REnewALL: 21st Century Solutions for 20th Century Wind Projects

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

REnewALL: 21st Century Solutions for 20th Century Wind Projects is the final report for the REnewALL project (Contract Number EPC-16-019) conducted by the University of California, Davis and DNV GL. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the [CEC's research website](www.energy.ca.gov/research/) (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

The REnewALL project sought to improve the integration of pre-2000 wind turbines into modern grid operations. These older turbines cannot be shut down or restarted remotely, leading to higher costs for wind plant operators and constraining the ability of the grid to respond to imbalances between supply and demand. The REnewALL project addressed this problem in three ways: (1) by developing a low-cost remote communications and control system using wireless mesh networks to provide remote monitoring and dispatch capabilities; (2) by constructing a forecasting algorithm to assist operators in deciding when to dispatch turbines; and (3) by analyzing the financial aspects of a battery energy storage system to reduce demand peaks at a wind power plant site. Economic analysis found that a properly sized energy storage system could greatly reduce peak loads and associated demand charges, with a payback of three to four years. The remote dispatch system and forecast algorithm successfully operated during a three-month field test involving nine turbines at a wind plant in Tehachapi, California. All designs and software used for these systems are publicly available, with details provided in this report.

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EXECUTIVE SUMMARY

Introduction

California installed several thousand small-capacity wind turbines between 1980 and 2000 in the state's best wind resource areas. The combined generating capacity of these legacy turbines is more than half a gigawatt or about 10 percent of the total installed wind capacity in the state. These turbines produce electricity that contributes to California's renewable energy targets and — most of the time — that electricity generates revenue for wind energy project owners. During certain periods, however, the supply of electricity is greater than the demand, contributing to grid instability and driving market prices below zero as producers must pay to supply their energy to the grid. Negative prices are intended to provide a market-based signal to reduce production, but legacy wind turbines cannot be remotely coordinated or controlled and, therefore, cannot be dispatched on or off in response to signals from the market or the grid operator. Retrofitting aged turbines with the sophisticated control systems and subterranean wired communications common on wind turbines installed in the last two decades would be ill-suited and prohibitively expensive.

Legacy wind plants are also exposed to costs as a result of electricity demand. During periods without wind, electrical equipment required for plant operations remains energized, drawing grid power at high retail rates and costing owners up to $100,000 per year. Energy storage offers the potential to address both oversupply and demand costs by storing excess energy and discharging it during high load periods. However, battery energy storage systems have a large initial capital cost and, without a thorough analysis of the financial case for storage, plant owners have hesitated to make that initial investment.

Project Purpose

The purpose of the REnewALL project was to cost effectively improve the grid performance of legacy wind plants using existing technologies. Enhancing the ability of legacy wind turbines to respond to grid operations allows turbines to continue producing low-carbon electricity without incurring high costs. Specific objectives of this project were to:

- Identify and demonstrate cost-effective turbine modifications that enable remote dispatch of aged wind turbines.
- Create and implement an innovative forecast and dispatch algorithm that enables timely control of turbines for the benefit of both wind plant owners and grid operations.
- Improve project economics by modeling the cost-effectiveness of energy storage to mitigate demand charges.
- Distribute the technical findings and dispatch algorithm to enable straightforward implementation of the system by California wind plant owners and electric utilities.

Project Approach

The REnewALL team was drawn from DNV GL Energy – Renewables Advisory and the College of Engineering at the University of California, Davis. In August 2017, the REnewALL team traveled to Tehachapi, California, to gather input from stakeholders and visit the potential test site. Stakeholders included owners and operators of wind projects with legacy turbines, engineering consultants, maintenance providers, and representatives of the California Energy

Commission (CEC). Feedback from the stakeholder workshop guided the subsequent project scope and system development.

The discussions identified three main areas of research for the REnewALL project: developing a low-cost remote dispatch system for legacy wind turbines; developing a forecasting algorithm to identify when to dispatch turbines on or off; and analyzing the financial costs and benefits of energy storage at legacy wind plants.

The REnewALL team used existing, low-cost, off-the-shelf technologies to create a remote dispatch system. The team chose wireless communications to connect aged turbines with a central controller because they are less expensive than installing subterranean wired communications in an existing wind plant. The system monitors turbine performance and provides controls tailored to the capabilities and needs of aged turbines, allowing the turbines to dispatch remotely.

The REnewALL team used its extensive experience with renewable energy forecasting, market pricing, and grid management requirements to develop a grid, market, and weather forecasting system capable of predicting periods of oversupply and periods of no or low wind. This forecasting tool provides wind plant owners with the ability to automate the remote dispatching of aged turbines, as it can automatically issue on/off commands in response to wind or grid conditions.

To address the costs associated with energy demand during periods of little or no wind, the REnewALL team analyzed the potential for an energy storage system to reduce demand from the electricity grid, based on one year of electricity usage data from a wind plant in Tehachapi, California.

Specific tasks included:

- Identifying necessary turbine modifications to enable remote dispatch
- Selecting and developing appropriate components to install on aged turbines
- Obtaining recent historical data on wind plant electrical loads and energy market prices for energy storage analysis and training of forecast algorithm
- Identifying best input variables for market price forecasting algorithm
- Bench testing the remote dispatch system
- Simulating performance of energy storage systems based on historical load data
- Installing remote dispatch system on turbines selected for field demonstration

Finally, the REnewALL team conducted a three-month field test of prototypes of the turbine upgrades on several aged turbines at an operating wind plant in the Tehachapi region. The field test demonstrated the operation of the remote communication and control system and forecast algorithm to turbine owners and other stakeholders.

Project Results

Key results from each of the project focus areas are as follows:

- Remote communication and control system: The REnewALL team developed a system-level remote communication and control system using off-the-shelf commercially available components and software to enable remote start/stop of the test turbines based on the results of the dispatch algorithm. The team developed controllers for the

turbine level and the wind plant level and conducted bench testing to refine the system design prior to field testing. The cost of the prototype system was approximately $350 per turbine, plus $300 for the main controller located in the site office that controlled at least nine turbines. Manufacturing the prototype system involved several one-time costs; if controllers were produced for 100 turbines or more, the REnewALL team found that the cost per turbine could be reduced to approximately $100. In comparison, a similar commercial system cited at the stakeholder workshop had cost approximately $2,000 per turbine, which was too expensive to build a market.

- Dispatch algorithm: The REnewALL team developed a forecasting algorithm to identify periods in which it is financially advantageous to dispatch turbines. The team tested the dispatch algorithm over a three-month period. Overall, the initial performance metrics show that the dispatch algorithm can successfully predict negative locational marginal prices nearly 80 percent of the time at forecast horizons of 12 hours or less. At forecast horizons of six hours or less, the dispatch algorithm correctly predicted nearly 89 percent of each negative price event.

- Energy storage analysis: The REnewALL team simulated several sizes of energy storage systems using a year of electric load data from a wind plant site in Tehachapi. The team analyzed the performance of the storage systems under two scenarios: demand charge reduction alone and with wholesale market participation. Results showed that systems with capacities between 70 and 1,000 kilowatt-hours have positive returns on investment for demand charge reduction alone, with payback periods ranging from 2.5 years to 7.5 years. The addition of energy arbitrage on the wholesale market reduced payback periods and increased the net present value of the investment.

Conclusion and Next Steps

The REnewALL team installed the remote communication and control system on nine turbines at the field demonstration site, where it operated for more than three months. The researchers and wind plant operators had access to real-time data from each turbine and were able to dispatch the turbines using a web-based interface. During the field demonstration, the team identified several areas for improvement. The team addressed some of them during the demonstration period; recommendations for future work include:

1. Adapt turbine interface electronics for other wind turbine models and controllers.

2. Configure the user interface to handle larger numbers of turbines. Whereas the underlying software is capable of monitoring many devices, the team customized the format and layout of displays based on the field test of nine turbines and the displays may begin to feel cluttered with the addition of data from more turbines. Site operators also expressed interest in having the ability to view and control together defined groups of turbines.

3. Explore the effects of braking turbines at various wind speeds and power outputs to develop guidelines for safe and economic dispatch of turbines.

Another important consideration for implementing the REnewALL dispatch system is developing guidelines for automated dispatch based on the forecast algorithm. Guideline development will require consultation with the grid operator to ensure that generating resources are responding appropriately to grid requirements.

California's aged turbines are a critical piece of efforts to meet California's Renewables Portfolio Standard, Senate Bill 100 (de León, Chapter 312, Statutes of 2018), and Assembly Bill 32 (Nuñez, Chapter 488, Statutes of 2006) emissions goals. Senate Bill 100 mandates that 60 percent of electricity sold to retail customers must come from eligible renewable energy resources by 2030, and 100 percent of electricity must come from eligible renewable energy resources and zero-carbon resources by 2045. The turbine upgrades developed by the REnewALL team can reduce the cost of energy for legacy wind plants during oversupply, and energy storage can reduce costs in low- or no-wind conditions. Reducing costs for these existing turbines will improve the value of generating from existing sites, extend the life of these turbines, and ensure that their generating capacity will remain on-line in high wind regime locations, maximizing California's use of wind resources. The turbine upgrades developed by the REnewALL team also allow aged turbines to operate more similarly to modern turbines on the grid. The ability to dispatch off legacy turbines during periods of oversupply adds flexibility for grid operators and reduces the need for other adjustments on the grid in response to the excess wind generation. Thus, grid management tasks during oversupply periods will be less complex, which contributes to overall system reliability. For the remainder of these turbines' useful life, these increases in flexibility and reliability will help grid operators incorporate a larger share of wind energy into the California energy mix.

Technology/Knowledge Transfer/Market Adoption

The REnewALL team made engagement with stakeholders a top priority throughout the project. At the outset of the project, the team held a workshop to gather input from potential users of the REnewALL remote dispatch technology on their needs and expectations. Once the technology had been developed and demonstrated, researchers held a webinar to share information about how legacy wind plants could adopt this technology. All of the design information and software required to build and operate the REnewALL remote dispatch system and market price forecast are publicly available on GitHub (https://github.com/ewandersonUCDavis/REnewALL). The technical advisory committee provided valuable assistance in informing potential users of the REnewALL project, in particular through the membership and mailing lists of the California Wind Energy Association.

Benefits to California

This project will benefit ratepayers through increased electricity reliability and decreased costs. Enabling the dispatch of aged turbines from on-line to off-line during periods of oversupply on the grid reduces the need for other grid adjustments to respond to excess wind generation. Thus, grid management tasks during oversupply periods will be incrementally less complex, which contributes to improvement in overall system flexibility and reliability. By adding dispatch capability, the turbine owners and grid operators gain needed flexibility. Augmented by a forecast system, a half gigawatt changes from a grid management liability to a grid management asset that can be brought on-line and off-line when it is advantageous to both owners and grid operations.

CHAPTER 1:
Introduction

California is home to several thousand wind turbines installed in the 1980s and 1990s, with a combined generating capacity of more than half a gigawatt (Table 1). Many of these turbines will continue to operate for several years with very low costs and environmental impacts. The most popular models include the Kenetech KCS-56, the Micon 108, and Vestas models V-16, V-17, and V-27, though many other makes and models are in operation.[1] The control systems on these turbines are rudimentary by today's standards. Dispatching turbines on or off requires a technician to go to each turbine to engage or disengage the brake. Because the turbines have low generating capacities (typically below 300 kilowatts [kW]), legacy wind plants often contain hundreds of individual turbines. As a result, the turbines remain on-line during periods of oversupply, continuing to generate when the price of electricity is negative and contributing to grid instability. During periods without wind, the turbines remain on-line and energized, drawing grid power at high retail rates and costing owners up to $100,000 per year. Though the lack of remote dispatch capability adversely affects both wind turbine owners and grid operators, there is currently no solution to this problem. The sophisticated control systems and subterranean wired communications common on modern wind turbines would be ill-suited and prohibitively expensive as retrofits to legacy turbines.

Table 1: Legacy Wind Turbines in California

Turbine Characteristics	Number
Turbines installed before 2000	5,924
Turbines less than 300 kW capacity	3,708
Pre-2000 turbines with capacity not reported	1,986
Total (reported) generation capacity of pre-2000 turbines	565 MW

Source: U.S. Wind Turbine Database https://eerscmap.usgs.gov/uswtdb/

The goal of REnewALL was to develop affordable upgrades for legacy wind plants that would improve their responsiveness to market signals, contributing to better functioning of the electric grid and reducing plant owners' costs. The REnewALL team aimed to provide a low-cost, robust remote communication and control system and an innovative predictive forecast algorithm that dispatches turbines based on grid, market price, and weather conditions. These two tools intend to alleviate excess wind generation during oversupply conditions. An economic analysis of battery energy storage systems found that a properly sized system could reduce plant operating costs during periods of low/no wind. The upgrades will benefit ratepayers, turbine owners, and grid operators by reducing the cost of energy from aged

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[1] Other turbines in California include those manufactured by NordTank, Windmatic, Micon, NEG Micon, Wincon, Bonus, Norwin, WEG, NedWind, Mitsubishi, and DanWin.

turbines and improving the flexibility and reliability of the grid. In addition, the upgrades will help California meet its renewable energy goals by extending the life of these aged turbines.

Modern wind plants typically use subterranean wired communications installed, along with subterranean power lines, when the wind plant is built. Installing this type of communication system in a legacy wind plant would be prohibitively expensive. Instead, REnewALL took advantage of significant advances in wireless data transmission, communication, and microprocessor-based devices to develop a wireless communication system for aged turbines. Researchers relied on existing "off-the-shelf" equipment and technologies to develop low-cost, robust turbine upgrades that enable remote control and communication. This approach and its demonstrated performance in the field provides a basis for local companies in the supply chain to advance further commercial deployment.

Through development of an innovative, real-time dispatch system for legacy turbines and implementation of a low-cost, robust form of remote communication and control, this project addressed a key technical barrier for legacy wind plants — the inability to efficiently and quickly dispatch turbines on or off when grid and market conditions demand. Timely control of approximately 500 megawatts (MW) of wind power generation within high wind regime locations can enable better overall management of the state's power resources. This will help maintain reliability and manage system integration costs because other grid adjustments will not be necessary to compensate for continuous generation from aged wind plants during oversupply periods. Implementing this system will also enable continued operation of legacy wind plants in high wind resource areas, thus contributing to state energy goals.

Senate Bill (SB)100 mandates that 60 percent of electricity sold to retail customers must come from eligible renewable energy resources by 2030, whereas, 100 percent of electricity must come from eligible renewable energy resources and zero-carbon resources by 2045, and California's aged turbines are critical to meet California's Renewables Portfolio Standard. The turbine upgrades developed by the REnewALL team can reduce the cost of energy for legacy wind plants during oversupply, and energy storage can reduce costs in low- or no-wind conditions. Reducing costs for these existing turbines will improve the value of generating from existing sites, extend the life of these turbines, and ensure that their generating capacity will remain on-line in high wind regime locations, maximizing California's use of wind resources. The turbine upgrades developed by the REnewALL team also allow aged turbines to operate more similarly to modern turbines on the grid. The ability to dispatch legacy turbines during periods of oversupply adds flexibility for grid operators and reduces the need for other adjustments on the grid in response to the excess wind generation. Thus, grid management tasks during oversupply periods will be less complex, which contributes to overall system reliability. For the remainder of these turbines' useful life, these increases in flexibility and reliability will help grid operators incorporate a larger share of wind energy into the California energy mix.

CHAPTER 2:
Project Approach

The REnewALL team investigated three main areas: 1) selecting and implementing low-cost and reliable over-the-air remote communications and control for legacy wind plants; 2) creating an innovative weather and market fundamentals forecasting system and turbine dispatch algorithm; and 3) analyzing the financial value of installing an energy storage system at a legacy wind plant. The technical approach and methods to perform the necessary activities in these areas were different, as discussed below.

2.1 Remote Communications and Control

This project took advantage of modern wireless data transmission systems and related equipment to enable remote communications and control between a master site computer and wind turbines in the field. The team drew on its existing experience with data transmittal and control communications from modern wind projects and chose systems that were most cost effective for aged turbines. To enable increased commercialization, the team sought "off-the-shelf" and non-proprietary systems to the maximum extent possible. Wireless data transmission is well-suited to this application as it avoids the excavation required to install wired communications, as well as the prohibitive economic payback and site permitting issues related to installation of wired communication systems.

To assist in identifying viable communication and control technology systems, the REnewALL team held a workshop in Tehachapi, California, to seek input from owners regarding their previous efforts to deploy remote communication and control systems in the Tehachapi region. The lessons learned from these previous efforts helped the team to focus its efforts on the most promising potential solutions. The team performed an evaluation of the trade-offs between cost effectiveness and wireless data transmittal reliability. There is no increased safety risk related to infrequent interruption of communication and control signals on these aged turbines. Therefore, the reliability of the wireless communication system does not need to be as high as the reliability expected for modern wind plants, where some mechanical load mitigation strategies are implemented and monitored at the plant-level supervisory control and data acquisition (SCADA) system in addition to turbine level controllers.

2.2 Turbine Modification

In addition to developing a wireless communication system, the REnewALL team developed a system capable of receiving remote dispatch signals and interfacing with the turbines' existing controls to turn the turbines on or off. Given advances in modern control devices, this is a relatively straightforward activity, but does require appropriate care and attention to detail to ensure that the turbine is safely started and stopped using its existing brake systems and capabilities. The project team worked with the site technicians to draw on their familiarity with the turbines, ensuring that the augmented controller performs and behaves in the same manner as the existing manual start/stop system.

The team also evaluated options to measure turbine power levels and local operation status, so that this information could be fed back into the forecasting and dispatch control algorithm. The team then ensured that communication between the remote communication/control

equipment and the local turbine controller functioned as desired. This system was developed and tested in a laboratory setting prior to being deployed on the demonstration turbines.

2.3 Forecasting and Dispatch Control Algorithm

DNV GL applied their considerable skill and experience in short-term power forecasting of wind and solar, combined with new capabilities to ingest grid and market price data streams, to develop a forecast model that seeks to identify periods in which it is advantageous for grid operators and wind plant owners to dispatch turbines either on or off. DNV GL modified an existing market fundamentals forecast program to reflect conditions in the Tehachapi control area and power market pricing in California. The forecast system uses the Weather Research Forecasting model run at horizontal resolutions of one to two kilometers (km) and exponentially spaced vertically to approximately 1000 meters (m). The system derives hourly weather predictions and uses them to forecast variables such as plant-level production and system-level wind and solar generation. The system ingests additional data streams for electrical load and market prices from the California Independent System Operator (California ISO) to derive forecasts of future load and prices. The project team used historical load and price data from California ISO to help train the forecasting models.

After developing and implementing the forecast system, the project team developed a turbine dispatch algorithm configured with site-specific parameters such as production tax credits and retail power consumption pricing. The team developed flags for dispatching turbines on and off by analyzing historical data and observing the performance of the forecasting model. The algorithm identifies periods of negative prices when dispatching the turbine off is beneficial to the grid and owners. The algorithm considers the duration of the forecasted "dispatch off" events to avoid excessive on/off cycling of the turbines. When run on a 24/7 basis, the forecast and dispatch algorithm learns from past performance and adjusts projections as weather, grid, load, price, and other variable energy generation conditions change.

2.4 Energy Storage Analysis

DNV GL performed a techno-economic analysis to determine cost-effectiveness and operational requirements of deploying battery energy storage systems (BESS) co-located with wind generators in California. The primary BESS application was demand charge reduction, with energy arbitrage as a secondary goal. The modeled BESS charged during periods when little energy was consumed at the site (or the price of energy was low) and discharged during periods of high demand (high price).

DNV GL modeled hourly BESS operation based on hourly market prices, renewable generation, and other interconnection constraints. The team aggregated hourly modeling results to inform project technical requirements and annual operational costs and savings. The team combined annual operational savings and costs with capital and fixed cost estimates to determine project cost-effectiveness through cash-flow analysis. The team performed a sizing scenario analysis to determine the optimal BESS project size in terms of power and energy capacity that met application requirements and maximized cost-effectiveness.

2.5 Technical Advisory Committee

The REnewALL team also sought input from a technical advisory committee (TAC) with the following members:

- Edward Duggan, ZCF Wind Wall, LLC
- Robert Gates, Wind Stream Properties, LLC
- Amber Motley, California ISO
- Nancy Rader, California Wind Energy Association (CalWEA)

The TAC met three times at various stages of the project, in December 2017, May 2018, and December 2018. At each meeting, members of the REnewALL team gave presentations on the current project status and plans for next steps, and TAC members provided feedback.

CHAPTER 3:
Development of Forecasting Algorithm

The purpose of the forecasting algorithm is to identify periods in which it is advantageous to dispatch turbines because generating power will cost more than shutting down. The algorithm aims to predict when the real-time price of electricity will drop below a particular threshold, nominally zero, indicating an oversupply of generation relative to demand. The price of electricity on the day-ahead market exhibits seasonality at the daily and weekly levels, and to a lesser extent at annual levels. Real-time or dispatch prices, on the other hand, exhibit a dependence on a larger set of fundamental drivers including system loads, meteorological variables, fuel costs, reserve margin, and scheduled or forced outages.

In the California ISO control area, negative prices in the real-time market occur throughout the year (Figure 1). During the first quarter of 2017, approximately 10 percent of intervals in the 15-minute market and 13 percent in the 5-minute market had negative prices. For the remainder of 2017, the frequency of negative pricing in the real-time market decreased, with the last six months of the year averaging 0.3 percent negative pricing intervals in the 5-minute market and 1.2 percent in the 15-minute market. In the first quarter of 2018, approximately 2 percent of intervals in the 15-minute market and around 4 percent in the 5-minute market had negative prices. This increased in the second quarter of 2018, where negative prices occurred in 4 percent and 6 percent of intervals in the 15-minute and 5-minute markets, respectively. In the third quarter of 2018, negative prices decreased significantly, where they occurred in less than 0.5 percent of intervals in both the 15-minute and 5-minute markets.

Figure 1: Frequency of Negative Prices by Month in the 5-Minute Market
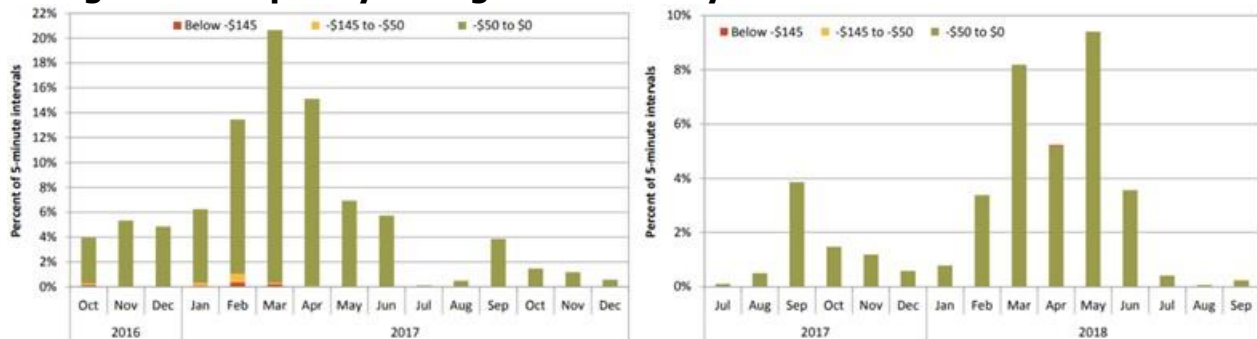
The frequency of negative prices in the California ISO 5-minute market by month aggregated for three load points.

Source: California ISO Q4 2017 and Q3 2018 Report on Market Issues and Performance – Department of Market Monitoring

Although the frequency of negative pricing may be low in some months, there is considerable value in the accurate prediction of these intervals of negative pricing. In this chapter, we detail the development of a forecast algorithm to detect intervals of negative pricing for the real-time market.

3.1 Methodology and Data Selection

Due to the volatility in the real-time price market and the number of potential independent variables, linear modelling approaches would likely be unsuccessful at capturing the

complicated relationships. Machine learning approaches lend themselves to complex relationships, and forecasting experts successfully use artificial neural networks (ANN) to forecast loads. Short-term load forecasting and short-term price forecasting both involve a number of potentially unrelated, yet fundamental variables, so an ANN is an appropriate modelling technique to use for this project.

Artificial Neural Networks

Neural networks have been widely applied to various fields to solve problems involving complex, non-linear relationships. In its simplest form, a neural network is a pool of simple processing units that exchange data and operate in parallel. Figure 2 shows a typical three-layer feed-forward neural network.

Figure 2: Example of a Simple Feed-Forward Neural Network
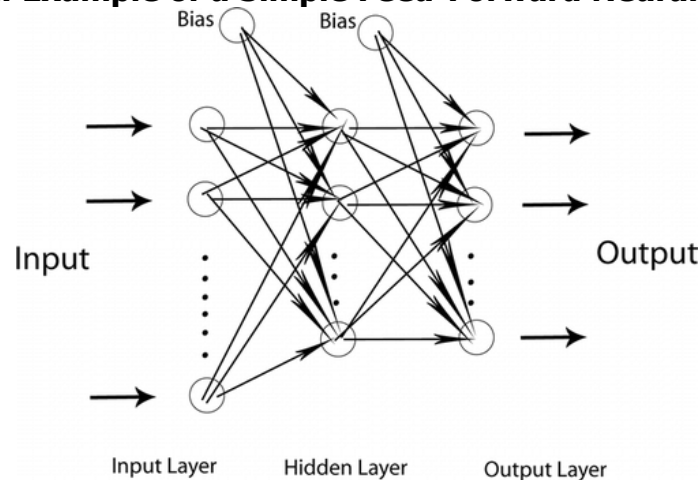
Source: Han, G. and Shi, Y., 2008

The input nodes receive data and transmit them to any number of hidden layers, which themselves can contain any number of nodes. The connections between the input, hidden nodes and output start out with specific weightings and biases to apply to the data. During training, the network compares each output node to the correct answer and generates an error function. This error function back-propagates through the network, adjusting the individual weights and biases. This process continues until the change in the output error function is smaller than some user-defined threshold. The weightings and biases can then be applied to a new dataset to generate a predicted output. For this project, the team used RStudio[2] in combination with H2O,[3] an open-source math engine for use with big data.

Historical Data Analysis

The available data for use in this project consists of:

    a. Actual hourly real-time price at the node closest to the field test site

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[2] Studio Team (2015). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA https://www.rstudio.com/.

[3] H2O.ai (Oct. 2016). *R Interface for H2O*, R package version 3.10.0.8. https://github.com/h2oai/h2o-3.

b. Actual hourly solar and wind generation for the California ISO SP-15 and NP-15 regions[4]

c. Actual hourly load for the entire California ISO region and each individual utility region

d. Derived actual temperature at the field test site

e. Day-ahead forecast load for the entire California ISO region

f. Hour-ahead forecast solar and wind generation for the California ISO SP-15 and NP-15 regions

Because the sign rather than the magnitude of the price is important, the project team scaled price data to values between -1 and 1 as follows:

For prices greater than 0,

$$P_s = \begin{cases} \dfrac{P_A}{\text{astd}(P_A)}, & P_A \leq astd(P_A) \\ 1, & P_A > astd(P_A) \end{cases}$$

where: P_s = scaled price

P_A = actual price

astd(P_A) = average + standard deviation of all positive prices during the time period.

For prices less than 0:

$$P_s = \begin{cases} \dfrac{-P_A}{\text{astd}(P_A)}, & P_A \geq astd(P_A) \\ -1, & P_A < astd(P_A) \end{cases}$$

where: astd(P_A) = average + std. dev. of all negative prices during the time period.

With the price data now scaled, the team trained the ANN model on the January to June 2015 data and tested it on the July to December 2015 data to determine its accuracy and the best combination of available data. Through a process of trial and error, the combination of input data that resulted in the best relationship to the scaled price was:

a. Total California ISO load

b. Difference between total California ISO load and SP-15 solar and wind generation

c. Hour of day

3.2 Dispatch Algorithm

The real-time dispatch algorithm consists of three major parts: training on historical data, application of the model to forecast data, and an adjustment for recent model performance. The training process is performed five times in sequence, once per day, while the latter two parts are performed once at the top of each hour. The team wrote all technical scripts and

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[4] https://www.ferc.gov/market-oversight/mkt-electric/california/2008/02-2008-elec-ca-archive.pdf.

code in R or interactive data language (IDL).[5] These, along with example comma-separated-value (.csv) and text (.txt) data files, are on GitHub.[6]

Training of ANN Model

ANN model training occurs five times in sequence, once per day, using the previous 12 months of input data. This results in five sets of weights and biases for application to forecast data to generate a price forecast. This reduces the potential for any one-trained model to be an outlier. Each subsequent day, the algorithm generates a new set of five trained ANN models for use on that day's forecasts.

Application of ANN to Forecast Data

The algorithm applies each of the five-trained models to the same forecast data at each hour of the day, and then averages the five output time series together to create a forecasted scaled price time series. Figure 3 shows a scaled price forecast time series with a maximum forecast horizon of 37 hours. The initial assumption is that forecasted scaled prices above zero represent positive pricing, while forecasted scaled prices below zero represent negative prices.

Figure 3: Example Scaled Price Forecast
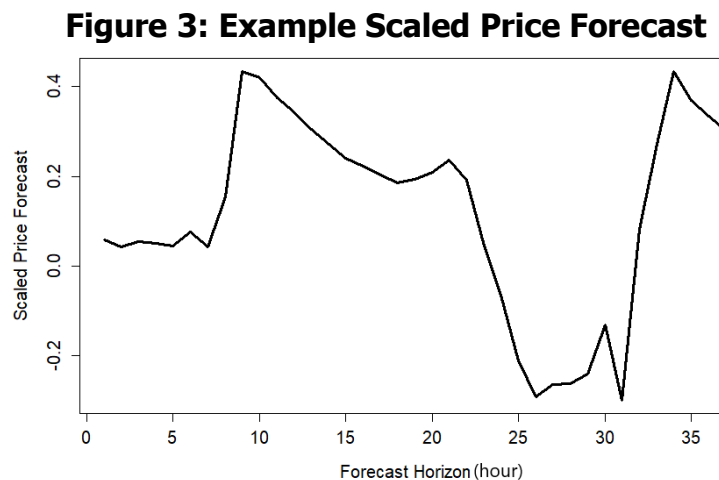
Source: University of California, Davis (2019)

Adjustment for Recent Model Performance

Even though the ANN attempts to account for all of the complexities in the price relationship, there will still be inherent idiosyncrasies that the model cannot resolve. This leads to forecasted scaled prices that are greater than zero although the actual price is negative. To account for the recent model performance a new threshold is calculated, under which all forecast scaled prices represent negative prices:

a. The previous seven days of scaled price forecasts are compared to the previous seven days of actual prices.

b. For all hours when the actual price is above zero, the average of the forecast scaled price is calculated.

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[5] R and IDL are commonly applied programming languages. For a comparison of these and other languages, see https://modelingguru.nasa.gov/docs/DOC-2625.

[6] github.com/ewandersonUCDavis/REnewALL/tree/master/NegativePriceForecastAlgorithm.

c. This value becomes the new threshold to distinguish between negative and positive prices.

d. The scaled price forecast is converted to a binary forecast wherein negative prices (below the new threshold) are represented by -1 and positive prices (above the new threshold) are represented by zero.

For wind turbines that are eligible for some form of energy credit (for example, Production Tax Credit [PTC]) the calculation of the above threshold can be modified to adjust the forecast dollar amount that is treated as negative and given a flag of -1 in the final forecast.

Implementation of Dispatch Algorithm

The goal of the dispatch algorithm is to inform the operator of a wind plant whether to expect negative pricing for a period and to shut down any turbines if necessary. The algorithm uses the forecast price time series in conjunction with the most recent real-time price to determine if a turbine should be shut down for that hour. Four potential scenarios exist with either the actual price or the forecast price being positive or negative:

1. Actual Price less than (<) 0 and Forecast Price Flag = -1 (Correct Negative Price Forecast)

   - Turbines are shut down until actual price returns to greater than (>) 0.

   - Any subsequent hourly forecast is ignored.

2. Actual Price < 0 and Forecast Price Flag = 0 (Missed Negative Price Forecast)

   - If turbines are on, keep turbines on.

   - If turbines are off, continue to keep off until actual price returns to > 0.

3. Actual Price > 0 and Forecast Price Flag = -1 (False Alarm Negative Price Forecast)

   - Keep turbines on.

4. Actual Price > 0 and Forecast Price Flag = 0 (Correct Positive Price Forecast)

   - Keep turbines on.

3.3 Performance Assessment

The team tested the dispatch algorithm for the three-month period of September 18, 2018 through December 18, 2018, using the locational marginal price (LMP) at the NORTHWND_6_N002 node, near the test site in Tehachapi. Overall, there were 104 hours where the LMP fell below $0 per megawatt-hour (MWh) and only three hours where the LMP fell below -$14/MWh (PTC threshold). The team initially assessed on the ability of the dispatch algorithm to predict negative LMPs at several forecast horizons: 12 hours ahead, six hours ahead, three hours ahead, one hour ahead, and zero hours ahead (real time). Table 2 summarizes a hit rate and a false alarm rate at each forecast horizon. The calculation method for these values is as follows:

$$Hit\ Rate = \frac{\#\ correctly\ forecast\ negative\ LMP\ hours}{total\ observed\ negative\ LMP\ hours}$$

$$False\ Alarm\ Rate = \frac{\#\ incorrectly\ forecast\ negative\ LMP\ hours}{total\ observed\ positive\ LMP\ hours}$$

Table 2: Initial Performance of the Dispatch Algorithm

	12-hr Ahead	6-hr Ahead	3-hr Ahead	1-hr Ahead	0-hr Ahead
Hit Rate	79.8%	78.6%	79.0%	80.2%	81.2%
False Alarm Rate	14.4%	14.4%	14.6%	14.6%	14.4%

Source: University of California, Davis (2019)

Overall, the initial performance metrics show that the dispatch algorithm can successfully predict negative LMPs nearly 80 percent of the time at forecast horizons of 12 hours or less. Although anything greater than one hour ahead is not necessarily useful for turbine dispatch, the potential for the algorithm to predict negative LMPs 12 hours into the future could prove to be useful for other applications.

The dispatching algorithm is more useful when looking at the length of potential negative LMP events that last for several hours. This information can be used to determine if it would be cost-effective to dispatch a turbine off in cases where the financial cost of braking a spinning turbine is higher than the potential savings from dispatching it off. Over the three-month test period, there were 17 distinct negative LMP events, defined as a consecutive period of more than two hours where the LMP decreased below $0/MWh, as summarized in Table 3.

Table 3: LMP Event Statistics Over the Test Period

Total # of Events	17
Maximum Length	7 hours
Minimum Length	3 hours
Average Length	4.2 hours

Source: University of California, Davis (2019)

The team undertook a similar analysis with these events to determine the performance of the dispatch algorithm at various forecast horizons. However, instead of determining the hit rate and false alarm rate, the team calculated the average event correctness and number of false alarm events, where the average event correctness is the average percent duration of each event that the dispatch algorithm correctly predicted. Table 4 summarizes these results.

Table 4: Performance of the Dispatch Algorithm on LMP Events > 2 Hours Long

	12-hr Ahead	6-hr Ahead	3-hr Ahead	1-hr Ahead	0-hr Ahead
Event Correctness	79.6%	88.7%	88.7%	88.7%	88.7%
# of False Alarm Events	22	26	26	27	26

Source: University of California, Davis (2019)

At forecast horizons of six hours or less, the dispatch algorithm correctly predicted nearly 89 percent of each negative LMP event, with 26 to 27 false alarm events predicted. The fact that there were more false alarm events predicted than actual observed events shows that some refinement of the algorithm is necessary to reduce this number. On the other hand, since the dispatching of turbines occurs for the current hour and is based on the scenarios outlined in Section 3.2, one would have knowledge of the current hour's LMP and any false alarm event predicted for the current hour would not result in any turbines being shut off.

CHAPTER 4:
Remote Communications and Control System Development

This chapter describes the development of the remote communications and control system for dispatch of aged turbines. Figure 4 illustrates how the components of the communication and control system interact. Arrows indicate the flow of information while solid outline blocks indicate system components. The turbine-level components and wind plant-level control discussed below are highlighted with dashed outlines.

Figure 4: System Level Block Diagram of the Remote Communication and Control System
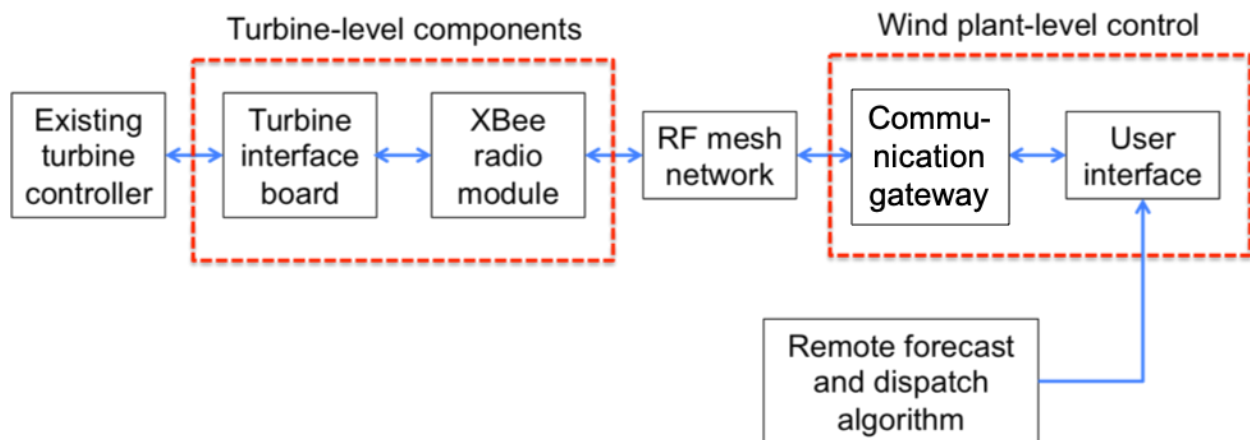
Source: University of California, Davis (2019)

4.1 Turbine-Level Components

The main components installed on each turbine are a radio-frequency (RF) microprocessor and a custom-designed circuit board that interfaces with the turbines' relay-based control systems. These components are mounted inside the weather-resistant enclosure containing the turbine's existing control system.

Radio Frequency Transmitter with Microprocessor

The Programmable XBee-PRO 900HP (model no. XBP9B-DMUTB002, Figure 5), manufactured by Digi International, was selected to provide the communications link between the turbine and the wind plant-level controller. The XBee contains a 900-megahertz (MHz), 250-milliwatt (mW) radio frequency transmitter as well as a programmable microprocessor. It consumes 229 microamperes (mA) of 3.3-volts (V) direct current (DC) power when transmitting data, but only 44 mA when not transmitting. The project team paired the XBee with a 3-decibels (dBi) gain antenna, which extends out of the bottom of the existing turbine control box. Transmitter range can be difficult to estimate, because it depends on terrain, obstructions, and the chosen antenna. However, Digi International estimates the maximum line-of-sight range of this module to be four miles when paired with a 2.1 dBi gain antenna. At the time of writing, the cost of the wireless module was $42; the cost of the antenna and connecting cable was $6.50. Each turbine requires one XBee and one antenna.

Figure 5: Programmable XBee-PRO 900HP, Model XBP9B-DMUTB002

Source: University of California, Davis (2019)

The XBee monitors turbine behavior and reports that behavior to the wind plant-level controller. In addition, the XBee can start or stop the turbine at the request of the wind plant-level controller. The wind plant-level controller and XBee communicate via mesh networking, which enables relatively short-range devices to communicate across long distances and complex terrain. Radio signals have limited range, must travel in a straight line, and cannot travel through massive objects such as hills. In mesh network communication (Figure 6), each XBee communicates with all of the other XBees that are within transmission range and within line of sight. Data travels through the mesh network by making a series of line of sight jumps from one XBee to another. This allows data to be transmitted over very long distances and/or beyond line of sight. The route that data travels is not predetermined, which means communication can be maintained if an XBee fails.

Figure 6: Mesh Network Schematic
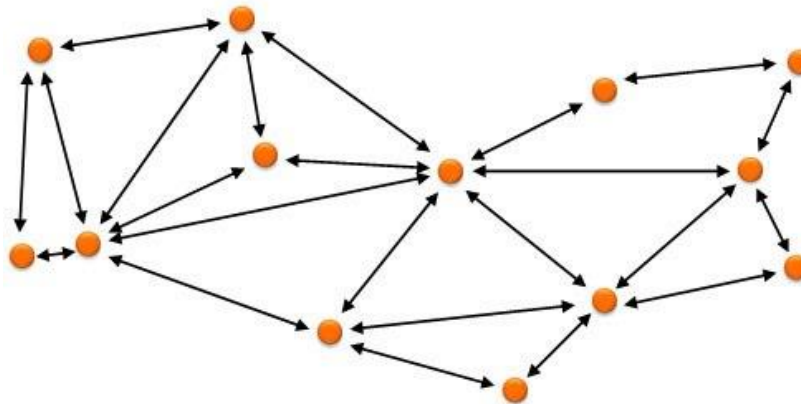
Orange circles represent individual XBee wireless modules. Arrows indicate possible routes for data transmission. Data can be transmitted between any two points via several alternate routes.

Source: University of California, Davis (2019)

The XBee monitors faults and turbine on/off status using DIO (Digital Input/Output) change detection. In DIO change detection, the XBee monitors a specified input pin and immediately transmits a message to the wind plant-level controller when the voltage on that pin changes between low and high. Five XBee pins have been configured for DIO change detection and assigned to monitor important indicators in the existing control system. One pin is assigned to monitor the "Brake On" indicator light, which indicates that the rotor brake is energized and the turbine is stopped. The other four pins are assigned to monitor the indicator lights corresponding to the wind speed, overspeed, low pressure, and vibration faults. DIO change

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detection is a feature built into all XBee modules, including the non-programmable versions. More details on DIO change detection can be found in the XBee user's manual.[7]

Monitoring power production and starting/stopping the turbine are accomplished through software written by the REnewALL team and run by the microprocessor of the programmable XBee module. This software can be found on GitHub.[8] Each turbine has an electric meter that generates a KYZ pulse every time a pre-determined amount of electricity has been generated. For example, the meter might generate a KYZ pulse for every 50 kilowatt-hour (kWh). To measure power production, one XBee pin is configured as an input and assigned to monitor voltage on the KYZ output of the electric meter. The XBee module counts KYZ pulses and transmits the pulse count to the wind plant-level controller every 15 minutes. For starting and stopping the turbine, two XBee pins are configured as outputs. Ordinarily voltage on these pins is set to low. To start or stop the turbine the corresponding pin is set to high for 0.5 seconds. This signal causes the turbine interface electronics, as described in the following section, to engage the "Reset (Start)" or "Stop" button of the existing control system.

The XBee module accepts two different types of "Stop" commands. The first is a hard stop command. In this case, the XBee module immediately stops the turbine. The second is a threshold-based stop command. In this case, the XBee module is given a pulse count threshold. The turbine controller software running on the XBee module continuously compares the pulse count threshold to the number of KYZ pulses the turbine has generated in the previous 30 seconds. The turbine is stopped if and when the 30-second pulse count is below the pulse count threshold. The goal of the threshold-based shutdown is to avoid stopping the turbine in high wind speeds, when wear and tear on the braking system would be greatest.

Appendix A includes instructions to configure XBees for turbine-level control.

Turbine Interface Board

The programmable XBee just described operates on 3.3-V power. The existing turbine control system operates on 24-V power. As a result, the XBee cannot directly interact with the existing turbine control system. To solve this problem, the REnewALL team developed a custom designed circuit board that allows the XBee and the existing turbine control system to interface with each other (Figure 7). The turbine interface board has three core functions: providing a well-regulated (free of voltage fluctuations) 3.3-V power supply for the XBee, allowing the XBee to safely monitor voltages in the existing turbine control system, and allowing the XBee to start and stop the turbine.

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[7] https://www.digi.com/resources/documentation/Digidocs/90002173/

[8] https://github.com/ewandersonUCDavis/REnewALL/tree/master/turbineControllerSoftware

Figure 7: Turbine Interface Board
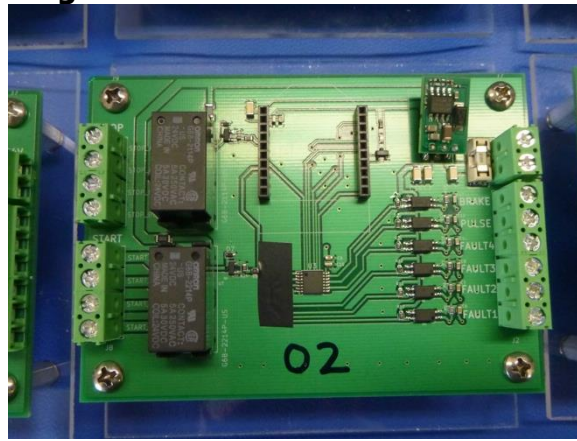
Source: University of California, Davis (2019)

Figure 8 shows a schematic of the turbine interface board. Well-regulated 3.3-V power is provided by an integrated circuit that can be found at 2-A on the schematic. Input stages are located in a dashed box in the lower right of the schematic. Each input stage uses an optically isolated relay to convert a 0 V/24 V digital signal in the existing turbine controller to a 0 V/3.3 V digital signal that can be safely read by an XBee. These input stages allow the XBee to detect turbine on/off status, fault status, and electric meter pulses. The upper left of each input stage (labeled on the schematic as EXT_FAULT1, EXT_FAULT2, and so forth) is connected to a point in the existing turbine controller that the operator wants to monitor, while the right side of each input stage (labeled on the schematic as IN_FAULT1, IN_FAULT2, etc.) is connected to an input pin on the XBee. Output stages, which are used to start and stop the turbine, are located in a dashed box in the upper right corner of the schematic. The lower left of each output stage (labeled OUT_START or OUT_STOP) is connected to an output pin of the XBee. When the XBee sets the output pin to 3.3 V the output stage relay (the large rectangle near the top of the output stage) is energized. The output stage relays are connected to the existing control system in such a way that energizing the start relay is equivalent to pushing the "Start (Reset)" button on the front panel of the existing control system and energizing the stop relay is equivalent to pushing the "Stop" button on the front panel of the existing control system.

Figure 8: Turbine Interface Board Schematic Design
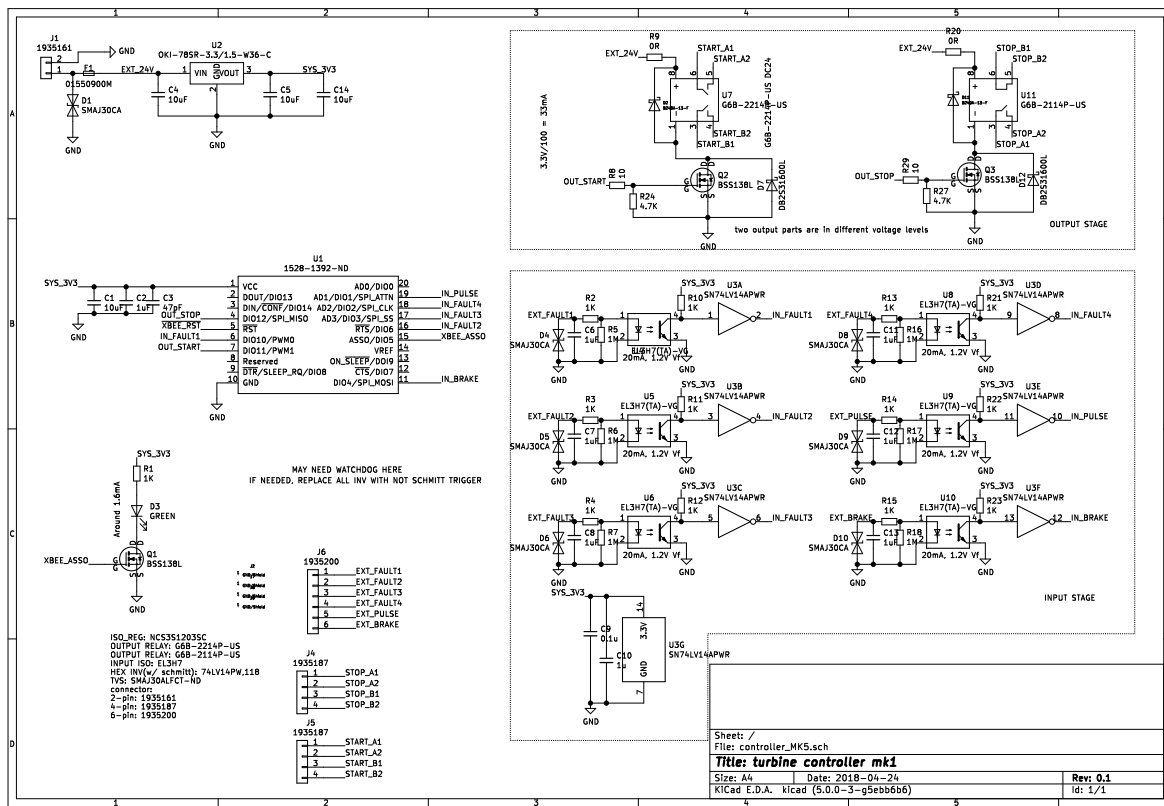
Source: University of California, Davis (2019)

The turbine interface board was designed using KiCad,[9] a free software suite for electrical circuit and printed circuit board (PCB) design. The design files for the turbine interface board are available on GitHub.[10] These files can be used to manufacture turbine interface boards and/or modify the design of the boards. Ten turbine interface boards were manufactured for the REnewALL field test by Bay Area Circuits at a cost of $299 each. However, ordering larger quantities can significantly reduce the per-unit manufacturing cost. Another manufacturer, Wonderful PCB, estimated a cost of $47 each for an order of 100 boards.

4.2 Wind Plant-Level Control

The wind plant-level controller has three functions: to act as a gateway for communication with the XBee mesh network, to store data, and to generate a web-based user interface. All software used by the wind plant-level controller is free and available for Windows, Mac, and Linux operating systems. Hardware for the wind plant-level controller consists of a single XBee radio module and a desktop computer. For the REnewALL field test the team purchased a fairly low performance Intel NUC computer running the Ubuntu 18.04 operating system. The cost of the wind plant-level controller was approximately $300.

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[9] http://kicad-pcb.org/,

[10] https://github.com/ewandersonUCDavis/REnewALL/tree/master/turbineInterfaceElectronics/kicad/controller_MK5.

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Communication Gateway and Data Storage

The wind plant-level controller uses its XBee to receive data sent by all of the turbines on the mesh network. When data are received, a communication gateway script processes, reformats, and stores the data. The communication gateway script was written in the Python 3 programming language by the REnewALL team and is available on GitHub.[11] Data are stored in two ways. The first data store is a set of comma-separated-value (csv) files. Two csv files are generated for each turbine on the mesh network. One file contains all power production data and the other contains a log of all events (faults and turbine starts/stops). The csv files are stored on the wind plant-level controller and can be opened with Excel. The second data store is a Cassandra database that is operated by the user interface software. This database contains all of the data from all of the turbines on the mesh network, but the data are not easily accessible except through the user interface.

The communication gateway script also performs a few other functions. If the communication gateway script goes more than an hour without receiving data from a turbine it sends a message to the user interface indicating there has been a communication error with that turbine. The communication gateway script also listens to the user interface for stop commands. When a stop command is received, the communication gateway script forwards the command to the appropriate turbine(s).

As described in the previous section, there are two types of "Stop" commands. Hard stop commands are initiated by pushing a button on the user interface (more details follow). Each hard stop command is directed at a specific turbine the user wants to shut down. Threshold stop commands are directed at all turbines simultaneously and are generated based on an automatic forecast and dispatch algorithm. This automatic shutdown capability is an optional feature that can be enabled or disabled based on user preference.

User Interface

The team used ThingsBoard to develop the user interface,[12] which is a free software for managing devices and data over the Internet via a web browser. ThingsBoard provides a variety of tools for aggregating and displaying data from multiple devices as well as security tools to prevent unauthorized users from accessing the user interface. Authorized users can be granted different levels of access; for example, a restricted set of users can be given the ability to remotely start and stop turbines. ThingsBoard can also send notifications (for example, when a turbine fault occurs) via email or text message.

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[11] https://github.com/ewandersonUCDavis/REnewALL/tree/master/communicationGateway

[12] http://thingsboard.io

Figure 9 shows the wind plant overview screen of the user interface.

Figure 9: User Interface, Wind Plant Overview Screen
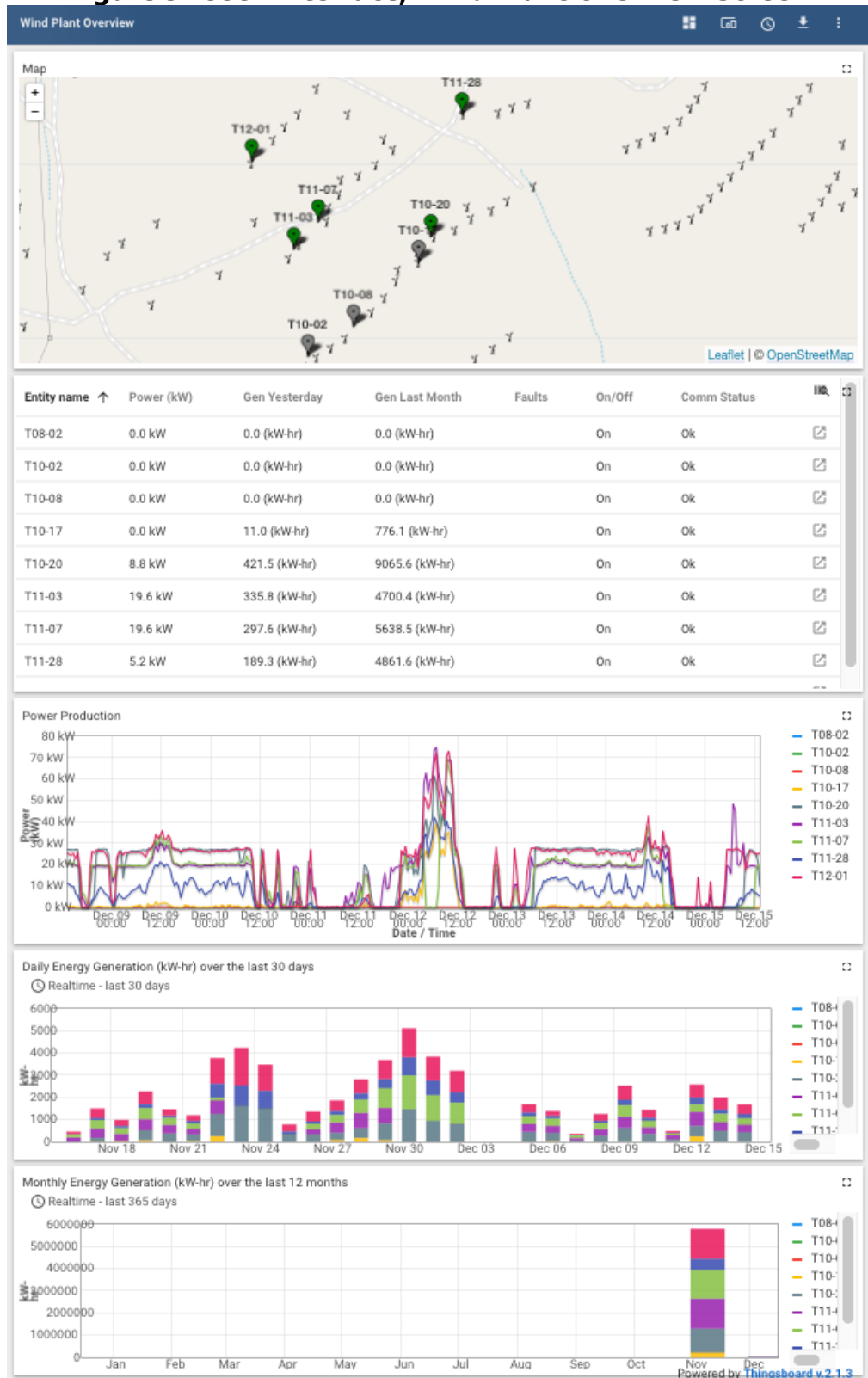
Source: University of California, Davis (2019)

The top of the screen shown in Figure 9 displays a map with markers indicating the nine turbines used in the REnewALL field test. The marker color indicates the status of each turbine. A green marker means the turbine is on and currently producing power. Gray means

the turbine is on, but not currently producing any power. Red means the turbine is stopped and the rotor brake is engaged. Yellow means the turbine is experiencing a communication error. Following the map is a table containing more detailed quantitative information about each turbine. For each turbine, the table lists the current power production, the previous day's total energy generation, the last month's total energy generation, whether the turbine is currently experiencing any faults, whether the turbine is on or off, and whether the turbine is communicating with the wind plant-level controller. Following the table in Figure 9 are charts showing the 15-minute average power production over the last 7 days, the daily total energy generation over the last 30 days, and the monthly total energy generation over the last year. Clicking the clock symbol near the upper left allows the user to modify the time frame of each chart. To read quantitative data from a chart, a user can hover the mouse cursor over the point of interest as shown in Figure 10. Data for individual turbines can be hidden or displayed by clicking on the turbine name in the chart legend.

Figure 10: Displaying Quantitative Data at a Specific Time
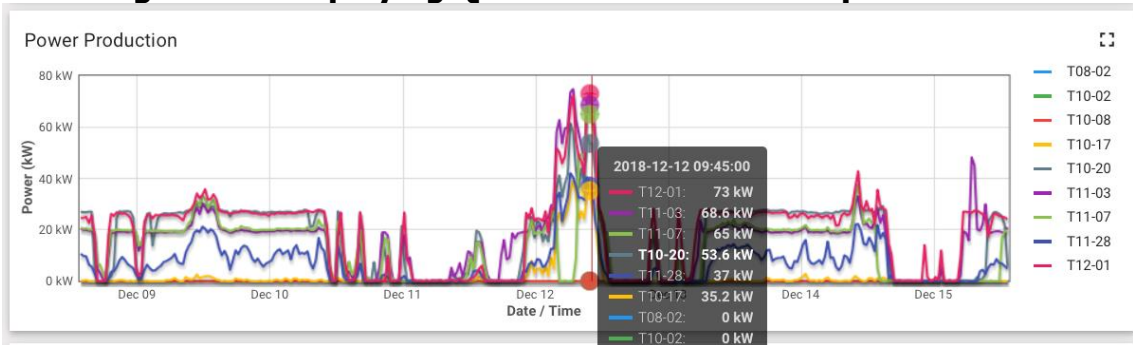
Source: University of California, Davis (2019)

To focus on a specific turbine, a user can open the turbine details screen shown in Figure 11. To open the turbine details screen, select a turbine in the map and click on "Details" or select the symbol in the rightmost column of table after the map. The turbine details screen displays the location of the selected turbine, as well as graphs of 15-minute average power production, daily energy production, and monthly energy production. In addition, this screen has a table displaying the status of each fault/error and a pair of buttons that can be used to start or stop the turbine. Pushing one of these buttons instructs the turbine-level controller to energize the start or stop relay for 0.5 seconds.

Figure 11: User Interface, Turbine Details Screen

Source: University of California, Davis (2019)

A separate dashboard on the user interface depicts price data and forecast information (Figure 12). The chart displays the current locational marginal price of electricity at a local node, as well as the price forecast flag. A forecast flag of -1 indicates that turbines should be dispatched off, while a zero forecast flag indicates that turbines should continue normal operation or be dispatched on. The user interface can display several charts of this type with different threshold values ($/MWh) for the forecast flag. This feature allows plant operators to dispatch turbines at different price levels, based on characteristics such as tax credits that apply to specific groups of turbines.

Figure 12: User Interface, Market Forecast Dashboard
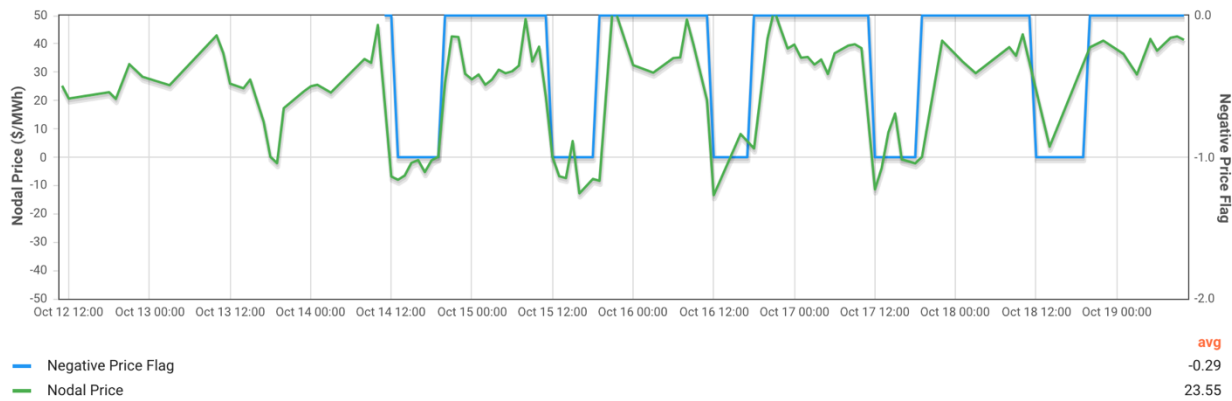
The green line indicates the locational marginal price at a local node (nodal price in $/MWh on the left axis), while the blue line indicates the negative price forecast flag (0 = keep turbines on; -1 = dispatch turbines; on the right axis).

Source: University of California, Davis (2019)

ThingsBoard can have multiple user accounts that have different levels of access. For the REnewALL project, the team set up three accounts. The user interface pages displayed in Figure 9 through Figure 12 correspond to the Controller account. The Observer account has a very similar user interface except that it does not include buttons to start and stop the turbines. There is also a Tenant account that has authority to view and modify the user interfaces of the Controller and Observer accounts. Using the Tenant account, a wind plant owner can add, remove, or modify the components of the user interface to best suit their needs. ThingsBoard software is available at thingsboard.io. Files that can be used to recreate the user interfaces from the REnewALL field test can be found at GitHub.[13]

4.3   Remote Communication and Control System Bench Testing

Bench testing was done throughout the development of the remote communication and control system. Individual components, such as XBee radio modules and turbine interface electronics boards, were tested to ensure they worked as expected. In addition, a small mesh network consisting of a computer and three XBees was built. This small mesh network was used to bench test software and the interaction between system components.

XBees were tested with the help of XBee development boards (Figure 13). These boards provide stable power to the XBee and have a variety of buttons and light-emitting diodes (LEDs) that are useful in testing. The buttons can be used to switch the voltage on an XBee pin from 0 V to 3.3 V. These buttons were used to test input features such as fault detection and electric meter pulse counting. The LEDs turn on or off based on the voltage of an XBee pin. These LEDs were used to visually verify that output features of the XBee radio module, such as start and stop sequencing, worked properly.

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[13] github.com/ewandersonUCDavis/REnewALL/tree/master/thingsBoardFiles/Dashboards

Figure 13: XBee Development Board
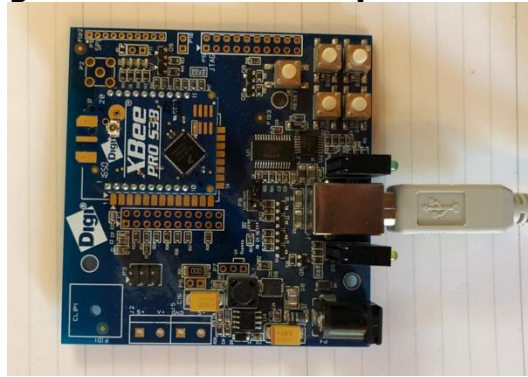
Source: University of California, Davis (2019)

Several versions of the turbine interface board were bench tested, with the results of early bench testing influencing design revisions and late bench testing verifying that the board reliably performed as it was designed to. A 24-V power supply was used to verify that the board supplied stable 3.3-V power for the XBee. That power supply was also used to verify that all of the board's input stages worked as expected and sent 3.3-V power to the correct XBee pins. The project team also verified that the board's output stages worked as expected by applying 3.3-V power to the appropriate XBee pins and monitoring the behavior of the output relays. These tests were performed on every board manufactured, including all nine boards that were installed in Tehachapi for the REnewALL field test.

Two longer-term tests were also performed on the turbine interface board. The first was an output stage endurance test. In this test, an output stage on one of the turbine interface boards was switched once per second for 11 days. At the end of the test, the output stage was still performing as expected. The second test verified that the turbine interface board and XBee could accurately count electric meter pulses. In this test, a function generator applied a half-second pulse to the board's IN_PULSE input stage every 10 seconds for two days. The XBee counted the pulses and reported the number of pulses every 15 minutes. Throughout the test, the number of pulses reported by the XBee matched the number of pulses created by the function generator. These longer-term tests were each performed on a single turbine interface board.

A small mesh network was set up to test software and the interaction of components. The mesh network consisted of the wind plant-level controller (an XBee plugged into a computer running the communication gateway and user interface software) and two programmable XBees that were running turbine controller software and were plugged into XBee development boards. This system was used for testing and debugging throughout the development of the turbine controller software, the communication gateway software, and the user interface. It was also used to verify that the hardware components worked together as expected. This system was operated for several months before the wind plant-level controller was moved to Tehachapi and installed at the test site.

CHAPTER 5:
Field Demonstration

This chapter describes the field demonstration, including the location and equipment, data collection procedures, and results. The objectives of the field test were to

- Demonstrate that the project hardware could perform required tasks (communication, status monitoring, and remote dispatch) in the field environment throughout the test period

- Work with plant operators to identify hardware or software problems and potential improvements

- Operate market forecast system and quantify financial impact of turbine dispatch

- Monitor brake events on dispatched turbines and non-dispatched (control) turbines to estimate impact of additional brake use on maintenance costs

- Test the remote dispatch system at various levels of autonomy, such as dispatch by operator, text or email notifications, automated dispatch by forecast algorithm, etc.

5.1 Test Site and Turbines

The project team conducted the field demonstration at the Wind Stream wind plant southeast of Tehachapi, California (Figure 14). Field test site marked with red star. Circles indicate wind turbine locations, with colors denoting various generating capacities. Gray circles are predominantly aged turbines that could be retrofitted with the REnewALL dispatch system.

Figure 14: Field Test Location

Source: U.S. Wind Turbine Database. https://eerscmap.usgs.gov/uswtdb/
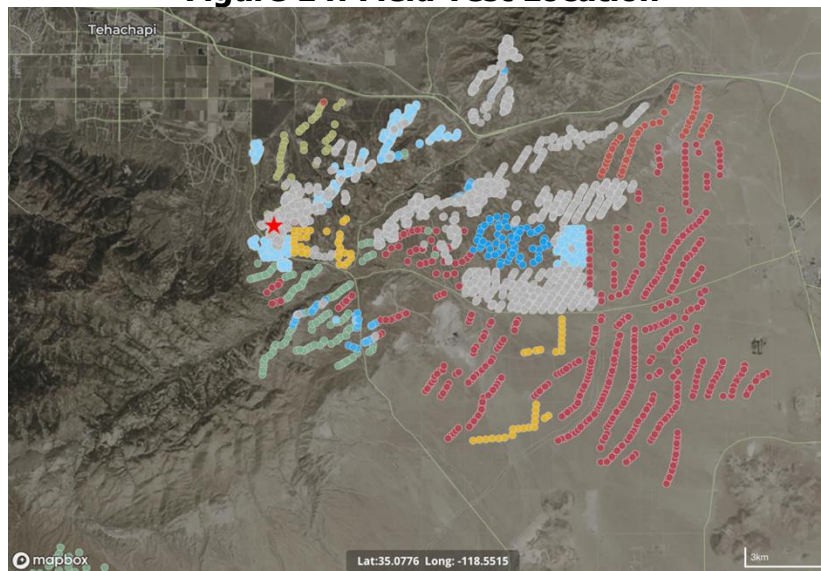
The field test involved nine Vestas V-17 wind turbines, including seven turbines that used the full capabilities of the REnewALL dispatch and communications system and two control turbines that were monitored without being dispatched (Figure 15).

Figure 15: Locations of Turbines with REnewALL Communication and Control Systems

Source: U.S. Wind Turbine Database. https://eerscmap.usgs.gov/uswtdb/
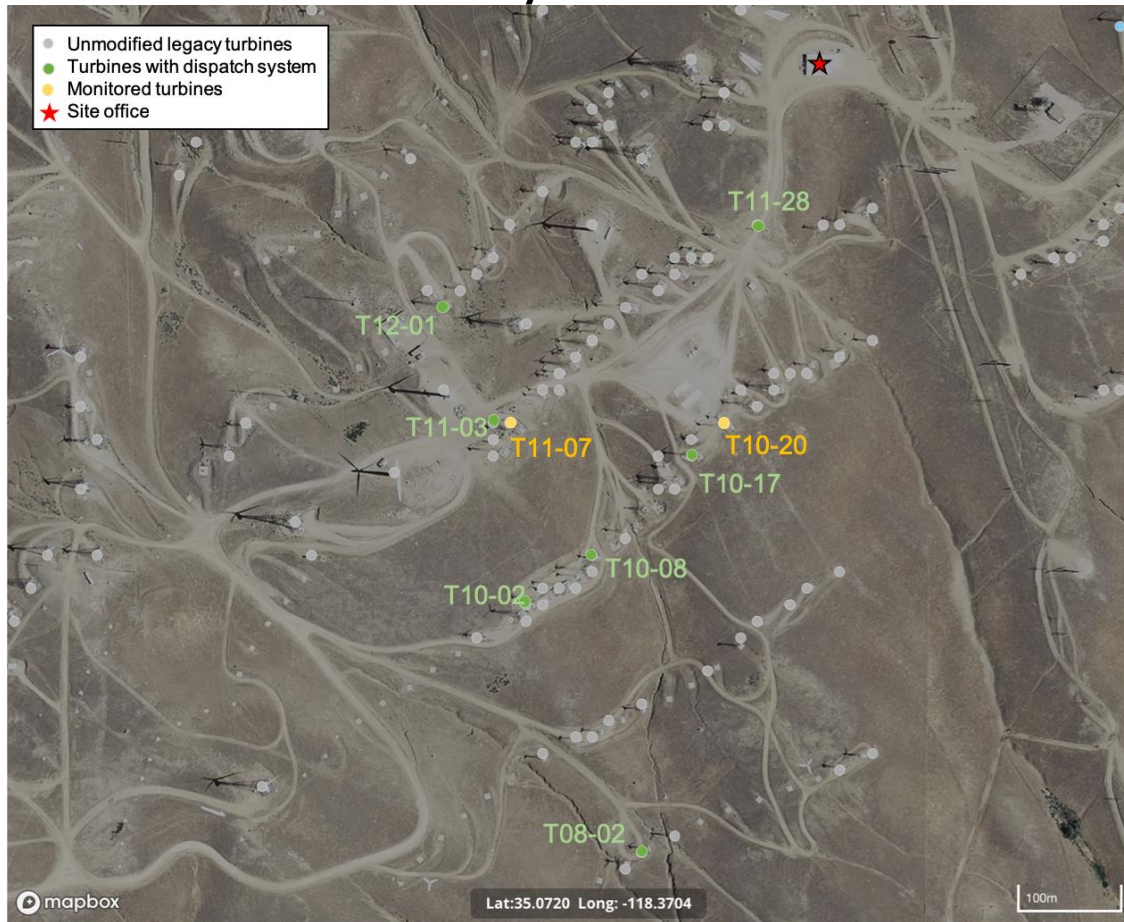
The turbines have a rotor diameter of 17 meters (56 feet[ft]) and a generating capacity of 100 kilowatts (kW). The generators operate from a minimum wind speed of seven meters per second (m/s) or 15 miles per hour (mph) up to a maximum wind speed of 28 m/s (62 mph). Each turbine has a hydraulic brake that can be activated to stop the turbine. The REnewALL control system utilizes this brake for turbine dispatch, while the existing controller is also capable of braking automatically in situations such as turbine overspeed, overheating, or grid failure. Each turbine also has a yaw system that turns the rotor into the oncoming wind direction and can rotate the turbine out of the wind to reduce loads when the brake is applied.

One of the aims in selecting turbines for the field test was to test the performance of the communication system in complex terrain. Turbine selection was also influenced by characteristics of the individual machines. Legacy wind plants in California are often comprised of groups of turbines with different manufacturers and models installed at various times during the 1980s and 1990s. Throughout the turbines' operational lifetimes, new components have been installed as repairs or upgrades to the original parts. To keep the field test manageable, the REnewALL turbine interface electronics were configured to work with a specific turbine model and control board layout, which constrained the selection of turbines within the wind plant.

The hardware installed on each turbine consisted of an XBee wireless module, antenna, and a turbine-interface board. These components were enclosed for protection from weather and

wildlife. A desktop computer and wireless module were placed in the main site office to manage communications with the turbines and store data.

5.2 Data Collection

Data collection began with the installation of the wind plant-level controller at the site office and monitoring hardware on a single turbine in early August 2018. During installation, the team found that commands from the REnewALL system were not being properly output to the turbines, requiring a minor design change to the prototype turbine interface boards. The team installed updated remote communications and control hardware on all nine turbines in mid-October (Figure 16). The time required for installation at each turbine ranged from 40 to 60 minutes.

Figure 16: Installation of REnewALL System

Clockwise from left: View of installation at base of turbine; installation in progress at turbine T11-28; interface electronics boards for nine turbines; REnewALL hardware installed in turbine: XBee radio and microprocessor is the blue rectangle, vertical white cable at center leads to antenna; turbine control panel open for installation.

Photo Credits: Steven Sultan, DNV GL

The team encountered two compatibility issues on some of the selected turbines:

- Power supply. The 24-V power supply used by the original turbine controller was poorly regulated on four of the turbines, which meant that the turbine interface electronics were unable to use the 24-V supply to generate a well-regulated 3.3-V signal to power the remote communications module. The other five turbines had newer power supplies that provided better regulation of the signal. Poorly regulated power supplies had caused other problems at the wind plant in the past, and there was an ongoing process of upgrading the power supplies throughout the wind plant. Equipment was available on site to upgrade the power supply on the four problematic turbines within a few days of the REnewALL hardware installation.

- Power meter compatibility. Monitoring of power production by the REnewALL system involves reading an output KYZ pulse produced by a power meter on the turbine. While KYZ pulse counting is standard for electric metering, not all power meters are equipped for electronic output (as opposed to visual reading of the meter). Only three of the turbines selected for the field test had meters with KYZ outputs, but meters were

available on site to replace those in three other turbines during the week following the REnewALL hardware installation. The remaining three turbines did not record power production data during the field test.

Each turbine transmitted two types of data via the radio-frequency mesh network to the wind plant-level controller in the site office: power production data was transmitted every 15 minutes, while status changes (brake or fault status) were transmitted when they occurred. Data were recorded and stored on the wind plant-level controller and were also accessible via the web-based user interface. Internet outages at the wind plant occurred on several occasions; during these periods, the user interface was inaccessible, but data continued to be recorded and were available via the user interface once internet service was restored.

5.3 Results and Discussion

The period of analysis for data collected during the field test ran from October 16, 2018 to January 18, 2019. Table 5 presents a summary of the communication system performance. During the approximately 2,200-hour period, power production data was reported at 15-minute intervals. The team defined communication outages as periods when the difference between two consecutive power data timestamps was longer than 15 minutes and 30 seconds. Most of the turbines experienced approximately 250 hours of communication outages. Several of these outages (approximately 12 hours per turbine) were brief and mainly uncorrelated between turbines, representing isolated 15-minute periods of missed communication. The largest source of communication downtime (238 hours) was failure of the communication gateway script, which crashed on several occasions and required manual restarts. In the future, it may be possible to develop an automatic reboot procedure; otherwise, plant operators should incorporate regular checks of the system output into operational routines.

Table 5: REnewALL Communication System Data Summary

Turbine ID:	08-02	10-02	10-08	10-17	10-20	11-03	11-07	11-28	12-01
# hours recorded	2,259	2,083[14]	2,260	2,259	2,259	2,259	2,259	2,259	2,259
Comm outage hours	251	680	250	247	339	251	248	249	250
% time comm outage	11.1	32.7	11.1	10.9	15.0	11.1	11.0	11.0	11.1
# faults + brakes	14	25	12	18	8	18	16	8	33

Source: University of California, Davis (2019)

The REnewALL system also recorded faults and brake events for each turbine. Each of the four types of monitored faults (wind speed, vibration, low pressure, and overspeed) causes the brake to be applied as well as lighting an indicator LED on the turbine. Some faults can reset

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[14] Data collection did not begin at T10-02 until October 23, when a compatible power supply was installed. During the first three weeks of operation, T10-02 experienced 430 hours of communication outages due to a faulty antenna which was replaced on November 14.

automatically (for example, the wind speed fault is triggered in winds above 62 mph and clears when the wind speed has remained below that level for 30 minutes), while others require a technician to manually inspect and restart the turbine. Brake events may also occur independently of faults; for example, during routine maintenance.

Alerts can be configured to send text or email messages when a fault is detected. Based on the team's experience with fault detections during the field test, this feature should only be used with a timed filter that prevents the generation of repeated alerts in a short time. In one extreme example, 4,400 status changes ("brake on," "wind speed fault detected." "brake on," and so forth) were recorded within a two-minute period. The number of repeated status changes for a single fault event varied by turbine and is most likely related to the level of electrical noise in the legacy control system.

Figure 17 provides an example of fault detection and related changes in power production for two turbines on December 1 and 2, 2018. During the period shown, the brake was applied on turbine T12-01 due to wind speed faults at the shaded time periods. The two turbines in the figure are located approximately 136 m (450 ft) apart and likely experienced very similar wind speeds during the time period shown. Most of the time, power production values are quite close between the two turbines. Wind speed faults were detected on turbine T12-01 twice in the evening of December 1, causing the brake to engage, while turbine T11-07 continued to operate normally. The brake periods show up in the power production as significant drops that do not match the power production history of T11-07. Time series of 15-minute average power production for two turbines on December 1 and 2, 2018. During the period shown, the brake was applied on turbine T12-01 due to wind speed faults at the shaded time periods.

Figure 17: Power Production Comparison for Two Turbines
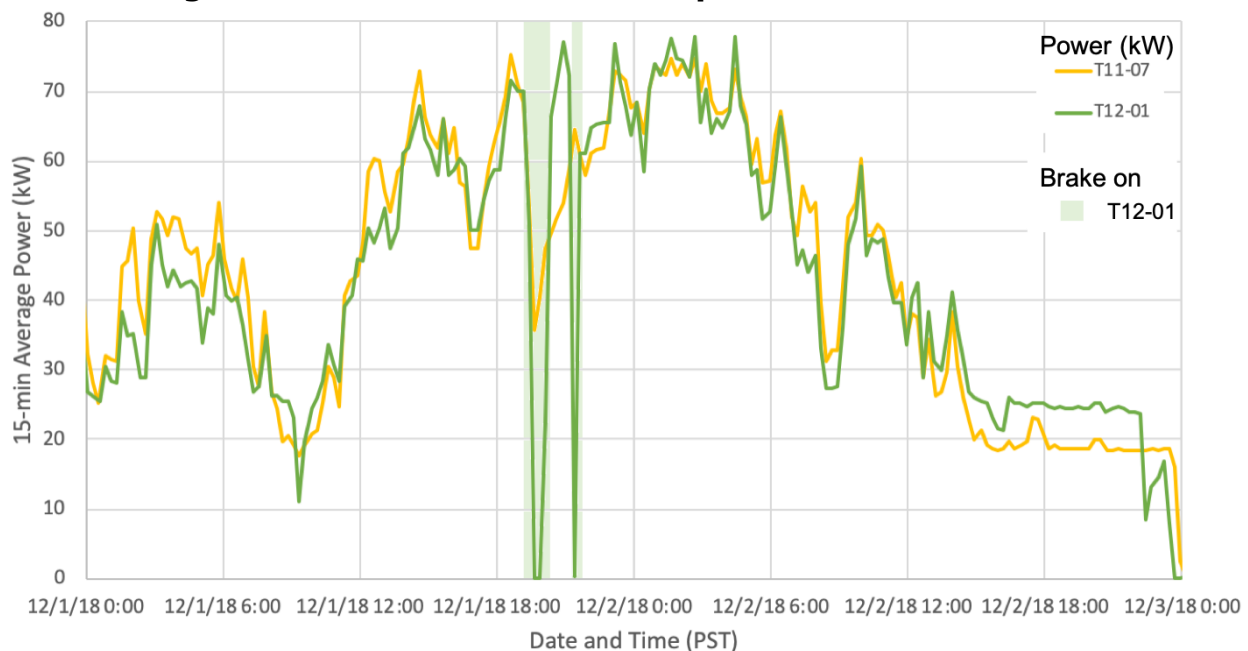
Source: University of California, Davis (2019)

CHAPTER 6:
Energy Storage Analysis

6.1 Background

In the August 2017 stakeholder workshop held in Tehachapi, California, stakeholders raised the idea of using energy storage and/or solar to improve wind project economics. During periods of low wind generation, on-site electronics consume energy and incur high monthly demand charges that dampen the overall revenue of the project. The idea of incorporating storage and/or solar into the wind site could potentially serve two purposes: (1) reduce demand charge by shaving the monthly peak demand, and (2) perform arbitrage to capitalize on nodal price differentials, especially in periods with negative prices.

Commercial customers are subject to capacity or demand charges by the electric utility. This is a non-coincident demand charge assessed on the maximum demand of the monthly billing cycle. Since the demand charge is quite high, peak demand reduction can result in substantial savings, making this application very attractive for the customers.

Standalone photovoltaics (PV) or standalone storage have the potential to reduce demand charges by lowering the peak demand or shifting peak demand load to a different time. However, the reduction from standalone solar PV systems cannot be guaranteed because the output of a solar PV system is intermittent, and dependent on atmospheric and ground conditions. For example, a sudden cloud cover during the customer peak demand hour may jeopardize the demand reduction potential from the stand-alone solar PV system over the entire month. Therefore, standalone PV for peak demand reduction is not analyzed in this report.

Battery energy storage systems (BESS), by themselves or complemented with solar PV systems, can guarantee peak demand reduction due to their ability to charge and discharge independently from weather conditions. The volume of demand reduction achieved by solar plus storage systems is generally higher than the sum of the demand reduction possible through either system on its own.

DNV GL evaluated the economics of a BESS installed behind-the-meter (BTM) on the customer premises, with and without co-located solar. DNV GL used historical load data and wind generation data from a California wind plant in the Tehachapi Wind Resource Area. The battery system is configured to primarily perform demand charge reduction (DCR) on the customer's utility bill.

The following sections describe the methodology of the cost-effectiveness analysis, the results, as well as storage technologies that are suitable for this application.

6.2 Methodology

To evaluate the value proposition of the BESS, DNV GL simulated the performance of characteristic solar plus storage systems under realistic site conditions. The team modeled the operation of BTM energy resources at 15-minute intervals over the entire year under inputs of customer load, renewable production, utility tariffs for energy and demand, and performance characteristics of the solar modules, solar inverter, battery modules, inverter interface, and

interconnection constraints. The utility tariffs include an energy charge based on the total electricity use (in kilowatt-hours) during a month, as well as a demand charge based on the maximum 15-minute electricity demand (in kilowatts). BESS dispatch controls are optimized over each 24-hour horizon to maximize customer energy and demand charge savings.[15]

The modeled BESS dispatch considers perfect foresight and perfect controls. The perfect foresight assumption implies that load and renewable production is perfectly known over the optimization horizon. Perfect controls assume that there are no measurement errors or other disturbances that affect the system and control outputs are perfectly actuated. These assumptions help derive the maximum savings potential for a specific resource configuration at a facility. In reality, savings may be reduced due to forecasting and control errors in the range of 10-30 percent.

6.3 Operational Assumptions

DNV GL considered unit sizes from 70 kW up to 500 kW, based on demand data for the site and commercially available systems, with durations of one, two, and four hours. The overall roundtrip efficiency of the storage modules and inverter combined is taken as 88 percent. The operating range of the BESS is from zero to 100 percent state of charge (SoC). The maximum charge and discharge power capacity of the BESS is equal to the inverter capacity, and the minimum is zero.

Since the optimization horizon is 24 hours (midnight to 11:59 p.m.), a modeling construct requires that there is no net energy gain or loss over the 24-hour control horizon. This is done by assuming that the BESS SoC at the beginning of the first time interval (0:00-0:15) and the end of the final time interval (11:45-0:00) in the optimization horizon is equal to 50 percent of built energy capacity.

An aggregated load obtained from a California wind plant in the Tehachapi Wind Resource Area was used for this analysis (Figure 18).[16] The data set provided contained hourly data for an entire year, split into total energy consumption (kWh) and peak demand (kW) for each hour. Customer consumption was converted into 15-minute intervals by assuming the first 15-minute interval is the hourly peak and dividing the remaining hourly consumption into the other three 15-minute intervals. The load profile used has a peak demand of 448 kW and average monthly consumption of 92.8 MWh. The 15-minute PV production profile was taken from PV Watts calculator[17] analyzed for the Tehachapi wind site.

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[15] Energy charges are billed on a $/kWh basis where energy indicates the total electricity usage for a billing period. Demand charges are billed on a $/kW basis where demand indicates the highest electric power usage for a billing period.

[16] The load data are from May 2015 to April 2016.

[17] https://pvwatts.nrel.gov/

Figure 18: Annual Load Profile of Wind Plant
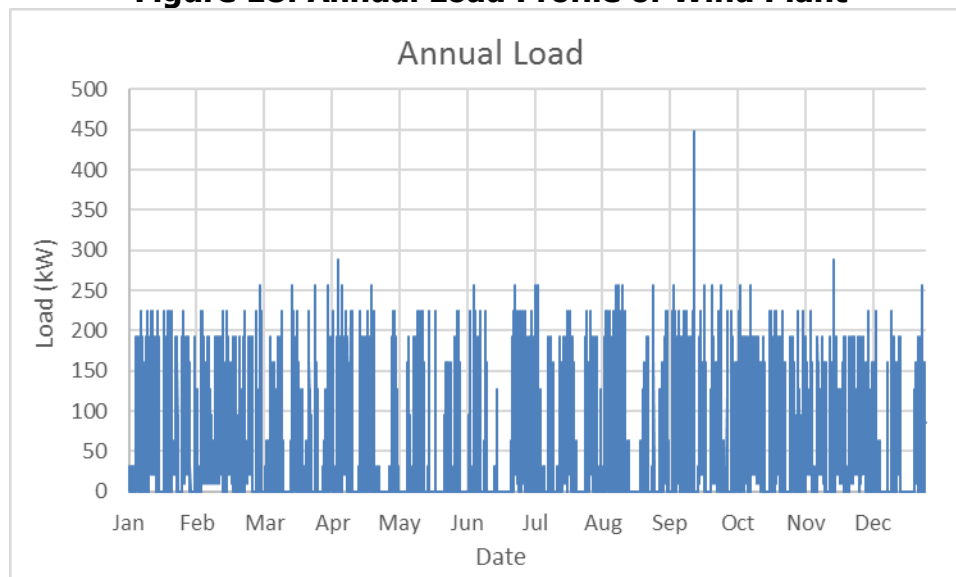
Source: University of California, Davis and DNV GL (2019)

Southern California Edison (SCE)'s time-of-use, general service, demand metered (TOU-GS-2a) and TOU-GS-2a Option R tariffs were considered for this analysis, where the reduced rate for 2kV-50kV service was used. The Option R was only applied to storage systems that are coupled with PV. Table 6 shows the range of charges for these tariffs. As shown below, neither tariff has coincident demand charges, meaning demand charges are the same throughout the day.

Table 6: Demand and Energy Charges

Tariff	Energy Charge (cents/kWh)	Non-Coincident Demand Charge ($/kW)
SCE TOU-GS-2a	5.34 – 26.66 cents per kWh	$14.91 per kW
SCE TOU-GS-2a Option R	6.58 – 27.90 cents per kWh	$11.28 per kW

Source: University of California, Davis and DNV GL (2019)

6.4 Cost and Financial Assumptions

The results of the optimized BESS dispatch model are integrated into a financial model to analyze the overall system value, including total system cost, annual cash flows, and financial returns across system life. The model assumes a 10-year system life with a 6.6 percent discount rate where the system capital costs are paid in year 1, and operations and maintenance (O&M) costs are paid on an annual basis. An additional capacity maintenance cost is assigned for the BESS annually across 10 years, and an avoided tax income is given over the first five years using depreciation rates for energy systems defined by the Modified Accelerated Cost Recovery System. The model assumes a 2.5 percent annual escalation rate to O&M costs and three percent escalation rate to annual energy rates and peak demand charge. Net annual cash flows for the first 10 years are used to calculate the overall net present value

(NPV), internal rate of return (IRR), and payback period for systems. Table 7 provides a summary of financial inputs.

Table 7: Financial Inputs

Input	Unit	Value
Capital Cost of PV	$/kW	2,000
Year-1 PV O&M Cost	$/kW/year	20
Year-1 BESS O&M Cost	$/kW/year	8
BESS Capacity Maintenance Cost	$/kWh/year	15
Discount Rate	%	6.6
Combined Federal and State Tax Rate	%	29.8
Self-Generation Incentive Program Rate	$/kWh	300
O&M Escalation Rate	%/year	2.5
Demand Charge Escalation Rate	%/year	3
Energy Charge Escalation Rate	%/year	3

Source: University of California, Davis and DNV GL (2019)

Table 8 details the cost by component of installing the BESS. Costs are split into battery, interface, controls, balance of system, and installation. These costs account for the battery rack, battery management system, inverter, container, system controls, interconnection, metering, construction, site development, transportation, and labor. The cost assumptions have been developed considering recent trends and publicly available industry cost forecasts for 2019. DNV GL considered the impact of low, middle, and high costs for the optimized system solution.

Table 8: BESS Cost Assumptions

Cost Category	Unit	Low Cost	Middle Cost	High Cost
Battery Cost	$/kWh	$130	$160	$230
Interface Cost	$/kW	$180	$260	$340
Controls Cost	$/kW	$60	$70	$80
Balance of Systems Cost	$/kW	$60	$70	$80
Installation Cost	$/kWh	$70	$90	$120

Source: University of California, Davis and DNV GL (2019)

BESS can take advantage of Federal Investment Tax Credits (FITC) when co-located with and charging from new solar PV systems. The maximum FITC of 30 percent on the all-in capital cost of the BESS can be obtained if the batteries derive 100 percent of charging energy from solar output, with reduced incentives affected by the percentage of charging from the grid. For cases of standalone BESS, the BESS receives no FITC. Since the storage unit is placed BTM to offset customer's demand charge, it is unlikely that it can be paired with an existing utility-side

wind facility to be eligible for FITC.[18] The BESS is eligible for California's Self-Generation Incentive Program (SGIP), where the incentive is based on energy capacity for customer-sited generation. For this analysis, an incentive of $0.30 per watt-hour (Wh) was applied to all systems, which corresponds to Step Four of SGIP. Currently, SCE is on Step Three for large-scale storage, so it is likely to be in Step Three by early 2019. Half of the SGIP incentive is given in year one, where five additional 10 percent increments are given for years one to five as performance-based incentive (PBI) payments.

DNV GL used a screening tool to estimate a wide range of system configurations and found that system financials are improved without PV. An installed PV system, whether paired with storage or standalone, has low returns due to a combination of the load shape and the project's tariffs. The baseline load is generally small, even zero kW at some points, with short peaks that only occur within a 15-minute period. While storage with short duration can perform peak shaving, this means a majority of PV generation would be underused during the day. While the PV could perform self-consumption, energy charges are too low to provide positive returns. DNV GL also found that long-duration storage beyond two hours is not advantageous for the same reason: the main source of revenue is DCR for brief peaks. DNV GL performed annual optimized dispatch analysis for 70 kW, 125 kW, 200 kW, 250 kW, and 500 kW standalone BESS with one-hour and two-hour durations. Table 9 shows total installed cost and cost per installed kWh of the different storage system sizes. The cost per unit size reduces as the duration increases since some system costs incur over equipment, balance of plant, and materials on the ac-side of the BESS.

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[18] The latest information on FITC for retrofitting storage systems to existing renewable plants is the Internal Revenue Service letter ruling on residential solar plus storage issued in March 2018. Letter rulings do not hold legal precedence and are applicable on an individual case basis.

Table 9: Total BESS Low and High Installed Costs for Size Sensitivities

BESS Size	Total Installed Cost ($)			Unit Installed Cost ($/kWh)		
	Low Cost	Middle Cost	High Cost	Low Cost	Middle Cost	High Cost
70 kW, 1 hour	$35,000	$45,500	$59,500	$500	$650	$850
70 kW, 2 hours	$49,000	$63,000	$84,000	$350	$450	$600
125 kW, 1 hour	$62,500	$81,250	$106,250	$500	$650	$850
125 kW, 2 hours	$87,500	$112,500	$150,000	$350	$450	$600
200 kW, 1 hour	$100,000	$130,000	$170,000	$500	$650	$850
200 kW, 2 hours	$140,000	$180,000	$240,000	$350	$450	$600
250 kW, 1 hour	$125,000	$162,500	$212,500	$500	$650	$850
250 kW, 2 hours	$175,000	$225,000	$300,000	$350	$450	$600
500 kW, 1 hour	$250,000	$325,000	$425,000	$500	$650	$850
500 kW, 2 hours	$350,000	$450,000	$600,000	$350	$450	$600

Source: University of California, Davis and DNV GL (2019)

6.6 Demand Reduction and Benefit Results

Each site configuration is simulated at 15-minute time scales over an entire year. Storage controls regulate charging and discharging to maximize bill savings at the facility. Figure 19 shows 24-hour site operation with 250-kW two-hour BESS on May 31 at the site. Storage primarily charges in the morning when loads are low. During the peak period, the storage discharges to ensure that net facility load is below the demand target for the day. The original customer demand of 224 kW is reduced to 64 kW, in effect reducing demand by 71 percent.

Figure 19: BESS Operations for 250-kW Two-Hour System
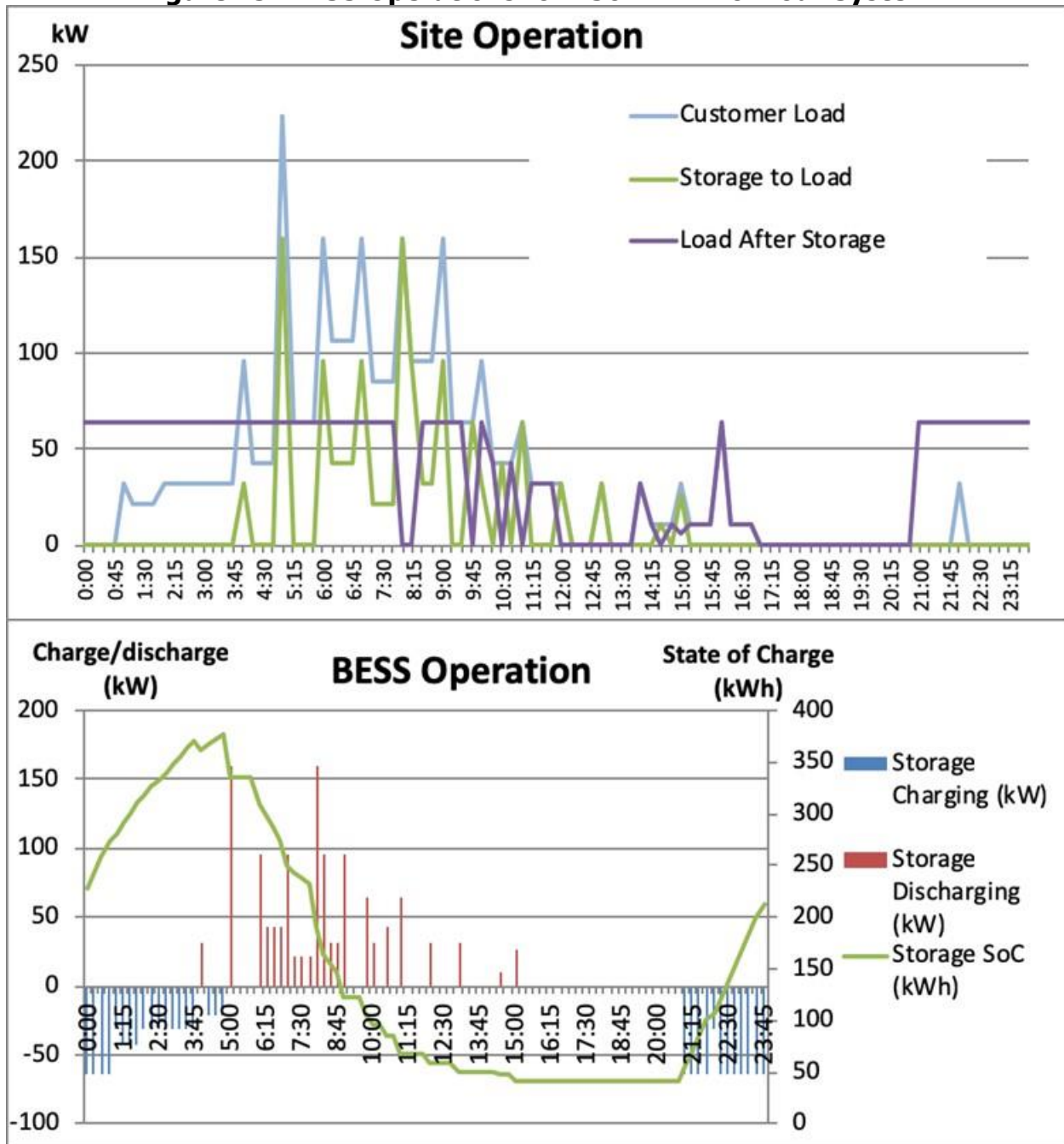
Source: University of California, Davis and DNV GL (2019)

Table 10 shows the annual benefit for the evaluated scenarios under SCE's TOU-GS-2a tariff. The savings are attributed to reduction in energy charges and demand charges. Energy charge reduction is marginal, which is due to the BESS charging only from the grid. The annual savings show that there is very little added benefit in adding additional storage duration. However, additional power capacity has a considerable impact.

Table 10: Comparison of Annual Savings for Standalone BESS

Storage Power Capacity (kW)	Storage Duration (hours)	Energy Charge Savings ($)	Demand Charge Savings ($)	Total Savings ($)
70	1	$489	$11,436	$11,925
70	2	$892	$11,853	$12,746
125	1	$836	$18,615	$19,451
125	2	$1,353	$20,293	$21,646
200	1	$1,356	$21,756	$23,112
200	2	$1,540	$25,823	$27,363
250	1	$1,749	$23,111	$24,860
250	2	$1,801	$27,211	$29,012
500	1	$1,848	$27,464	$29,312
500	2	$1,182	$30,057	$31,239

Source: University of California, Davis and DNV GL (2019)

6.7 Financial Results

Table 11 represents the overall financial results of the BESS deployment scenarios The BESS is cost-effective, with an optimization point shown at 250 kW, two-hour duration.

Table 11: Financial Results for BESS Optimization Analysis Using Median Cost

Storage Power Capacity (kW)	Storage Duration (hours)	NPV ($)	IRR (%)	Payback Period (Years)
70	1	$72,929	71.0%	2.5
70	2	$75,556	64.7%	2.7
125	1	$114,349	62.1%	2.7
125	2	$125,317	60.2%	2.8
200	1	$113,965	40.4%	3.6
200	2	$137,894	43.3%	3.5
250	1	$107,747	32.4%	4.1
250	2	$127,653	34.1%	4.1
500	1	$39,732	11.8%	6.8
500	2	$24,609	9.7%	7.5

Source: University of California, Davis and DNV GL (2019)

6.8 Additional Analysis: Behind-the-Meter Energy Storage Wholesale Market Participation

The California ISO allows BTM storage to participate in the wholesale market under proxy demand resource (PDR). This application is in the pilot phase and several projects are being demonstrated across California. This allows BTM BESS to bundle DCR application with wholesale market price arbitrage. Since DCR applications only use the BESS for a maximum of a few hours a day, the BESS can perform arbitrage to increase revenue potential of the battery. The bundled applications of DCR and arbitrage can be evaluated through 15-minute operational modeling. DCR would be the primary application and would always be prioritized; after DCR is met, the secondary application of arbitrage is opportunistic. The BESS would dispatch to maximize arbitrage revenue from the California ISO nodal energy market while ensuring that the system has the capacity to perform DCR. The market optimization dispatch could be performed by solving an hourly linear mixed integer programming problem over a 24-hour time horizon for every day of the year. Historical market prices at the Tehachapi node could be used as inputs. The BESS would charge during periods of negative or low pricing and discharge during periods of high-energy price.

Background

In February 2018, the Federal Energy Regulatory Commission (FERC) passed Order 84,1, which paved the path for energy storage resources to participate in wholesale electricity markets operated by regional transmission organizations or independent system operators. FERC defines an electric storage resource as a resource capable of receiving electric energy from the grid and storing electric energy for later injection back to the grid. The energy storage resource can be located on the interstate transmission system, a distribution system or behind the meter.[19]

Participation Methods

In California, the ISO allows behind the meter energy storage resources to participate in energy and ancillary service markets by providing load curtailment or demand response through a few methods. The energy storage resource can participate as a non-generator resource, which is defined as a resource that operates as either generation or load and can be dispatched to generate, curtail or consume energy.[20] The energy storage resource can also participate through California ISO's demand response framework as a proxy demand resource (PDR) or reliability demand response resource (RDRR). As a PDR, the energy storage resource acts as a traditional demand response resource and as a RDRR the energy storage resource is only dispatched when the California ISO system is at or approaching a system emergency.[21]

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[19] FERC 2018. Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators Order No. 841, 162 FERC ¶ 61,127, February 15, 2018.

[20] California ISO 2019. California Independent System Operator Corporation, Fifth Replacement Electronic Tariff, Appendix A, January 1, 2019.

[21] California ISO 2018. California Independent System Operator Corporation, Docket No. ER19-468-000, Compliance with Order No. 841, December 3, 2018.

Additionally, California ISO also allows energy storage resources, including smaller resources, to aggregate into a single virtual resource to meet its minimum capacity requirements.

Pricing and Metering

Sale of energy and ancillary services to energy storage resource is at wholesale nodal locational marginal pricing.[22] When an energy storage resource charges, California ISO treats it as negative generation instead of load or demand. As such, if the storage resource is dispatched by California ISO to provide a service in its markets it is not assessed any transmission access charges.

In order to account for wholesale and retail activities of the energy storage resource, California ISO requires that it be directly metered either by California ISO or by a scheduling coordinator. Additionally, if a storage resource participates in other markets, it can also participate in the California ISO market without changing its existing meters. California ISO highlights that storage resources might benefit under the scheduling coordinator metered entity framework since a scheduling coordinator can work with a regional transmission organization or independent system operator and local distribution company to make sure that the storage resource is in compliance with all applicable metering standards.

Performance Evaluation

California ISO offers five performance methodologies for calculating customer load baselines and demand response energy measurements for PDRs and RDRRs. These include the 10-in-10 day-matching method, metering generator output method, 5-in-10 day-matching, control group method, and weather-matching method.[23] All of these methods depend on historic performance data, which is used to compare performance at the time of dispatch to typical use.

The most applicable method for energy storage is the metering generator output method. This method accounts for both load and BTM generation. A sub-meter is required for this approach as it allows separation between resources and isolates demand curtailment from load reduction. Similarly, demand curtailment can also be isolated from the production of the BTM generation. The use of the sub-meter allows California ISO to measure a demand response resource's performance by examining the load only, the generation only or both, depending on the resource's setup.[24]

Results for Demand Reduction and Wholesale Energy Participation

Similar to the simulation for demand charge reduction, each site configuration is simulated at 15-minute time scales over an entire year. Storage controls operate to primarily reduce monthly demand charge, and secondarily to perform energy arbitrage on California ISO nodal prices. Figure 20 shows 24-hour site operation of the same 250-kW two-hour BESS on May 31 at the same site as analyzed above. Like the DCR-only scenario, storage charges in the

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[22] Ibid.

[23] California ISO 2019. California Independent System Operator Corporation, Fifth Replacement Electronic Tariff, Section 4.13.4, January 1, 2019.

[24] California ISO 2018. California Independent System Operator Corporation, Docket No. ER19-468-000, Compliance with Order No. 841, December 3, 2018.

morning when loads are low, and discharges during peak load periods. As a result, the customer peak demand reduced from 224 kW to 64 kW, which is the same peak demand reduction as the previous DCR analysis.

In the DCR-only analysis, the battery charges from 9:00 pm to 4:00 am, and discharges from 4:00 am to 3:00 pm. However, it has no activities between 3:00 pm to 9:00 pm. In the demand reduction and wholesale energy participation scenario, the battery also actively charges and discharges during this period to perform energy arbitrage on wholesale market prices. These activities do not affect the battery's performance in demand reduction, but add another revenue stream for the project.

Figure 20: BESS Operations for 250-kW Two-Hour System With Energy Arbitrage
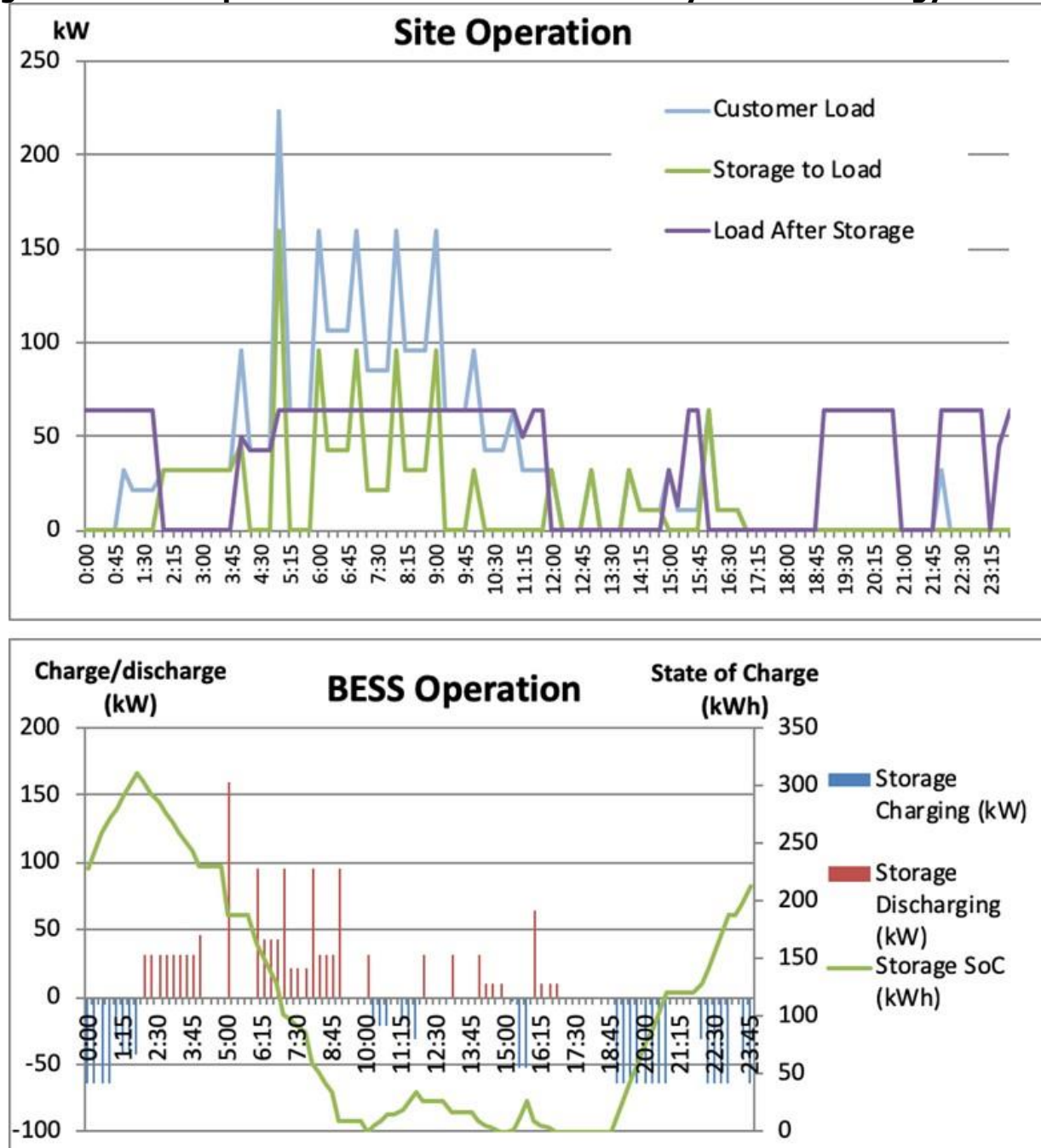
Source: University of California, Davis and DNV GL (2019)

Table 12 shows the annual benefit for the evaluated scenarios under SCE's TOU-GS-2a tariff and LMP prices from the nearest node. The demand charge savings remain the same, but energy savings increased due to additional revenue from energy arbitrage during the late afternoon and early morning hours.

Table 12: Annual Savings for Standalone BESS with Wholesale Market Participation

Storage Power Capacity (kW)	Storage Duration (hours)	Energy Charge Savings ($)	Demand Charge Savings ($)	Total Savings ($)
125	1	$2,996	$18,615	$21,611
125	2	$3,363	$20,293	$23,655
200	1	$3,617	$21,756	$25,373
200	2	$3,750	$25,823	$29,573
250	1	$4,031	$23,111	$27,142
250	2	$3,980	$27,211	$31,191
500	1	$4,243	$27,464	$31,707
500	2	Not cost-effective		

Source: University of California, Davis and DNV GL (2019)

Financial Results

Table 13 represents the overall financial results of the BESS deployment scenarios. The BESS is cost-effective, with an optimization point shown at 200 kW, two hours.

Table 13: Financial Results for BESS Optimization Analysis Using Median Cost

Storage Power Capacity (kW)	Storage Duration (hours)	NPV ($)	IRR (%)	Payback Period (Years)
125	1	$132,947	72.6%	2.4
125	2	$142,627	68.5%	2.6
200	1	$133,439	46.2%	3.3
200	2	$156,928	48.2%	3.3
250	1	$127,404	36.9%	3.8
250	2	$146,420	37.9%	3.9
500	1	$60,362	14.4%	6.3
500	2	Not cost-effective		

Source: University of California, Davis and DNV GL (2019)

CHAPTER 7: Technology/Knowledge/Market Transfer Activities

7.1 Stakeholder Workshop

At the outset of the project, the REnewALL team traveled to Tehachapi, California, to gather input from stakeholders and inspect the site of the planned field test. A stakeholder workshop was held on August 10, 2017. The goals of the workshop were to inform wind energy project owners, maintenance providers, and other interested stakeholders about the REnewALL project, to learn from their experiences in operating legacy wind energy projects, and to seek information on remote communication and control strategies and technologies. The on-site inspection the following day was an opportunity to obtain details about the turbines addressed by this project and to gain a better understanding of the terrain, control systems, grid equipment, and other relevant parameters affecting turbine operation.

The workshop agenda (Table 14) consisted of a presentation introducing the REnewALL project and its objectives, followed by small-group discussions seeking stakeholder input on several topics. Following the breakout sessions, the main points from the discussions were summarized for the entire group to wrap up the workshop.

Table 14: Stakeholder Workshop Agenda

Time	Agenda Item
1:00 – 1:45 pm	**Introduction to REnewALL Project and Objectives** *Case van Dam, Kevin Smith*
1:45 – 3:15 pm	**Breakout Discussion Groups** *Facilitated by UC Davis and DNV GL personnel* • Station 1: What remote communications/control systems have been tried before on legacy wind turbines? • Station 2: What functionality is required for a remote dispatch system? • Station 3: Budget and operations and maintenance requirements • Station 4: What unique field conditions or limitations need to be considered? • Station 5: What level of communications data transmittal and status awareness are desired?
3:15 – 3:45 pm	**Reports on Breakout Sessions**
3:45 – 4:00 pm	**Summary / Wrap-up**

Source: University of California, Davis (2019)

Stakeholders in attendance included owners and operators of wind projects with legacy turbines, engineering consultants, maintenance providers, and representatives of the California Energy Commission. A total of 24 people participated in the workshop, including nine members of the project team from UC Davis and DNV GL. Appendix B provides a participant list and detailed notes from the discussion stations.

Several common themes emerged from the discussions at each station and during the workshop wrap-up:

- Low system cost is a priority, in the range of $200 – $250 (or lower) per turbine.

- Two main cases drive up operators' costs: exposure to negative pricing during periods of oversupply and consumption of energy (at retail prices) by turbines and grid equipment during periods of low or no wind. The relative importance of these two cases depends on the type of contract under which a site sells its power.

  o Dispatching turbines off in high winds leads to wear and tear on braking systems; the benefits of avoiding negative prices need to be balanced against increased maintenance and replacement costs.

  o Energizing and de-energizing transformers (a major source of parasitic loads) has a high risk of damaging expensive equipment.

- Energy storage has the potential to address both concerns. Energy can be stored during oversupply periods and used to keep grid equipment energized during low-wind periods. A combined market/weather forecasting system could help owner/operators make decisions about how to effectively use energy storage. Economic analysis would need to be carried out to determine costs and benefits of storage options.

7.2 Site Inspection

Members of the REnewALL project team from UC Davis and DNV GL visited the Wind Stream site on August 11, 2017. The visit included a tour of the site and inspections of relevant turbine systems such as controllers and brakes. Craig VanWagner from SCADA Solutions, Inc. was also present to discuss the prototype remote dispatch system that the company had installed on a subgroup of 10 turbines at the site.

The site visit allowed members of the REnewALL team to gain a general appreciation for the terrain, climate, and layout of the wind project site (Figure 21). The team also observed relative distances from the site operations and maintenance (O&M) building to turbines that could be used in the field test activities.

Speaking with project owners, the REnewALL team gained a deeper understanding of the project owners' priorities and issues, particularly related to finding an approach to mitigate energy consumption and demand charges during periods of low or no wind. Although slightly tangential to the project scope, the economic impact on the projects is as important as that of negative price periods. At the site, the team examined the substation and transformers that are the main source of parasitic loads. Although de-energizing the entire substation and collection system would allow project owners to reduce energy consumption and demand charges, they expressed their concern that the old equipment on site is not capable of being cycled in this manner as it will cause damage and ultimately increase costs.

Figure 21: Site Inspection Photos

Clockwise from top left: Wind Stream, REnewALL, and California Energy Commission personnel at field test site; example of a damaged brake disc; inspecting the control system on a typical legacy turbine (V15); legacy turbines (Vestas models V15 and V17) at the Wind Stream site in Tehachapi

Photo credits: Steve Sultan, DNV GL and Aubryn Cooperman, UC Davis

The team inspected existing control systems representative of those implemented on a majority of the turbines at the site, as well as the remote dispatch system built and installed by SCADA Solutions, which incorporates many features included in REnewALL project goals but costs more than project owners are willing to pay. It was encouraging to see that a California-based vendor is in a position to potentially use the results of REnewALL. In examining the integration of wireless communication into legacy turbine control relays, the team noted that no other turbine modifications were necessary to enable remote start/stop capability.

Researchers also examined the brake system on a grounded nacelle undergoing repair, compared new and damaged brake pads, and discussed potential effects of more frequent braking events. They identified a need to quantify costs related to increased wear and tear of the brake systems due to the REnewALL dispatch system.

7.3 Recommendations from Workshop and Site Visit

The REnewALL team developed the following recommendations and project scope adjustments based on the Stakeholder Workshop and Site Inspection:

1. Modify the project scope to include a desktop technical and economic analysis of a solar PV plus storage system to reduce energy consumption and demand charges identified as relevant by all project owners. The objective of the analysis would be to provide the Energy Commission and project owners with a robust and technically feasible analysis of the concept such that future research and implementation decisions could be evaluated and justified. The solar plus storage system could also contribute to reducing

effects of negative price exposure from putting energy on the grid during negative pricing periods, but would not be sufficient to replace the turbine dispatch system envisioned in the original REnewALL project scope.

2. Leverage the work done by SCADA Solutions in the development of a new, more cost-effective turbine communication and control system, using methods that they have successfully tested in the operating environment. The project team decided to focus the design process on reducing the cost of turbine communication and control without compromising reliability or safety.

3. Incorporate an economic analysis that compares the costs of increasing the frequency of braking events to any cost reductions or savings related to negative pricing or offsetting energy and demand charges. The objective would be to determine whether there is a start/stop frequency at which dispatching turbines becomes more expensive than letting them run due to increased wear and tear on the brakes.

7.4 Stakeholder Webinar

At the conclusion of the project, the REnewALL project team held a webinar on February 12, 2019, to present results from the project to interested stakeholders. The team provided information on the published open-source and public domain hardware and software designs that would allow interested wind plant owners to build, install, and operate similar systems at other legacy wind turbine sites. A total of 15 people participated in the webinar, including four members of the project team from UC Davis and DNV GL.

CHAPTER 8:
Conclusions and Recommendations

8.1 Forecast Algorithm

Although the dispatch algorithm in its current form is valuable in being able to predict not just individual negative LMP hours, but also negative LMP events, some recommendations have been developed.

1. Findings suggest the need of further testing and performance assessment over a longer period, particularly where more than 17 negative LMP events and 104 negative LMP hours occur. Based on California ISO's quarterly reports, the most useful period would be from February through May in any given year. This would also allow a better assessment of the performance of using a PTC threshold.

2. Assessment of the dispatch algorithm to predict the relative magnitude of the LMP. This could prove useful in helping to inform a wind plant operator if it will be financially prudent to dispatch turbines off or on when negative LMPs are predicted.

3. Coordination with California ISO and site operators on the best manner in which to determine the financial benefit and risks associated with dispatching turbines off during negative LMP events. Using only the LMP to determine financial benefits is insufficient, as the Dispatch Operating Target of a wind plant and settlement charges would also need to be considered.

8.2 Remote Dispatch System Field Demonstration

Members of the REnewALL team installed the remote communication and control system on nine turbines at the field test site, where it operated for more than three months. The REnewALL team and wind plant operators had access to real-time data from each turbine and could dispatch the turbines using a web-based interface. During the course of the field test, several issues and areas for improvement were identified. Some have already been addressed, such as installing compatible power supplies and altering how data are displayed on the user interface. Recommendations for future work include:

1. Adapt turbine interface electronics for other wind turbine models and controllers.

2. Configure the user interface to handle larger numbers of turbines. Although the underlying software is capable of monitoring many devices, the team customized the format and layout of displays based on the size of the field test, and it may begin to feel cluttered with data from more turbines. Site operators also expressed interest in having the ability to define groups of turbines that can be viewed and controlled together.

3. Explore the effects of braking turbines at various wind speeds and power outputs in order to develop guidelines for safe and economic dispatch of turbines.

8.3 Energy Storage Analysis

Several sizes of battery energy storage systems were simulated using a year of electric load data from a wind plant site in Tehachapi. The addition of solar PV to the storage system was considered, but it was not found to be cost effective. The performance of the BESSs was

analyzed under two scenarios: demand charge reduction only, and DCR with wholesale market participation. Systems with capacities between 70 and 1000 kWh were found to have positive returns on investment for DCR only, with payback periods ranging from 2.5 to 7.5 years. The addition of energy arbitrage on the wholesale market reduced payback periods and increased the net present value of the investment.

CHAPTER 9:
Benefits to Ratepayers

The benefits of this project to ratepayers include greater electricity reliability and lower costs.

Studies of the impact of increased penetration levels of renewables in California have found that imbalances between power supply and demand are becoming increasingly problematic as more renewable energy generation is incorporated into the grid. These imbalances are most common in months where the load is low, but are becoming more common throughout the year. The California ISO "duck curve" famously illustrates this issue. During periods of oversupply, market prices go negative to encourage generators to reduce production or go off-line.

The current inability to dispatch turbines in legacy wind plants adversely affects both turbine owners and grid management. The lack of flexibility to dispatch the aged turbines off in oversupply conditions forces grid operations to make adjustments elsewhere in the system, which leads to inefficient use of generation. Also, owners of legacy wind plants (that receive revenue via market-based pricing), are exposed to negative power prices that add to their cost of operation and reduce the economic viability of this no-carbon generating resource.

Enabling the dispatch of aged turbines from on-line to off-line during periods of oversupply on the grid reduces the need for other adjustments on the grid to respond to the excess wind generation. Thus, grid management tasks during oversupply periods will be incrementally less complex, which contributes to improvement in overall system flexibility and reliability.

Howarth and Monsen (2014) noted that California ISO estimates a 33 percent renewables portfolio standard could result in 96 hours of curtailment annually due to oversupply and a 40 percent renewables portfolio standard could increase this to 822 hours annually. Figure 22 shows curtailments of wind energy that occurred in the California ISO operating area during 2018. Wind energy production is shown in the lower half of the figure; note the change in scale. The impact of curtailment on owners of legacy wind plants, assuming they all transition to market-based pricing (as increasing numbers of their current 30-year power price agreement PPAs expire), is estimated based on the following. Assuming that the half gigawatt of wind generation is operating at rated power (high winds) and the market price is -$150/MWh in an oversupply condition, the owners are exposed to costs of $75,000 per hour. During a year with 96 hours of curtailment (and negative pricing) this corresponds to $7.2 million in costs. During a year with 822 hours of negative pricing the costs jumps to $61.6 million in costs. Exposure to these costs quickly erodes the economic useful life evaluations of these aged wind turbines.

Figure 22: 2018 Wind Energy Curtailment and Production in California ISO Operating Area

2018 Wind Energy Curtailment

2018 Wind Energy Production
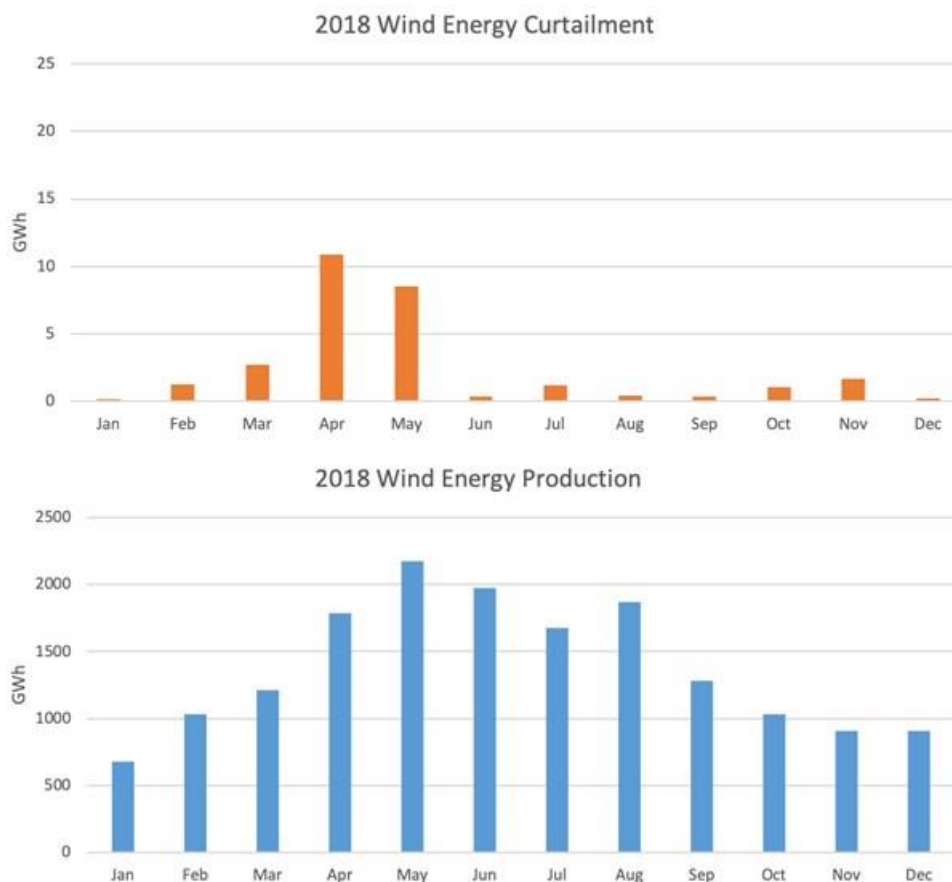
Source: http://www.caiso.com/Documents/ProductionAndCurtailmentsData_2018.xlsx

By adding dispatch capability, the turbine owners and grid operators gain needed flexibility. Augmented by a forecast system, half a gigawatt changes from a grid management liability to a grid management asset that can be brought on-line and off-line when it is advantageous to both owners and grid operations. Taking turbines off-line in oversupply conditions is an obvious mutual benefit, but it is also possible that aged turbines could be brought back on-line during high ramp events when generation is scarce and prices are high. Redispatching aged turbines back on-line, if timed well with wind forecasts, could enable achievement of high ramp rates. Historically, wind generation has not been viewed as reliable enough to help meet ramp supply needs, however, through this project, California could develop new methods for deploying aged wind assets in a manner to meet ramp needs.

This work contributes to lowering ratepayer costs by reducing grid management and integration costs associated with excess wind generation during oversupply periods. In addition, project level revenue and operating costs can be improved for aged turbines, enabling them to continue to provide low-cost, wind-generated electricity that avoids volatile fossil fuel costs and helps to address externality costs associated with global warming and carbon dioxide.

LIST OF ACRONYMS

Term	Definition
ANN	Artificial Neural Networks
BESS	Battery Energy Storage Systems
BTM	Behind-The-Meter
DCR	Demand Charge Reduction
DIO	Digital Input/Output
DOT	Dispatch Operating Target
FERC	Federal Energy Regulatory Commission
FITC	Federal Investment Tax Credits
GW	Gigawatt
IRR	Internal Rate of Return
ISO	Independent System Operator
kW	Kilowatt
LED	Light-Emitting Diodes
LMP	Locational Marginal Price
mW	Milliwatt
MW	Megawatt
NPV	Net Present Value
O&M	Operations and maintenance
PCB	Printed Circuit Board
PDR	Proxy Demand Resource
PTC	Production Tax Credit
PV	Photovoltaic
RF	Radio-Frequency
RPS	Renewables Portfolio Standard
RDRR	Reliability Demand Response Resource
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
SGIP	Self-Generation Incentive Program
SoC	State of Charge
TAC	Technical Advisory Committee

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APPENDIX A:
Instructions for Setting Up Remote Communication and Control System

This document gives instructions for setting up the various components of the REnewALL remote communication and control system. The following sections contain detailed step-by-step instructions for obtaining and using the software and systems developed by the REnewALL team. However, the instructions for using third party software are more general. To complete these more general instructions, like installing ThingsBoard or loading software onto the microprocessor of a programmable XBee, please consult the documentation provided by the original software developers. Both Digi and ThingsBoard have good manuals and tutorials explaining how to use their products.

Before setting up the remote communication and control system, you will need to choose two parameters:

Network ID:_____ (a hexadecimal number of up to four digits)

AES Encryption Key:_____ (a hexadecimal number of up to 32 digits)

In a hexadecimal number each digit can be the numbers 0-9 or the letters a-f. For security purposes, it is important to record these two parameters but keep them private. Any 900 MHz XBee radio can connect to the mesh network if it has these two numbers. However, without these numbers it will be impossible to connect to the mesh network or to listen in on information traveling through the mesh network.

A.1 Instructions for setting up XBee radio modules for turbine-level controllers

You will need the following hardware:

- One programmable XBee development kit (including a development board and USB debugger)

- One programmable XBee-PRO 900HP radio module per turbine-level controller.

You will need the following software:

- XTCU (available from digi.com)

- Programmable XBee SDK (Software Development Kit), including codeWarrior (available from digi.com).

You will also need:

- The Serial Number Low (SL) of the XBee connected to the wind plant-level controller.

- The firmware version of the XBees you are using.

- The network ID (ID) and AES Encryption Key (KY) of the mesh network.

1) Download the turbine-level controller software. This software handles electric meter pulse counting and turbine start and stop sequencing. The software is available at:
   https://github.com/ewandersonUCDavis/REnewALL/tree/master/turbineControllerSoftware

2) If you wish to edit the turbine-level controller software, you can do so with the Programmable XBee SDK.

3) Use the Programmable XBee SDK and Programmable XBee development kit to load the REnewALL_turbine_controller program onto the microprocessor of each XBee.

4) Download the turbine-level controller configuration profile. It is available at:
   https://github.com/ewandersonUCDavis/REnewALL/blob/master/meshNetworkConfigurationProfiles/turbine_XBee_config.xml

5) Open `turbine_XBee_config.xml` and locate the following lines. Update these lines by replacing the `#`s with the network ID (`ID`) of the mesh network, and the Serial Number Low (`SL`) of the XBee connected to the wind plant-level controller.

- `<setting command="ID">####</setting>`
- `<setting command="SL">########</setting>`

6) If your XBees are not using firmware version 8074 edit the following line, replacing `8074` with the correct firmware version.

- `<description_file>XBP9B_8074.xml</description_file>`

7) Save changes to the configuration profile.

8) Use XTCU to load the configuration profile `turbine_XBee_config.xml` onto each XBee and to write the AES Encryption Key (`KY`) of the mesh network to each XBee (The AES encryption key cannot be loaded via the configuration profile).

A.2 Instructions for setting up the XBee radio module for the wind plant-level controller

You will need the following hardware:

- One XBee-PRO 900HP radio module (does not need to be programmable)

- One XBee interface board with USB connection (such as a Programmable XBee Development board or an XBee Grove Dev Board).

You will need the following software:

- XTCU (available from digi.com)

You will also need:

- The firmware version of the XBee you are using.

- The network ID (ID) and AES Encryption Key (KY) of the mesh network.

1) Download the wind plant-level controller XBee configuration profile. It is available at:
   https://github.com/ewandersonUCDavis/REnewALL/blob/master/meshNetworkConfigurationProfiles/central_office_XBee_config.xml

2) If the XBee is not using firmware version 8074 open the configuration file and edit the following line, replacing `8074` with the correct firmware version.

   `<description_file>XBP9B_8074.xml</description_file>`

3) Use XTCU to load the configuration profile `central_office_XBee_config.xml` onto the XBee.

4) Use XTCU to write the Network ID (`ID`) and AES Encryption Key (`KY`) to the XBee.

A.3 Instructions for setting up the user interface on the wind plant-level controller

You will need the following hardware:

- One desktop computer with an XBee (the one configured in the section A.2) plugged in via USB cable.

You will need the following software installed on the desktop computer:

- ThingsBoard (available at thingsboard.io)

1) Log in to ThingsBoard using the tenant account.

2) Create a new Device and designate it as a gateway.

3) Record the Access Token of the gateway.

4) Perform the setup instructions in section A.4 before continuing with these instructions.

5) Running `gateway.py` has created two new ThingsBoard Devices for every turbine listed in `inputFile.txt`. For half of the new ThingsBoard devices, the device name will match entries in the `Turb_Name` column of `inputFile.txt`. For the other half of the new devices, the name will be the entries of `Turb_Name` followed by an underscore. For example: "`Turbine1`" and "`Turbine1_`"

6) Open each of the new ThingsBoard devices. If the device name has an underscore at the end set the Device type to "`turbine_`". If the device name does not have an underscore set the Device type to "`turbine`".

7) The dashboards and rule chains created for the REnewALL field test can be downloaded at https://github.com/ewandersonUCDavis/REnewALL/tree/master/thingsBoardFiles/Dashboards then imported to ThingsBoard. The Wind Plant Controller dashboard will automatically display data from all "`turbine`" type devices, while the Wind Plant Observer dashboard will automatically display data from all "`turbine_`" type devices.

8) Set up two ThingsBoard Customers. Name one "`Controller`" and give it ownership of the Wind Plant Controller dashboard and all "`turbine`" type devices. Name the other "`Observer`" and give it ownership of the Wind Plant Observer dashboard and all "`turbine_`" type devices.

9) Any user accounts you set up under the Controller customer will be able to monitor turbine behavior and remotely start and stop turbines. Any user accounts you set up under the Observer customer will be able to observe turbine behavior, but will not be able to start or stop turbines.

A.4 Instructions for setting up the communication gateway on the wind plant-level controller

You will need the following hardware:

- One desktop computer with an XBee (the one configured in the previous section) plugged in via USB cable.

You will need the following software installed on the desktop computer:

- Python 3

You will also need:

- The Latitude and Longitude of all turbines with turbine – level controllers

- An identifying name for all turbines on with turbine – level controllers

- The Serial Number Low (SL) of the XBee used in each turbine – level controller

- The access token of the ThingsBoard gateway Device.

1) The instructions in section A.3 must be started before these instructions.

2) Download the `gateway.py` and `inputFile.txt` files from
   https://github.com/ewandersonUCDavis/REnewALL/tree/master/communicationGateway

3) Open `inputFile.txt` and update the data inside to match the name, latitude, longitude, and serial number low of each turbine with a turbine–level controller.

4) Open `gateway.py` and update the following lines, replacing the #s with the name of the USB port the XBee is plugged into (the method of finding this will depend on which operating system your computer uses), a client ID, and the access token of the ThingsBoard gateway device (obtained while following instructions in section A.3).

```
localXBeePort = '##########' #this is the USB port that the XBee is plugged into.
mqttClientId    = "###########" #This can be anything, but you have to pick a unique Id…
mqttUserName    = "#############" #this is the access token for the Thingsboard…
```

5) Uncomment the following lines in `gateway.py` by removing the # at the beginning of each line.

```
#MQTT.publish(topicAttr,json.dumps({name:{'startButton':False}}), qos=1, retain=True) …
#MQTT.publish(topicAttr,json.dumps({name:{'stopButton':False}}), qos=1, retain=True)…
#genData[name] = {'day':time.localtime().tm_mday,'dailyGen':0,'month':time.local…
#with open('genBackupFile.txt', 'w') as fp:
# json.dump(genData, fp)
```

6) Use Python 3 to run `gateway.py`

7) Open `gateway.py` and comment out the lines mentioned in step 5 by replacing the #s at the beginning of each line.

APPENDIX B:
Workshop Participant List and Notes

Name	Company
Manfred Wendt	EWT Direct Wind
Kevin Cousineau	KLC Electronics
John Nemila	Green Energy Maintenance
Silvia Palma-Rojas	CA Energy Commission
Rizaldo Aldas	CA Energy Commission
David Partovi	
Bob Gates	Wind Stream Properties
Al Davies	Wind Stream Properties
Glenn Baumann	ZC Firm Energy
Ed Duggan	Alton Energy
Craig VanWagner	SCADA Solutions
Jeremiah Soto	Terra-Gen
Naomi Brown	Terra-Gen
Pete Levitt	Calwind
Doug Levitt	Calwind
Kevin Smith	DNV GL
Nellie Tong	DNV GL
Alex Byrne	DNV GL
Doug Blodgett	DNV GL
Steve Sultan	DNV GL
Case van Dam	UC Davis
Eric Anderson	UC Davis
Aubryn Cooperman	UC Davis
Kiran Iyer	UC Davis

Participants in the stakeholder workshop were divided into groups that rotated through five discussion stations. At each discussion station, members of the REnewALL team facilitated discussions focusing on five core questions that sought to elicit stakeholders' knowledge and experience and guide the project scope. The information that stakeholders shared at each station is summarized in the following five subsections. Facilitators attempted to capture and record all statements made by stakeholders. Opinions listed below are not necessarily held by all stakeholders or the REnewALL team.

Discussion station 1: What remote communication/control systems have been tried?

- A prototype remote dispatch system for 10 V15/V17 turbines, designed by SCADA Solutions, Inc., measures power, has remote start/stop capability, and allows monitoring and reset of faults. Communication takes place over a mesh network, but the cost of the radio components is too high for wider adoption of this system. The SCADA Solutions system has a main control computer in the O&M building that is sized to communicate with up to 80 turbines. No automated turbine dispatch capability is present – an operator is required to remotely start/stop turbines.

- A radio communication and remotely activated breaker de-energizes strings of turbines in response to system-critical California ISO requests. This system is not frequently used and is in place mainly for emergency situations on the grid. De-energizing turbines like this can be hard on the mechanical brakes and electrical systems.

- Several stakeholders believe low-cost communication systems should be the focus of the project.

- Communication options in wind plants include fiber, wired, and radio communication. Fiber is the most reliable, but is expensive to install in legacy wind projects. Underground copper wires are also expensive to install, existing wires are often broken, and copper wires are subject to damage due to lightning.

- Vestas V15 and V17 turbines were initially wired for curtailment, but the wired communication systems have broken or disconnected over time (by previous project owners) and are no longer functional.

- Some older turbines used a system called Secondwind ADAMS with proprietary CTMs. This was a 3rd party SCADA solution built to communicate with any turbine; however, the system cost approximately $2000 per turbine. Secondwind's ADAMS system is no longer available in the marketplace.

- Mesh networks have been demonstrated to work in the TWRA environment. Line of sight/UHF (Ultra High Frequency) communication systems have failed. SCADA Solutions Inc uses a mesh radio network and the system has been reliable.

- Stakeholders stated that Raspberry Pi modules will not withstand the environment due to highly variable/extreme temperatures, dust/dirt, etc.

- One stakeholder had experience with the Moxa and Ubiquity brands of radio communication devices. He stated that they are affordable and have been shown to

work in the relevant environment. It may be possible to integrate input/output capabilities.

- Existing met towers typically have internet connectivity and could be used as nodes when implementing a new communication system.

- Automatic on/off control of turbines might be acceptable in low wind, but more operator oversight would be required before turning on/off in high winds. Due to the legacy turbine technology, if not done properly, stopping a turbine in high winds could result in the turbine going into an over-speed condition (an unsafe and damaging situation).

- Turbine braking wears out brake components. Repeated turbine braking events have the potential to cause significant repair and maintenance costs, especially if braking events occur in high wind conditions. Braking in high winds causes much more wear than braking in low wind conditions.

- Some stakeholders stated that alternatives to turbine braking should be investigated. For example, yawing turbines out of the wind before braking.

- Instead of stopping turbines, it may be possible to use storage or on-site energy dissipation to keep from putting energy on the grid during negative pricing periods. Energy storage is expensive.

Discussion station 2: What functionality is required?

- The ability to remotely report turbine status, turbine production (real time and/or cumulative).

- The ability to remotely start/stop the turbine and to reset faults.

- The ability to set a non-zero price point for automatic on/off.

- The ability to establish turbine groups.

- The ability to use California ISO forecasts.

- The ability to de-energize the collection system and pad-mount transformers would be beneficial, though duty cycles do impact transformer life.

- A way to store or dissipate energy.

- A new or modified braking system that will avoid hard stops. For example, yaw first then brake. In high winds, a set of brake pads can only endure 5-6 hard stops. Maybe we could identify turbines in lower wind speeds and only stop those.

- If the on-turbine hardware loses communication, it should continue to operate based on its last instructions. However, if the on-turbine hardware fails the turbine should revert to its legacy controls.

- The ability to adjust system functionality, ranging from a bare bones system to one with more functionality.

- The ability to stop a turbine within 10 minutes, or ideally within 5. California ISO uses a 10-minute signal to request curtailment, but they would like to go to a 5-minute signal in the future.

- The ability to ramp production up/down through selective turbine-by-turbine starts/stops. Operators often have many types of turbines. Consider optimizing curtailment based on which turbines are easiest and/or least damaging to shut down.

- Communication with each turbine at least once every 5 minutes.

- Data to support demand analysis. We need to be able to identify where the losses are coming from to quantify potential gains.

- Standby costs are larger than negative pricing costs for some wind projects.

Discussion station 3: What are the important Budget and O&M factors?

- Hardware costs per turbine (final cost to owners) should be $200-$250 maximum.

- Installation labor per turbine should be 4-6 hours maximum. If installation labor is low enough it may not lead to additional owner-operator costs. Existing technicians, who are already included in the annual budget, may be able to install the system.

- There should be no cost to turn off a turbine, especially in low wind. It may even reduce energy consumption if that turbine would otherwise be energized.

- Curtailment in high wind will lead to brake wear, which leads to repair costs. Each brake pad costs approximately $100 and replacing a set of pads requires 1-2 hours of labor.

- Some stakeholders stated that the payback period should be less than one year, but others stated that a payback of two to three years would be acceptable. Ultimately, the acceptable payback period will be influenced by site specific factors, such as how long the owner/operators plan to keep the legacy turbines in operation.

- Upgrading a wind plant in chunks (e.g., 50 turbines at a time) may be more financially viable than upgrading the entire wind plant at the same time.

- Are there opportunities for multiple projects to coordinate equipment orders and benefit from bulk pricing? How many legacy turbines in California are likely to adopt remote dispatch systems?

- A remote communication and control system was installed on a small number of turbines as a proof of concept demonstrations and has been functioning for 2-5 years. However, the cost of that system was approximately $1,000 per turbine, which was too much to justify wider deployment.

- Wind plants must buy electricity at significantly higher prices than they can sell electricity. Therefore, anything we can do to reduce/eliminate standby power consumption has the potential to make a significant impact.

- Stakeholders identified Micon 700, Vestas V15/V17, and Nordtank 75 wind turbines as candidates that we should consider for our demonstration project.

Discussion station 4: What field conditions and environmental limitations will we face?

- No one will use this system if it is too expensive.

- The system should be ruggedized, serviceable, reliable, maintainable and repairable.

- The system needs to fail safely. If power fails, if the network goes down or if any other failures occur the system must not create an unsafe situation.

- The system must not add fire or arc hazards.

- If radio communications are used, terrain may be a limiting factor. Complex terrain may limit line of sight to turbines, which can limit communication. Distances may also be limiting factors.

- This is a harsh environment. Equipment may be subjected to UV exposure, vibration, extreme temperatures (both hot and cold), dirt, dust, animals, humidity, rain, snow, and power transients.

- There may be other RF (radio frequency) communications at the site. Some stakeholders expressed concern that existing RF sources may interfere with our signals.

- Existing power lines could be used to carry signals.

- Most turbine control boxes have 24V power. It may be possible to use that power supply for our system.

- The turbine control boxes have relay-based controls.

- Our system must have good transient protection to interface with existing power and controls.

- We need to identify the exact point in the existing system to effect turn-on/turn-off.

- Physical size, cooling/airflow needs, and hardware mounting may be design limitations.

- The 24V power available at the turbine is low quality and has transients, which can be damaging to data storage devices. Data storage, if needed by the turbine control module, will need to have suitable power and protection provided.

- Our system must be adaptable to work across many different legacy turbine types.

Discussion station 5: What level of data transmission/status is required/desired?

- Several stakeholders stated that turbine status is the most important information to transmit (on/off, brake status, faults).

- Some measure of power output would be useful. Power output of individual turbines, groups of turbines, or the whole plant could be useful.

- Existing electric meters are analog, but meter pulses can be counted to measure power.

- Several stakeholders expressed concerns about mission creep. They stated that we should always be conscious of the tradeoffs between added functionality and cost.

- Some stakeholders wanted the system to be autonomous, while others wanted to have a human in the loop. Maybe our system could allow both options.

- Consider implementing operator text notifications (e.g., turbine X has fault Y, a negative pricing event will happen soon, etc.)

- Some stakeholders wanted communication with each turbine to happen at least every 5 minutes. Other stakeholders wanted communication at least once per minute. (Negative pricing is in 15-minute blocks.)

- Some sites have California ISO authorized rigs that measure instant and cumulative power for groups of turbines. This data is communicated to a central office at the site and is sent to operators over the web.

- Some stakeholders noted that scheduling coordinators may be interested in the information gathered by our system. It would be useful if we could make the data available to anyone who needs it.

- One stakeholder stated that using 24V turbine power and protecting our electronics from transients is probably less troublesome that using a solar panel and battery to power our system.