (hours). In the above example, the 20-watt light bulb, which draws 20 watts at any one moment, uses 20 watt-hours of electricity in the course of one hour.

Watts are very small units, so the terms kilowatt (kW = 1,000 watts), megawatt (MW = 1 million watts), and gigawatt (GW = 1 billion watts) are most commonly used to describe the capacity of generating units like wind turbines or other power plants. Electricity production and consumption are most commonly measured in kilowatt hours (kWh). A kilowatt-hour means one kilowatt (1,000 watts) of electricity produced or consumed for one hour. One 50-watt light bulb left on for 20 hours consumes one kilowatt-hour of electricity (50 watts x 20 hours = 1,000 watt-hours = 1 kilowatt-hour).[v]

How much electricity can a wind turbine create?

Most onshore wind turbines have a capacity of 2-3 megawatts, which can produce over six million kilowatt hours of electricity every year. That's enough to meet the electricity demand of around 1,500 average households. Up to a certain level, the faster the wind blows, the more electricity is generated. In fact, when the wind speed doubles, up to eight times more electricity is generated. But if the wind is too strong, turbines will shut themselves down to prevent being damaged.[vi] Figure 2 shows the electricity per capita that was generated by wind in 2019. The number of kilowatt hours will continue to increase as more wind turbines, onshore and offshore, pop up around the globe.

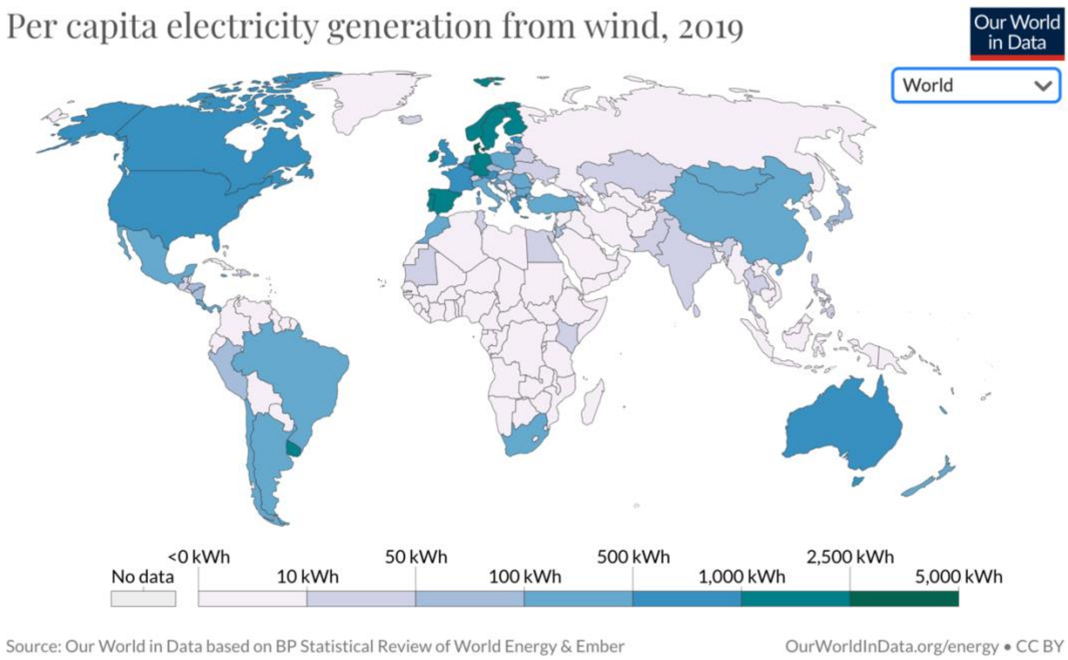

Figure 2: Per capita electricity generation from wind. Source: ourworldindata.org.

4 Business Case

The global renewable energy market was valued at €763 billion in 2017, and is expected to reach €1,243 billion by 2025.[vii] Wind was the second largest renewable energy source (after hydropower) for power generation, producing more than 5% of global electricity with 591 GW of global capacity.[viii] (Capacity is the maximum amount of electricity that can be generated when there is sufficient wind for a turbine to operate.) Given the increasing percentage of wind energy in the renewable energy mix, it becomes more important to deliver a constant output of power, particularly at moments of high electricity demand. For achieving this, turbines are clustered in large wind farms.[ix]

Electricity generated by wind turbines on Windy Willow's farm can be used to cover on-site energy needs, or it can be sold and transmitted over the electric grid. For sales over the electricity grid, an Independent System Operator (ISO) creates and manages a wholesale market for electric energy, capacity, and ancillary services.[x] At Windy Willow, we can sell our electric energy and capacity in spot markets organized by the ISO, or we can contract with wholesale buyers to sell these products for any term to utilities or other buyers operating in the ISO marketplace. Figure 3 shows price setting in a marginal cost electricity spot market for Denmark. The spot price of the hour occurs at the intersection of the demand curve and the supply curve.

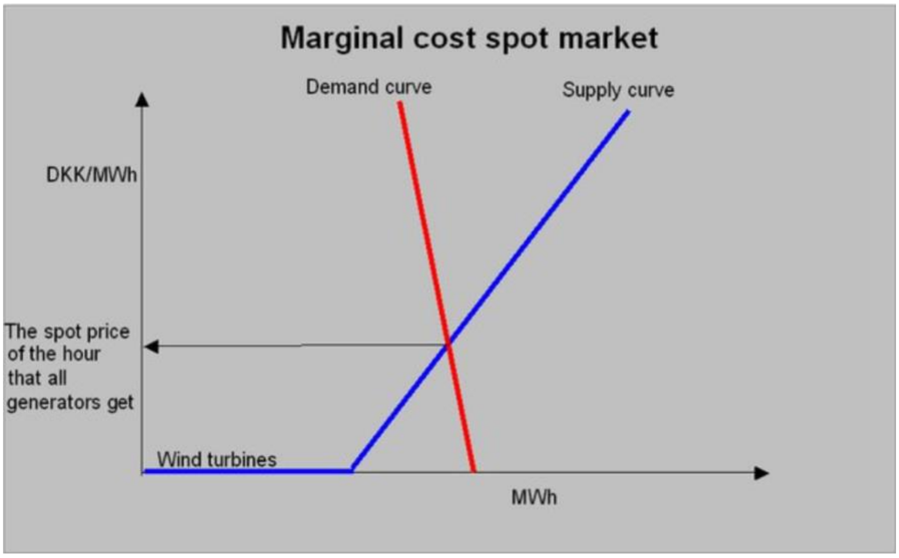

Figure 3: Price setting in a marginal cost electricity market[xi]

Big Players in Combining Wind Power and Streaming Data: AWS & Vestas

The AWS Big Data Blog lists turbine protection in the wind energy sector as a popular use case. Every wind turbine has a range of speeds, typically 30-55 miles per hour (48-88 kilometers per hour,) in which it produces maximum capacity.

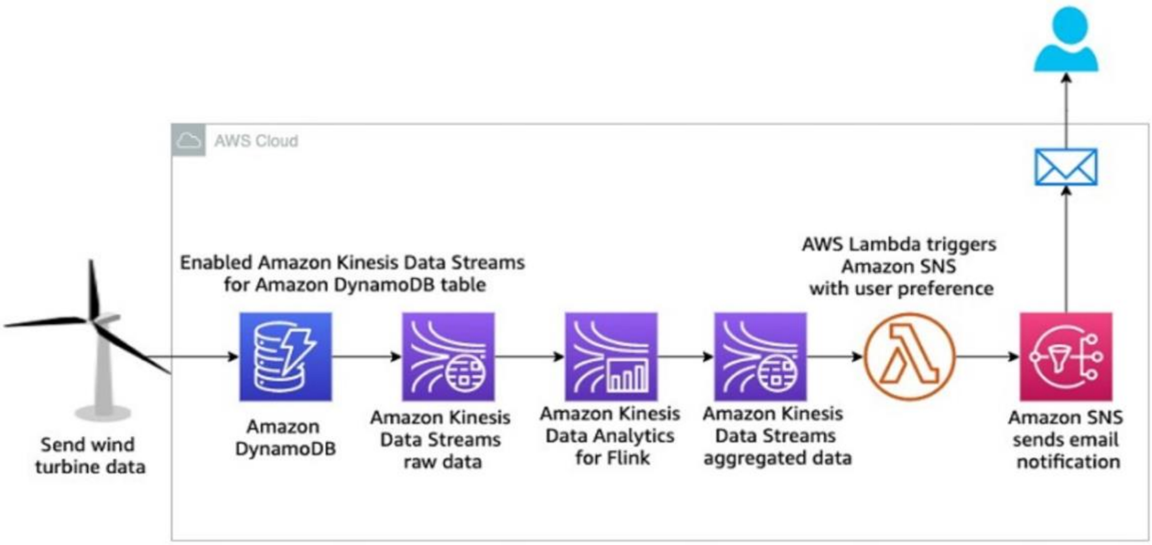

Figure 4: AWS architecture diagram illustrating the wind turbine protection system[xii]

When wind speeds exceed 70 miles per hour (112 kilometers per hour), it is important to start shutting down turbines to prevent damage.[xiii] Figure 4 illustrates how Amazon DynamoDB customers can use Amazon Kinesis streaming to extract wind turbine data and store it in a data lake. Customers then use Kinesis Data Analytics for Apache Flink to send real-time notifications when wind speed is greater than 60 miles per hour (95 kilometers per hour) so that the operator can take action to protect the turbine.[xiv] Windy Willow has a similar output on its *windConsumer* terminal window with an output that reads “Shutdown” when the wind exceeds a programmed threshold. Below is the code for Windy Willow’s *windConsumer* actions and an example of an output for the “Shutdown” action. The “wind” column shows the megawatts generated by the wind.

```python
def get_action(wind):
    wind_int = int(wind)
    if wind_int < 1800:
        return "Call the insurance"
    elif wind_int < 2500:
        return "Sell/Store"
    else:
        return "Shutdown"
```

Figures 5 & 6: Python code and output for Windy Willow’s windConsumer

```
+--------+-----------------+-----------+-------------+-----+
|  action|potential_revenue|price_euros|    timestamp|wind|
+--------+-----------------+-----------+-------------+-----+
|Shutdown|          96482.0|         38|12/01/20 7:05|2539|
+--------+-----------------+-----------+-------------+-----+
```

Vestas, a Danish company that manufactures, sells, installs, and services of wind turbines, now offers customers digital solutions to deliver greater predictability, increased renewable energy production, more efficient operations, and better integration with energy grids.[xv] These new digital solutions give customers easy access to portfolio-wide asset visualization, predictive maintenance, and wind power forecasting. Windy Willow has similar (albeit very basic) visualizations for the wind farm’s operators and decision-makers (see figures 7 & 13). The internal price forecast (*forecastProducer)* gets streamed along with our *windConsumer* so that Windy Willow’s owners can compare the forecasted price to the actual price. In the Tableau dashboard, Windy Willow can see near real-time wind generation in megawatts, a comparison of their internal price forecast versus the actual price streamed from the Red Electrica API, and the three different actions that assist in making business decisions.

```
Timestamp:      12/01/20 1:00   Price:  39.39   eur

Timestamp:      12/01/20 2:00   Price:  37.07   eur

Timestamp:      12/01/20 3:00   Price:  32.2    eur
```

Figure 7: Windy Willow's forcastProducer

Power Purchase Agreements (PPAs)

Wind turbine owners are often paid through a contract called a Power Purchase Agreement (PPA). PPAs are long-term contracts, spanning 10-20 years. PPAs are known as a fixed-for-floating swap, and are typically "settled" monthly. The amount the purchaser pays at settlement depends on the difference between the fixed price agreed to in the PPA, and the floating wholesale market price, which is what the wind farm actually sells the energy for. For example, if the PPA price is €15, but the wind farm sells the energy for €25, the wind farm will give the extra €10 to the purchaser. On the other hand, if the wind farm sells the energy for €10, the purchaser has to pay the wind farm €5 to make up the difference. Essentially, no matter what the wholesale price of energy happens to be over the next 10-20 years of the contract, the wind farm receives exactly €15 per megawatt hour: no more, no less.[xvi]

We used Pexapark's "PPA Price Report: Spain", published August 2020 to obtain PPA price indices and market indices. The report states,

> *"The increase in volatility coupled with a decrease in prices during the early stages of corona have put many deals on hold until summer. Nevertheless, the Spanish PPA market remains buyer-driven with most of the value in PPAs reliant on proper structuring and a diligent execution process."*[xvii]

The phrase "buyer-driven" market leads us to our next section, where we will explain why it is not in Windy Willow's best interest to sign a PPA.

5 Problem

Wind farms are missing out on potential revenue for two main reasons:

1. Signing Power Purchase Agreements (PPAs)

2. Expensive maintenance costs

Wind farms that sign a PPA do not have control over when and to whom they sell their energy. This means that they are missing out on extra potential revenue. The main reason for the owners of a wind farm to sign a PPA is to have income security, which is nice when dealing with something as volatile as wind. But with streaming data and advanced forecasting systems, why shouldn't these wind farms be in control of their business?

Problems with PPAs

In Windy Willow's example, the PPA price is around 13% less than the average yearly price that Windy Willow could get for their selling their wind power on the spot. market. However, PPA prices can be much lower. In fact, current low PPA rates can be 30-40% below what would have been received on the spot market.[xviii] And a lower price is just the beginning.

"Among the cons are that PPAs can be complex from a financial and contractual standpoint," says Alanya Schofield, senior director E Source, a Boulder, Colorado-based energy research and advisory company. Schofield adds, "Sometimes, [PPAs] have the potential for financial risk depending on the terms. It's important to be aware of the risks and nuances of the contract."[xix]

To give more reasons why a PPA is not beneficial for wind farms such as Windy Willow, we will use an example of a Power Purchase Agreement between a seller and the Bonneville Power Administration.[xx] The 38-page document is dense and complex, so we picked out just a few points.

- Buyer has access to the seller's wind farm at all times, even weekends and nights. This includes the control room and interconnection facilities
- Seller shall, at Seller's expense, install communication equipment that allows BPA to read the Metering Devices from a remote location (such as BPA headquarters) at any time.
- Seller shall supply from the Facility and sell to BPA, and BPA shall receive and purchase, the entire Energy Output of the BPA Wind Turbines in accordance with the terms of this Agreement.
- BPA shall not be obligated to purchase Energy Output that cannot be delivered due to disruptions, breakdowns, electrical system failures and/or mechanical failures, maintenance or repair, including, for reasons of Force Majeure, to the Facility Substation and/or the Grid; provided that such inability to deliver is not due, in whole or in part, to BPA's negligence or its breach of, or default under, this Agreement or the Delivery Arrangements Agreement. As between BPA and Seller, Seller shall not be entitled to recover lost revenues for events covered in this Section 6(d) from BPA (other than as referred to in the proviso in the previous sentence).
- Carbon dioxide credits and other air quality credits go to BPA, not the seller
- Seller shall be responsible for any and all present or future Federal, state, municipal, or other lawful taxes applicable by reason of the ownership and operation of the Facility and the sale of energy under this Agreement and all ad valorem taxes relating to the Facility and the Interconnection Facilities.

Maintenance Costs

Each turbine on the wind farm needs yearly replacement of parts and fluids. As mentioned in the introduction, operations and maintenance costs average between €35,000 and €40,000 per megawatt during the first 10 years of a wind turbine's operations.[xxi] However, costs can vary widely depending on the turbine's age and location as well as the operations and maintenance strategy. Besides this yearly maintenance, each time a component fails it needs to be replaced. In order to decrease lost revenue due to downtime, maintenance actions are ideally done during periods of low wind and low electricity demand. To be able to deal with the massive amount of measurement data coming from the 200+ sensors mounted on each turbine in a farm, it is best to use big data storage and a streaming approach.[xxii]

6 Technology Solution & Architecture

Windy Willow's solution involves a big data architecture utilizing two APIs, an internal price forecast, stream processing, and a data visualization tool. Below, we have listed the components of the architecture, in the form of a big-data ecosystem: data sources, data ingestion, data processing, data storage, and data serving.

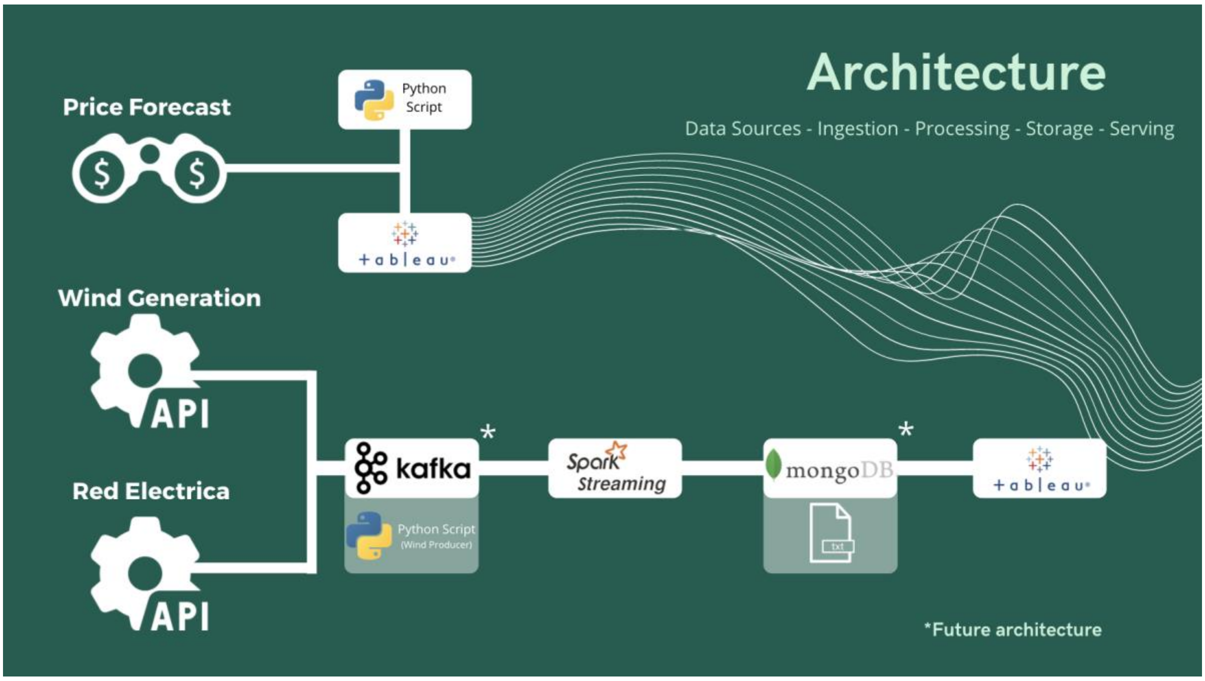

Figure 8: Windy Willow's Architecture

Data Sources: Windy Willow uses a wind generation API (BPA Wind Generation), a wind power pricing API (Red Electrica), and an internal price forecast. Below is the code block from Windy Willow's *windConsumer*, showing the parameters for Red Electrica.

```python
def get_price(date_times):
    resp = requests.get('https://apidatos.ree.es/en/datos/mercados/precios-mercados-tiempo-real?' +
                        'start_date=' + date_times[0] +
                        '&end_date=' + date_times[1] +
                        '&time_trunc=hour')
```

Figure 9: Code block from Windy Willow's windConsumer

Data Ingestion: A Python script is used now, but Kafka will be used in the future as Windy Willow scales. Apache Kafka is a distributed streaming platform that aims to provide a unified, high-throughput, low-latency system for handling real-time data feeds. Kafka was originally developed by LinkedIn, and was subsequently open sourced in early 2011. Jay Kreps (formerly the lead architect for data infrastructure at LinkedIn) chose to name the software after the author Franz Kafka because it is "a system optimized for writing", and he liked Kafka's work.[xxiii]
Although we do not require Kafka for our prototype, we have included it in our theoretical architecture. Our current architecture only needs a python script for ingestion, but we would need Kafka to scale this project. For example, if we are getting so much data that we need layering in processing, the Kafka layer would fit our needs. One major benefit of using Kafka is that it is a flexible system and can work for simple tasks as well as highly complex tasks.

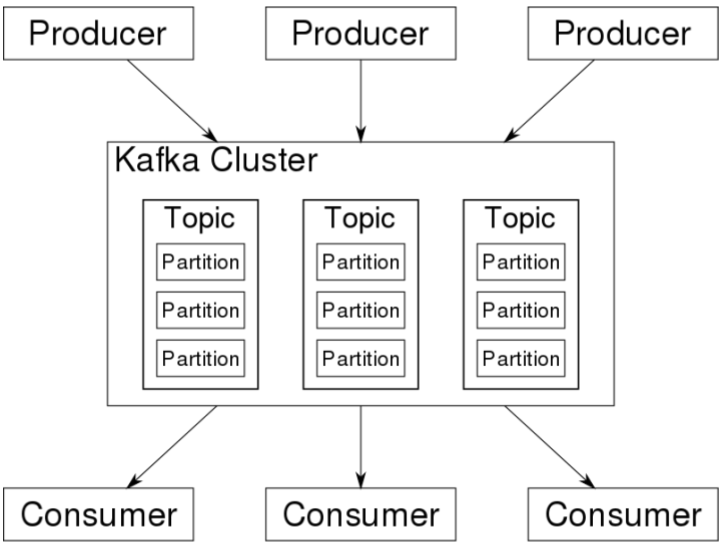

Figure 10: Overview of Kafka architecture[xxiv]

Kafka maintains feeds of messages in categories called topics. Producers write data to topics and consumers read from topics. Since Kafka is a distributed system, topics are partitioned and replicated across multiple nodes. Kafka treats each topic partition as a log, or an ordered set of messages. Partitions are a fundamental building block because they make Kafka what it is known for: being distributed, scalable, elastic, and fault tolerant (the image below shows the importance of partitions in Kafka). Each message in a partition is assigned a unique offset. Each topic has a user-defined category (or feed name) to which messages are published.[xxv]

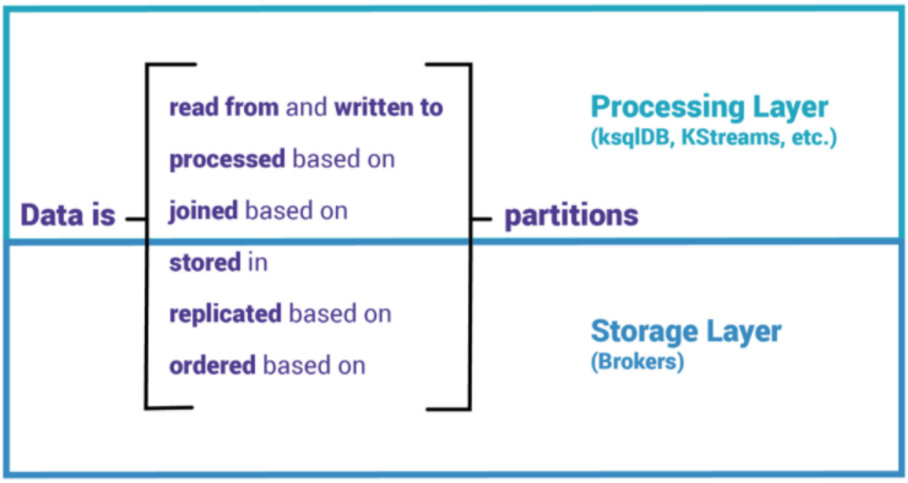

Figure 11: diagram showing the importance of partitions in Kafka[xxvi]

Data Processing: From Kafka, Windy Willow receives the data stream using Spark Streaming (an extension of the Spark API) to process its streaming data. Spark is a fast, general-purpose computing framework. Spark achieves its speed via a data model called resilient distributed datasets (RDDs) that are stored in memory while being computed on. This eliminates the expensive intermediate disk writes. Spark Streaming enables scalable, high-throughput and fault-tolerant stream processing. To initialize a Spark Streaming program, a StreamingContext object has to be created which is the main entry point of all Spark Streaming functionality. After a context is defined, the input sources must be defined by creating input DStreams (Spark Streaming provides a high-level abstraction called *discretized stream* or *DStream,* which represents a continuous stream of data). Now it is possible to start receiving data and processing it.

```
from pyspark import SparkConf, SparkContext
from pyspark.streaming import StreamingContext
from pyspark.sql import Row, SQLContext

# create spark context with the above configuration
sc = SparkContext('local[*]', appName="WindConsumer")
sc.setLogLevel("ERROR")
# create the Streaming Context from the above spark context with interval size 5 seconds
ssc = StreamingContext(sc, 5)
```

Figure 12: Code blocks from Windy Willow's windConsumer showing creation of a SparkContext and a StreamingContext

Data Storage: For Windy Willow's current architecture, we only need a text file for storing the data that was processed in Spark Streaming. However, in the future Windy Willow will use MongoDB, a cross-platform document-oriented database program where data is stored in JSON format, i.e., as name/value pairs. The storage engine is the primary component of MongoDB responsible for managing data. MongoDB provides a variety of storage engines, allowing Windy Willow to choose the one most suited to the business needs.

Data Serving: Finally, we get to the last stage of the architecture – where all of the charts and graphs come into play! For this stage, Windy Willow uses Tableau, an interactive data visualization software that is focused on business intelligence. The data that was streamed into our text file (or MongoDB) will now be fed to Tableau with a live connection – as more data streams in, the visualizations on our dashboard will change. This allows the owners of Windy Willow to easily see near real-time metrics in order to make better business decisions.

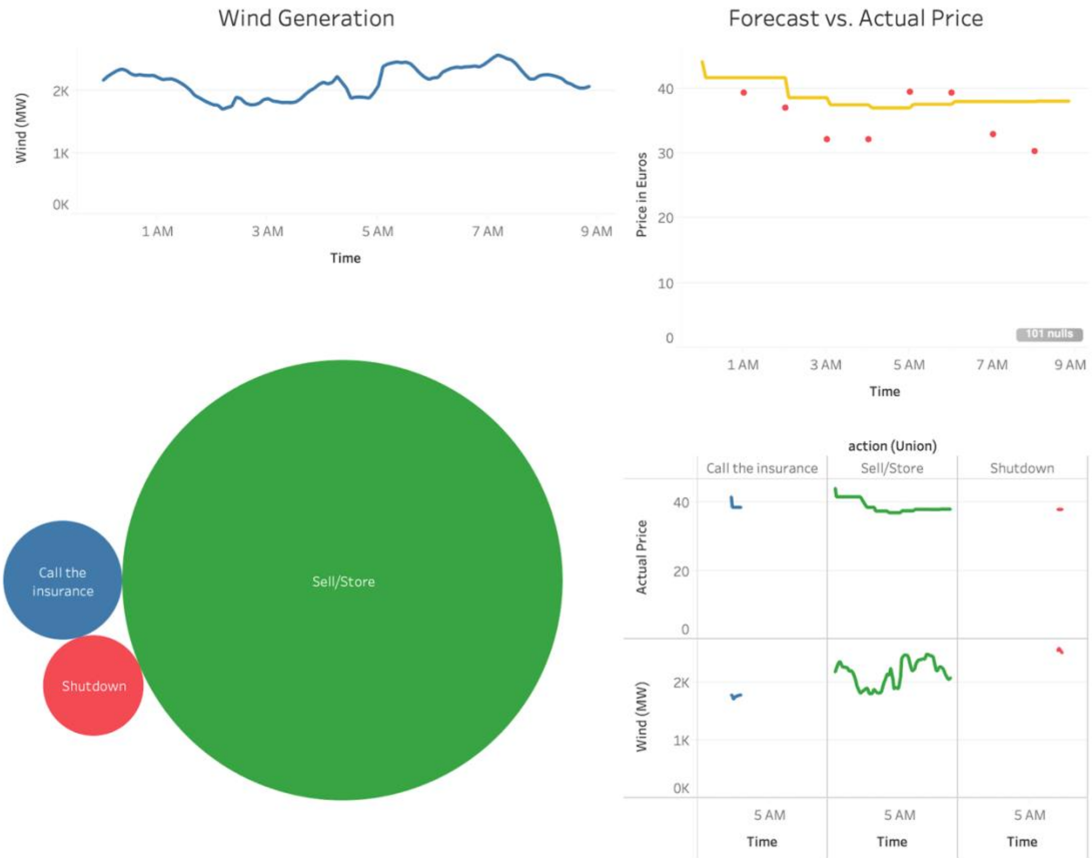

Figure 13: Windy Willow's Tableau dashboard

7 Benefits of Using Streaming Data (Business Results)

The two main areas where we find the biggest benefits of using streaming data are exactly what our technology solution aims to solve:

1. Making busines decisions, specifically whether or not to sign a PPA
2. Maintaining wind turbines

Streaming data allows us to not only solve the major problems that wind farms currently face, but it also enables Windy Willow to grow and enjoy economies of scale in the future. We will review how streaming data helps Windy Willow make better decisions and then state the business results.

Business Decisions

By looking at near real-time data, the Windy Willow operators can decide whether to sell or store wind power electricity, or to shut down the turbines if the wind picks up too much. If, on the other hand, there is not sufficient wind to make a profit, we can either call the insurance, or decide to shut down the turbines in order to perform maintenance. Streaming data allows Windy Willow to make these decisions in real time, and therefore give the wind farm owners an opportunity to capture more value from the wind.

In order to see how much more value Windy Willow could capture with these up-to-the-minute business decisions, we compared what Windy Willow would earn if they signed a PPA to what they would earn without a PPA. We obtained the price of wind power from the Pexapark report on the that we mentioned in the Business Case section. Based on Pexapark's "Composition of Spanish PPA Price," we will use the price of €35.82 for comparing the profit using a PPA and profit without using a PPA. This assumes a 10-year PPA. The per-year revenue with a PPA using Windy Willow's adjusted output would be €15,051,774. We already have the output "potential revenue" (Red Electrica price times value of wind power produced) for Windy Willow per day and per year. For Windy Willow's average output (adjusted for output to be sold) of 420,206 MW per year, this amounts to €16,947,792 per year, making Windy Willow's price per megawatt averages to be €40.33. This means that Windy Willow can potentially make €1,896,018 more revenue per year (a 13% increase) by not signing a PPA.

Maintenance Decisions

Failure of turbine subcomponents should be detected well in advance to allow early planning of all necessary maintenance actions. It is best if maintenance can be performed during low wind and low electricity demand periods. With the wind generation API, Windy Willow can immediately see when the wind is low and when the electricity demand is low (the streaming prices will be also be low).

According to Onyx Insight, a predictive maintenance firm, "by combining real world engineering expertise with the latest advancements in artificial intelligence and machine learning, [wind farms] can move to a predictive maintenance model and operations and management costs by up to 30%."[xxvii] With less costs, Windy Willow will end up with more profit.

8 The Future

Currently, wind speed is determining for each turbine how much energy it produces. In the future, the wind farm operator will decide how much each turbine in the farm produces. That way she can take into account the price of energy, the condition of the turbines and other factors.[xxviii] This is exactly where Windy Willow is heading, so the future is looking good.

From Onyx Insight:

> "Using the vast quantities of data generated by pre-installed sensors for detecting and measuring health indicators such as drive train vibration, operations and management experts can work with data analysis specialists to train algorithms to detect issues in wind turbines before they emerge. When combined with the specialist knowledge of operations and management professionals, these algorithms can be trained to diagnose problems with accuracy rates close to 99%. It is then possible to have an entire site of digitalized wind turbines, connected to the Internet of Things and to each other, delivering performance and health data to remotely situated operations and management teams."[xxix]

More sensors on turbines will provide better streaming data, and better streaming data will aid in making better business decisions. Windy Willow's hope is that wind farms make more profit, encouraging more wind farms to emerge all over the globe, and thereby decreasing the global reliance on fossil fuels.

9 References

[i] Advantages and Challenges of Wind Energy. (n.d.). Retrieved January 14, 2021, from https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy#:~:text=Wind%20power%20is%20cost%2Deffective,after%20the%20production%20tax%20credit.

[ii] Reuters Events: Renewables. (n.d.). Retrieved January 3, 2021, from https://www.reutersevents.com/renewables/wind-energy-update/us-wind-om-costs-estimated-48000mw-falling-costs-create-new-industrial-uses-iea

[iii] "Wind of Change." *The Economist*, The Economist Newspaper, Dec. 2008, www.economist.com/technology-quarterly/2008/12/06/wind-of-change.

[iv] How is Electricity Measured? (n.d.). Retrieved January 2, 2021, from https://www.ucsusa.org/resources/how-electricity-measured#:~:text=The%20typical%20US%20home%20uses,about%20600%20MW%20in%20size.

[v] Wind power, capacity, watts and kilowatt hours – how is it all connected? (2011, January 12). Retrieved January 2, 2021, from http://www.ewea.org/blog/2011/01/wind-power-capacity-watts-and-kilowatt-hours-%E2%80%93-how-is-it-all-connected/

[vi] How do wind turbines work? (n.d.). Retrieved January 3, 2021, from https://www.goodenergy.co.uk/how-do-wind-turbines-work/

[vii] "Renewable Energy Market Size, Share and Analysis: Forecast- 2025." *Allied Market Research*, May 2019, www.alliedmarketresearch.com/renewable-energy-market.

[viii] Renewable Energy. (2020, April 27). Retrieved January 03, 2021, from https://www.c2es.org/content/renewable-energy/

[ix] Helson, Jan. "Integrated Condition Monitoring of a Fleet of Offshore Wind Turbines with Focus on Acceleration Streaming Processing." *ResearchGate*, May 2017, www.researchgate.net/publication/317320333_Integrated_condition_monitoring_of_a_fleet_of_offshore_wind_turbines_with_focus_on_acceleration_streaming_processing.

[x] "Selling Wind Power." *WINDExchange*, https://windexchange.energy.gov/market-selling#:~:text=Owners%20of%20wind%20turbines%20interconnected,well%20as%20other%20generation%20attributes..

[xi] Karnøe, P. (2009, June). Price setting in a marginal cost electricity spot market. [Digital image]. Retrieved January 13, 2021, from https://www.researchgate.net/figure/Price-setting-in-a-marginal-cost-electricity-spot-market_fig2_242564617

[xii] Engdahl, S. (2008). Blogs. Retrieved January 10, 2021, from https://aws.amazon.com/blogs/big-data/building-a-real-time-notification-system-with-

amazon-kinesis-data-streams-for-amazon-dynamodb-and-amazon-kinesis-data-analytics-for-apache-flink/

[xiii] National Wind Watch. (n.d.). FAQ - Output. Retrieved January 10, 2021, from https://www.wind-watch.org/faq-output.php

[xiv] Engdahl, S. (2008). Blogs. Retrieved January 10, 2021, from https://aws.amazon.com/blogs/big-data/building-a-real-time-notification-system-with-amazon-kinesis-data-streams-for-amazon-dynamodb-and-amazon-kinesis-data-analytics-for-apache-flink/

[xv] Utopus Insights Corporate Video 2019. (n.d.). Retrieved January 14, 2021, from https://www.vestas.com/en/services/utopus-insights#!smart-data-analytics

[xvi] Johnson, J. (n.d.). 4 Ways to Get Renewable Energy Certificates. Retrieved January 11, 2021, from https://leveltenenergy.com/blog/clean-energy-experts/ways-to-get-renewable-energy-certificates/

[xvii] *PPA Price Report Spain* (Rep.). (2020, August). doi:https://quote.pexapark.com/#/ppa-prices/list

[xviii] No PPA, No Problem: The risks and rewards of wind hedge agreements - UL: Renewables. (2015, November 20). Retrieved January 08, 2021, from https://aws-dewi.ul.com/no-ppa-no-problem/

[xix] Steele, J. (2019, February 27). The ABCs of PPAs. Retrieved January 08, 2021, from https://www.cpexecutive.com/post/the-abcs-of-ppas/

[xx] Example of a Power Purchase Agreement. (n.d.). Retrieved January 3, 2021, from https://web.archive.org/web/20170501211035/http:/www.bpa.gov/power/pgc/wind/EX_C_PPA_2.pdf

[xxi] Reuters Events: Renewables. (n.d.). Retrieved January 3, 2021, from https://www.reutersevents.com/renewables/wind-energy-update/us-wind-om-costs-estimated-48000mw-falling-costs-create-new-industrial-uses-iea

[xxii] Helson, Jan. “Integrated Condition Monitoring of a Fleet of Offshore Wind Turbines with Focus on Acceleration Streaming Processing.” *ResearchGate*, May 2017, www.researchgate.net/publication/317320333_Integrated_condition_monitoring_of_a_fleet_of_offshore_wind_turbines_with_focus_on_acceleration_streaming_processing.

[xxiii] Apache Kafka. (n.d.). Retrieved January 14, 2021, from https://www.wikiwand.com/en/Apache_Kafka

[xxiv] Streams and Tables in Apache Kafka: Storage Fundamentals. (n.d.). Retrieved January 2, 2021, from https://www.confluent.io/blog/kafka-streams-tables-part-2-topics-partitions-and-storage-fundamentals/

[xxv] (n.d.). Retrieved January 2, 2021, from https://docs.cloudera.com/HDPDocuments/HDP2/HDP-2.6.3/bk_kafka-component-guide/content/ch_create-kafka-topic.html

[xxvi] Streams and Tables in Apache Kafka: Storage Fundamentals. (n.d.). Retrieved January 2, 2021, from https://www.confluent.io/blog/kafka-streams-tables-part-2-topics-partitions-and-storage-fundamentals/

[xxvii] Myrent, N. (2020, January 13). The winds of change: The future of predictive analytics in wind farm reliability. Retrieved January 10, 2021, from https://www.windpowerengineering.com/the-winds-of-change-the-future-of-predictive-analytics-in-wind-farm-reliability.

[xxviii] Helson, Jan. "Integrated Condition Monitoring of a Fleet of Offshore Wind Turbines with Focus on Acceleration Streaming Processing." *ResearchGate*, May 2017, www.researchgate.net/publication/317320333_Integrated_condition_monitoring_of_a_fleet_of_offshore_wind_turbines_with_focus_on_acceleration_streaming_processing.

[xxix] Myrent, N. (2020, January 13). The winds of change: The future of predictive analytics in wind farm reliability. Retrieved January 10, 2021, from https://www.windpowerengineering.com/the-winds-of-change-the-future-of-predictive-analytics-in-wind-farm-reliability.