Feasibility study on the installation of grid-scale energy storage at the 220 kV Jhimpir-II Grid Station

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Contents

Executive Summary

The *Jhimpir-2* substation will provide power evacuation of 810 MW from sixteen wind power plant projects. Power flow analysis reveals that power evacuation will at times need to be capped as low as 70% of installed capacity.

An Energy Storage would deliver multiple benefits such as (a) accrued savings from storing and later dispatching energy that would otherwise simply be curtailed, (b) reduced forecasting errors resulting in better day-ahead and hour-ahead dispatch, and (c) delivering ancillary services such as frequency and voltage control.

Various energy storage solutions are examined and the lithium-ion Battery Energy Storage Solution (BESS) is recommended due to its high energy density, small footprint and widespread usage in grid-scale applications.

An economic dispatch model optimizes the dispatch plan against a full year's worth of hourly wind power data amidst probabilistically occurring transmission grid outage events. The model estimates the amount of energy saved under different power-to-storage configurations. A cost-benefit analysis is conducted for both high-power and high-energy BESS configurations.

The "levelized annual cost of storage" is used as the financial metric for cost-benefit analysis of a Pilot project. This KPI is appropriate as NEPRA issues cost-plus tariffs. The resultant prices can be used as a reference when the regulator sets tariffs in the future for commercial projects.

Project justification

Identify the technical benefit, such as short-term (by minute) and long-term (hourly) power regulation capability as well as voltage regulation capability.

- An energy storage solution (ESS) with its own power converters provides two benefits –
  - Firstly, it can provide both active and reactive power support to help with system stability. Additional reactive power support can be provided by deploying a Static Synchronous Compensator as part of an ESS-STATCOM hybrid solution.
  - Secondly, the energy storage provides the system operator with the ability to dispatch up to 810 MW of wind power – smoothening out the natural variations in wind power thereby reducing the forecast error on a short-term basis. The day-ahead dispatch algorithm can then reliably dispatch the expected generation (as a function of the storage level) on an hourly basis.
- The ESS is a key enabler that allows for dispatching of distributed energy assets[1] as a single dispatch-able asset. In the view of a Dispatcher, he can treat the entire asset group spread across the electrical power system as a single *virtual* power plant (VPP), one of the most promising technologies of the Smart Grid.
  - Using the VPP aggregation and tele-control (SCADA) system, the Dispatcher in NPCC no longer has the need to monitor and control twenty or so wind farms. Instead the Dispatcher can dispatch all the wind farms coupled to Jhimpir-2 as a single dispatch unit that delivers 100 MW power and contains up to 200 MWh of energy.
  - With this dispatch tool in place, the Dispatcher can monitor and control large volumes of power flow in the extra-high voltage network using set-point instruction whilst delegating curtailment and voltage control of individual wind farms to the VPP.
  - The VPP approach to managing wind farms has proven successful in both the UK and Germany, two energy markets in which balance responsible parties trade large volumes of wind power on the day-ahead and intraday markets.

Assess the benefit if the storage is connected to SCADA's load frequency control (LFC) function.

- With the addition a power electronics-interfaced energy storage, the Jhimpir-2 substation can participate in Frequency Response. The Enhanced Frequency Response (EFR) auction[2] was oversubscribed six times and the tender winners were predominantly battery energy storage solutions (BESS) as few other energy assets can meet the stringent sub-second response time criteria. A similar solution could provide NPCC with an extremely fast responding asset for primary frequency control across the entire NTDC transmission network.

[1] Loads, distributed generators and storage assets

[2] 2016, United Kingdom: The year-long auction process secured 201 MW of capacity at prices between £7 and £11.97/MW/hour, at a total cost of £65.95 million over the 4 years. The deployment of EFR, with a sub-second response time, will provide NG with greater control over frequency deviations, resulting in potential cost savings of £200 million.

Estimate the cost-effectiveness quantitatively, and compare it with that of the case without the storage system where the similar benefit can be obtained from the resilience of the entire transmission grid.

- With two revenue streams, i.e. frequency control and savings from reduced curtailments, the levelized annual cost of storage in Jhimpir comes out at 205 $/MWh.
- The power flow model shows that wind power generation up to 90% of installed capacity can be safely evacuated from Jhimpir-2 if thermal generation is operating at minimum run levels. However, the transmission network is not resilient enough to evacuate any more wind power than 70% of installed capacity when thermal generation in the South is operating at full.

Compare the benefit with the case where the storage is installed at WPP sites, where reactive power compensation effect (or voltage regulation capability) is expected more.

- Smaller scale energy storages could also be installed at WPP sites to deliver frequency control in compliance with NTDC's "Grid Code Addendum for Grid Integration of Wind Power Plants" that was released in August 2017. However, the difficulty in this case would be coordinating the response times and durations of the various storage assets. It would be much simpler to have a single ESS asset connected at the main grid interconnection point from a power systems control perspective[3].

Evaluate the validity of the project as well as the risk of not having the storage at Jhimpir-II grid station.

- With an ESS in place:
  - The curtailed wind energy could be stored and fed into the transmission network at a later time when power evacuation capacity became available.
  - WPPs could become Grid Code compliant without having to make major investments of their own such as STATCOMS in order to provide voltage set-point control as mandated by the GC[4].
  - Improved fault management as voltage support from the ESS would help wind turbines get back to full power output after the mandatory low voltage ride-through (LVRT) period that only lasts for three seconds after a fault.
- Without an ESS:
  - Clean energy that must be paid for under the PPA even if it is not used would be curtailed. This would need to be added to consumer tariffs as a curtailment surcharge.
  - Less net energy would be delivered than the benchmark given in the PPA because the WPP has to maintain active spinning reserve[5] as mandated by the Grid Code.

[3] Section 7.4-b: A minimum Ramp Rate of 10% of plant available power per minute subject to availability of wind speed

[4] Section 8.2 (Reactive Power): A WPP shall manage at the point of interconnection the reactive power control within the set-points of Qmin and Qmax as Per Unit of full output of plant, where Qmin/Qmax = -0.33 p.u./+0.33 p.u. of full output

[5] Section 7.3: WPPs of sizes of 49 MW and above should have the technical capability for primary and secondary control and contribute to frequency stabilization by maintaining appropriate active spinning reserve in proportion to available power of plant dependent on availability of wind speed.

The economic cost of wind power curtailments

By 2016, six utility-scale WPPs with a total installed capacity of 306.4 MW were operational[6] in Pakistan. However, wind power curtailment has been a persistent occurrence. In just one recent month (April of 2017), FFC WPP reported curtailment commands by NPCC during 48 hours. This resulted in 4,282 MWh of lost energy. Net energy delivered was 34% compared to the April delivery benchmark of 36.7%. Based on a tariff of 140 $/MWh, the cost to consumers for energy not delivered was $599,480.

The figure for total energy curtailed in 2016 is not available. However, based on the curtailment information received from FFC, it would be reasonable to assume that annual curtailments would be at least 2% in the best-case scenario.

Table 1: Expected best-case economic cost of wind power curtailments from six WPPs in 2017

Wind Farm Installed Capacity	Annual energy curtailed	Economic Cost
306.4 MW	53,681.28 MWh (2%)	$7,515,379

To put this in perspective, German wind power curtailments in 2014 were also close to 2%, but from wind power generation of 55,970 GWh compared to 646 GWh in Pakistan.

Table 2: Wind power generation in selected European countries in 2014 compared to Pakistan in 2016

Country	Denmark	Germany	Spain	Ireland	Italy	Pakistan
Total wind power capacity installed (MW)	4855	40456	22845	2230	8700	306.4
Total wind generation (GWh)	13,100	55,970	50,742	5,058	14,966	646[7]
Wind curtailment (GWh)	26.2	1,217.37	-	230	121	-
Wind capacity factor (%)	31%	15.8%	25.4%	26%	19.6%	31%
Curtailment as a percentage of total wind generation (%)	0.2%	2.18%	<1.5%	4.3%	0.8%	-
Cost of Renewable energy curtailments	-	€83 million	-	-	-	-
Sources: Bundes Netz Agentur, German TSOs, Terna, REE, Energinet.dk, EDF, Eirgrid, NTDC (Power System Statistics 2015-2016)						

[6] NTDC Power System Statistics 2015-2016 page 6: Zorlu (56.4 MW), FFC (50 MW), China Three Gorges (50 MW), Sapphire (50 MW), Foundation 1&2 (100 MW)

[7] NTDC Power System Statistics 2015-2016 page 13: Energy Generation by Source

Reasons for wind power curtailment during present-day operations

Frequency

Large deviations in the system frequency (typically 0.8 Hz) will trigger over or under-frequency relays, leading to generator tripping (over frequency) or load shedding (under frequency). Frequency deviations are caused by an imbalance in the aggregate supply and aggregate demand of active power across the entire power system. The maximum amount of wind power entering the system is presently 600 MW, which is only 2.4% of peak demand of 25,000 MW. Therefore the effect of wind power generation on the system frequency is negligible and is not a reason for curtailment of wind farms.

Voltage

The Grid Code limits voltage variation on the transmission system to between 108% (max) and 95% (min) of nominal value during normal operations. Voltage (in the HV and EHV networks) is controlled by regulating flows of reactive power, measured in units of Volt-Ampere-Reactive (VAR). VAR control provides a number of benefits to the system such as controlling the voltage profile along a transmission line, damping power system oscillations, averting damage to rotating machinery, increasing power transfer capability, and potentially improving stability.

Wind turbines based on doubly-fed induction generator (DFIG) technology have been predominantly used globally in the last decade and the wind turbines installed in Jhimpir are also of this type. DFIG wind turbines can generate or consume reactive power independently of active power production. The requirement for remote VAR control of wind turbines by the Transmission System Operator exists in the Grid Code. However, the capacity for real time monitoring and control of wind farms does not currently exist at NPCC, not least due to the lack of a properly functioning SCADA system.

Voltage stability can be a big problem in weak (non-stiff) power grids such as is the case of Pakistan. This is further extenuated by large-scale bulk power transfers that can cause large reversals in reactive power flow. As the transmission grid has only a limited capability to allow large-scale wide area power transfers, large forecast errors in wind power production can impact voltage stability. Insufficient reactive power can lead to voltage collapse which can cascade into a system-wide blackout.

However, as voltage stability is a complicated topic, detailed information needs to be gathered from NPCC and further power flow analysis is required before any meaningful conclusions can be made with respect to voltage-related events as a cause of wind power curtailment.

Network Congestion

Curtailments, as well as load shedding for that matter, can come about due to reasons other than imbalances in active and/or reactive power.

Network congestion is a major problem in the greater Jhimpir region as some lines such as *Thatta-Jhimpir* have low thermal limits (0.49 kA). Furthermore, as these lines are well over fifty years old, NPCC has de-rated the lines by up to 50%. Therefore network congestion and breaches of thermal limits on such transmission lines requires wind generation to be curtailed.

Use Cases for Energy Storage

The storage of electrical energy is typically categorized based on the intended function—to provide power or to provide energy. Although certain storage technologies can be used for applications in both categories, most technologies are nether practical nor economical for both power and energy applications. In general, energy applications involve (relatively) long-duration discharge and power applications involve short duration discharge.

Power use cases

1. Frequency regulation – batteries and flywheels can delivery *enhanced* frequency reserve[8]. This can help stabilize system frequency until primary reserve from automatic generator control (AGC) kicks in. Frequency regulation also improves frequency ride-through capabilities of the wind farms so that the net effect is amplified
2. Voltage stability – minimize voltage fluctuation due to active power variations caused by wind variations as well as provide voltage support during faults to help wind farms with low voltage ride-through
3. Black-start capability – a DC power source such as a battery is usually used to start small generators and energize power lines before larger power stations can be started and synchronized with the grid
4. Capacity Firming – smooth the power output and control the ramp rate to eliminate rapid voltage and power swings created by intermittent power output from renewables, such as solar and wind.

Energy use cases

1. Load following – the output of fast modulating (ramping) power plants such as hydro or CCGT is frequently changed in order to respond to the changing balance between electric supply and load within a specific region or area. As fast ramping power plants are scarce in the NTDC system, energy storage can provide the same, with better efficiency and near-instantaneous response times
2. Energy arbitrage – shave generation and/or demand peaks and fill in the troughs for loads and generators. The unused energy can be utilized later when the wind stops blowing or when transmission capacity is available
3. Congestion management – ease congestion in transmission networks by temporarily absorbing surges and excess power flow, allowing deferral of expensive network expansion

[8] Enhanced frequency response is defined by the UK's National Grid Electricity Transmission as being a service that achieves 100% active power output at 1 second (or less) of registering a frequency deviation

Grid-scale energy storage applications by technology type

Application	Description	CAES	Pumped Hydro	Flywheels	Lead-Acid	NaS	Li-ion	Flow Batteries
Off-to-on peak intermittent shifting and firming	Charge at the site of off peak renewable and/ or intermittent energy sources; discharge energy into the grid during on peak periods	◑	◑	○	●	●	●	●
On-peak intermittent energy smoothing and shaping	Charge/discharge seconds to minutes to smooth intermittent generation and/or charge/discharge minutes to hours to shape energy profile	○	◑	◑	●	●	●	●
Ancillary service provision	Provide ancillary service capacity in day ahead markets and respond to ISO signaling in real time	◑	◑	◑	◑	◑	◑	◑
Black start provision	Unit sits fully charged, discharging when black start capability is required	◑	◑	○	●	●	●	●
Transmission infrastructure	Use an energy storage device to defer upgrades in transmission	○	○	○	●	●	●	●
Distribution infrastructure	Use an energy storage device to defer upgrades in distribution	○	○	○	●	●	●	●
Transportable distribution-level outage mitigation	Use a transportable storage unit to provide supplemental power to end users during outages due to short term distribution overload situations	○	○	○	◑	●	●	●
Peak load shifting downstream of distribution system	Charge device during off peak downstream of the distribution system (below secondary transformer); discharge during 2-4 hour daily peek	○	○	○	●	●	●	●
Intermittent distributed generation integration	Charge/Discharge device to balance local energy use with generation. Sited between the distributed and generation and distribution grid to defer otherwise necessary distribution infrastructure upgrades	○	○	○	●	◑	◑	◑
End-user time-of-use rate optimization	Charge device when retail TOU prices are low and discharge when prices are high	◑	◑	○	◑	◑	◑	◑
Uninterruptible power supply	End user deploys energy storage to improve power quality and /or provide back up power during outages	○	○	◑	●	●	●	●
Micro grid formation	Energy storage is deployed in conjunction with local generation to separate from the grid, creating an islanded micro-grid	○	○	○	●	●	●	●

Definite suitability for application ● ; Possible use for application ◑ ; Unsuitable for application ○

Source: Grid Energy Storage, U.S. Department of Energy, December 2013, page 29

Use Cases appropriate for Jhimpir and modelled in this Study

Energy Storage Use Case

The rationale for energy storage is based on reduction of forecast errors / smoothening of variable power generation as well as reducing curtailments due to network problems. The reduction in unserved energy from storing curtailed energy has been provided in the section entitled “Monte Carlo Simulation Results”.

Frequency Regulation Use Case

Frequency regulation is presently carried out primarily through load shedding as NPCC does not maintain sufficient spinning reserves or operational reserves even though section 5.2 of the Grid Code defines *minimum* levels for Contingency Reserve (at least equal to the largest thermal generator in the system) and Spinning Reserve (equal to one third of the largest generator in the system).

Table 3: Expected minimum reserves needed as per generation coming online

Spot Year	Largest Thermal Generator	Contingency Reserve	Largest Generator	Spinning Reserve
2016/17	365 MW (AES Pak Gen)	365 MW	432 MW (Tarbela)	144 MW
2017/18	689 MW (Sahiwal)	689 MW	689 MW (Sahiwal)	230 MW

From NPCC’s point-of-view, it is far easier (and cheaper) to disconnect loads (VOLL[9] is zero) since the only power plants that are presently capable of providing Spinning Reserve are the hydro power plants such as *Tarbela*. However, these plants are operated as “must-run” due to the low-cost of hydro generation.

BESS are very well suited to providing frequency response[10]. The “NTDC Grid Code Addendum No. 1 (Revision 1) for Grid Integration of Wind Power Plants” in section 7 lists the rules for Frequency Response for WPPs with capacity greater than 49 MW. This rule applies to all the WPPs connected to Jhimpir-2.

Specifically, Section 7-3 states:

- “For under-frequency dips when frequency enters “Tolerance Frequency Band”, with lower range defined as 49.5 Hz according to OC 4.8.1 (c, iii) of the Grid Code, the Grid-connected Wind Power Plants of sizes of 49 MW and above should have the technical capability for primary and secondary control and contribute to frequency stabilization by maintaining appropriate active

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[9] Value of Lost Load (VOLL) is set at 18,000 GBP/MWh in the UK

[10] The 2016 tender for Enhanced Frequency Response by UK’s National Grid Electricity Transmission plc was almost entirely allocated to BESS due to their fast response times which met the EFR response time criteria of full power in less than 1 second.

spinning reserve in proportion to available power of Plant dependent on availability of wind speed”

In order to provide Frequency Response during under-frequency dips a WPP would have to reduce its active power production below the maximum possible generation at all times. For example, a 50 MW WPP would either have to have its own 8-10 MWh energy storage facility or under-produce by 10% (15,330 MWh per year) in order to keep 10% of generation as “appropriate active spinning reserve in proportion to available power of Plant dependent on availability of wind speed”.

Instead, each WPP could delegate the requirement of “primary and secondary control” to an external central BESS controlled by the same virtual power plant (VPP) that also controls the 810 MW of wind power capacity connected to the Jhimpir-2 substation. The WPPs would pay the BESS to provide Frequency Response on their behalf.

Grid-scale Energy Storage Technologies

Batteries

There are two types of batteries that are used for energy storage – flow batteries and solid state batteries. Both are capable of changing their output in less than one second. Batteries are already being in various grid-scale applications including peak shaving and frequency regulation.

Flow batteries: while a conventional battery houses energy in one cell or package, a flow battery stores its energy in chemically reactive liquids, held in two tanks separate from the actual battery cell. The system pumps the two liquids from the tanks into a cell where a chemical reaction releases electrons that supply power onto the grid. To recharge the battery, the flow is reversed: electricity produced on the grid is channeled into the cell, breaks the chemical bond and pumps the liquids back to their respective tanks. This technology is scalable as larger tanks can store and provide more energy.

Solid state: solid state (lithium ion, nickel-cadmium, sodium sulfur) batteries are typically used today to charge laptops, cell phones and other devices. Unlike flow batteries, solid state batteries are divided into two sides by a perforated layer called an electrolyte. As the battery charges, chemical ions move through the electrolyte from the positive to the negative and from the negative to the positive electrode as the battery discharges.

Flywheels (also known as Kinetic Energy Storage Systems-KESS)

Flywheels can both store and quickly release energy as needed. Flywheels use a rotor placed within in a vacuum to store and then discharge kinetic energy. The roundtrip efficiency of flywheel modules is in the 80–85% range. During the power exchange the efficiency is relatively high, and it depends on the type of electric machine used. However, the time on standby (no power exchange) affects very much this value depending on the aerodynamic friction. Although flywheels are being installed for grid-scale applications, the technology is not as mature as batteries.

Compressed Air

Compressed air energy storage (CAES) uses electricity to compress air into a reservoir where it is stored at high pressure. When it's needed, the compressed air is expanded through a gas turbine with additional burn. Although the technology is relatively mature, with two CAES plants have been built and in use for years (in Germany and the USA), the technology has not yet been widely adopted. The lack of a suitable reservoir such as depleted gas well in the Jhimpir region renders this technology unsuitable for this project.

Power-to-Gas (Hydrogen)

Power-to-Gas is a hybrid solution which converts electricity to hydrogen through an electrolyser. The hydrogen can be injected into the SSGC gas grid or stored in a tank for reconversion to electricity using a hydrogen fuel cell. Unfortunately P2G has a very low roundtrip efficiency (less than 30%) and the requirement of water for electrolysis renders this technology unfit for the Jhimpir area.

A comparison of different storage technologies and the suitability for power and energy application is provided in the table below.

Table 9.1 BESS applications by category (power or energy) [Electricity Storage Association and Sandia National Laboratories 2010]

Technology	Advantage	Disadvantage	Power applications	Energy applications
Flywheels	High power	Low energy density	Fully capable and reasonable	N/A
Electrochemical capacitors (ECs)	Long cycle life	Very low energy density	Fully capable and reasonable	N/A
Traditional Lead-acid	Low capital cost	Limited cycle life	Fully capable and reasonable	Feasible but not practical
Advanced lead-acid with carbon-enhanced electrodes	Low capital cost	Low energy density	Fully capable and reasonable	Fully capable and reasonable
Sodium sulfur (Na/S)	High power and energy density	High cost and restrictive operating parameters (high-temperature operation)	Fully capable and reasonable	Fully capable and reasonable
Lithium-ion (Li-ion)	High power and energy density	High cost and extensive control circuitry	Fully capable and reasonable	Reasonable
Zinc bromine (Zn/Br)	Independent power and energy	Medium energy density	Reasonable	Fully capable and reasonable
Vanadium redox	Independent power and energy	Medium energy density	Reasonable	Fully capable and reasonable
CAES	High energy, low cost	Special site requirements	N/A	Fully capable and reasonable
Pumped hydro	High energy, low cost	Special site requirements	N/A	Fully capable and reasonable

Electricity Storage Association and Sandia National Laboratories 2011, Technology Comparison Chart, 2010, accessed July 2011. http://www.electricitystorage.org/images/uploads/static_content/technology/technology_resources/comparison_large.gif

Battery Energy Storage Systems (BESS)

Battery energy storage is a versatile technology that offers advantages for both power and energy applications by selecting from a variety anode and cathode materials to meet the needs of the specific application. The choice of battery chemistry depends on the application (power or energy), the depth of discharge and the number of charge/discharge cycles per year. Short-duration discharge (such as for frequency regulation) can be from a few hundred milliseconds up to about 15 minutes, depending on the application. In general, frequent discharge of short duration storage implies hundreds of discharges over the course of a year.

As an energy source, a BESS has electrical characteristics that are quite different from a traditional, mechanical generator which with a rotating mass that has a finite ramp rate. The absence of inertia allows the BESS to respond to load fluctuations orders of magnitude faster than any engine or combustion turbine in an electric power system. However, BESSs are limited in their available energy depending on their state of charge (SOC) at any given point in time. Practical size considerations and inherent characteristics of most battery chemistries generally limit the maximum energy storage times to between two and six hours for deep discharges.

Generally, an application that requires a shallow discharge or a series of shallow charge/discharge cycles over a sustained period can be successfully combined with a deep discharge application, as long as controls are in place to reserve the capacity needed for the deep discharge as and when needed. This is the case for the frequency regulation application combined with the deep discharge required for spinning reserve application. In this case there is a control to ensure that the frequency regulation duty does not push the battery below a set SOC, such as the 70–75 % SOC level for lead-acid batteries. Thus, the remaining energy capacity of the battery is always available as spinning reserve, as required by any spinning reserve duty source.

Chemistry

An optimized battery solution for an application is developed by balancing the choice of cell chemistry and internal cell design with the battery design (e.g., how the cells are interconnected).

In the case of the high-temperature batteries, the intrinsic material characteristics such as the melting point of the sodium metal anode necessitate high temperature operation, which in turn imposes operational constraints on the batteries. Since the battery inefficiencies and the associated heating during charge and discharge provided some of the energy necessary for maintaining operational temperature, those applications that require continuous charging and discharging are best suited for these chemistries.

In the case of flow batteries, the active electrode materials are generally liquids, and these are held in separate storage reservoirs and pumped through the electrochemical cell during charge and discharge. Since the storage reservoirs can be resized independently from the electrodes and cell stack, the energy and power of these battery chemistries can be independently controlled, unlike virtually every other battery chemistry having fixed cell geometry with a single compartment for both the active materials and electrodes.

Another chemistry that is gathering momentum is Zinc-Air. The technology is well suited to energy applications such as storage of wind power during times of insufficient power evacuation capacity. Zinc-air pioneer, Fluidic Energy, claims that zinc-air battery life is independent of temperature (0-50 degrees centigrade), humidity, number of cycles (charging and discharging), or nature of discharge (i.e., battery continues to operate at high efficiency even when repeatedly fully discharged). While less suited to power applications, Fluidic-Energy offers zinc-air / lithium-ion hybrid solutions in such cases. Another advantage of zinc air batteries is that they do not contain toxic components and are 100% recyclable.

Power Electronics

Two power electronic-based control systems are used in the BESS – the power conversion system (PCS) and the battery management system (BMS).

The PCS provides bidirectional power transfer from the grid to the battery and vice versa. The power converter will act as an inverter to transmit power from DC to AC, and it acts as a rectifier to transmit power from AC to DC. Power conversion in the PCS is accomplished using high-power switching circuits that can synthesize the sinusoidal currents or voltages at the fixed frequency needed on the AC side (e.g. 50 Hz.).

The BMS monitors the condition of the batteries, aids in balancing batteries during charge/discharge, and communicates critical information to the PCS. Monitoring is done using measurements of cell temperature, voltage, and current. The BMS can estimate the battery SOC or state-of-health (SOH) by using these measurements and information such as the battery age and the number of charge/discharge cycles. The BMS may also protect the battery by disconnecting it from the PCS in the event of an over voltage, under voltage, over temperature, or over current. The BMS may also include a thermal management or active cooling system, which will be essential for Jhimpir, where the temperature is quite often above 40 degrees Celsius.

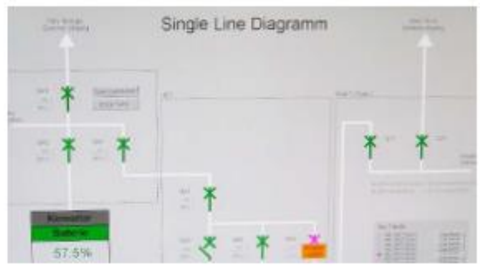
State of Charge (SOC)

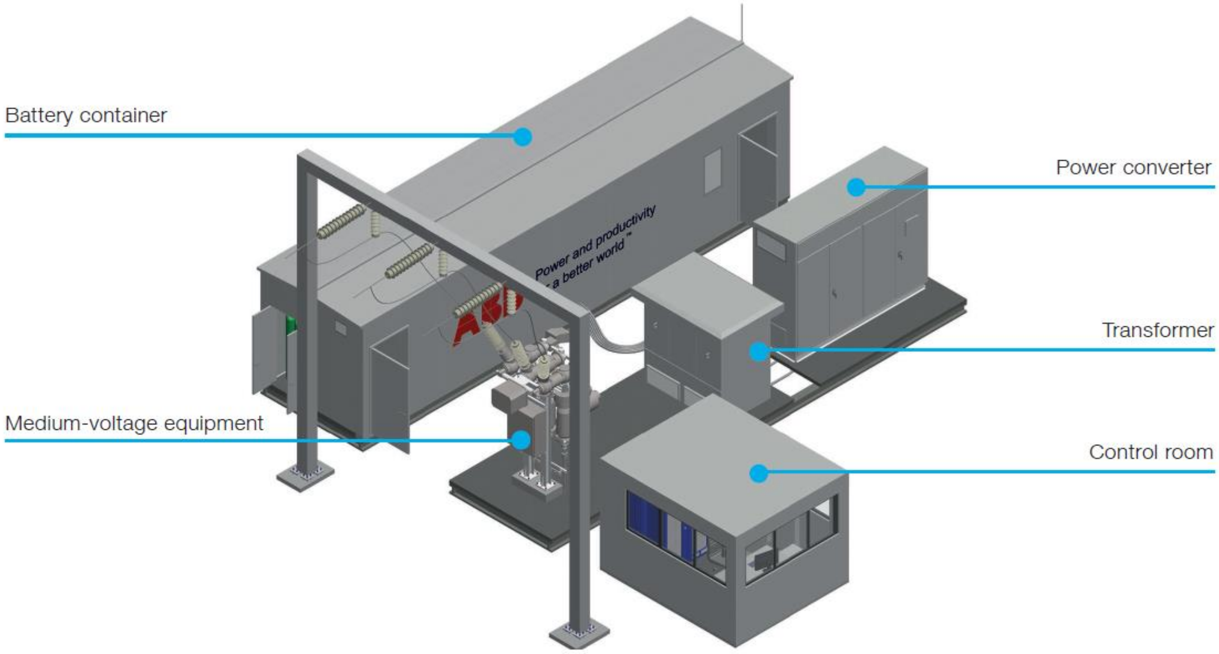
The battery SOC is not directly measurable. Instead, an estimate of SOC is calculated by continuously monitoring battery current, voltage, and other parameters, such as internal pressure or electrolyte acidity. It is assumed that the battery SOC is primarily a function of the charge/discharge schedule but it is also affected by time or battery temperature.

Sample layout of a grid-scale BESS

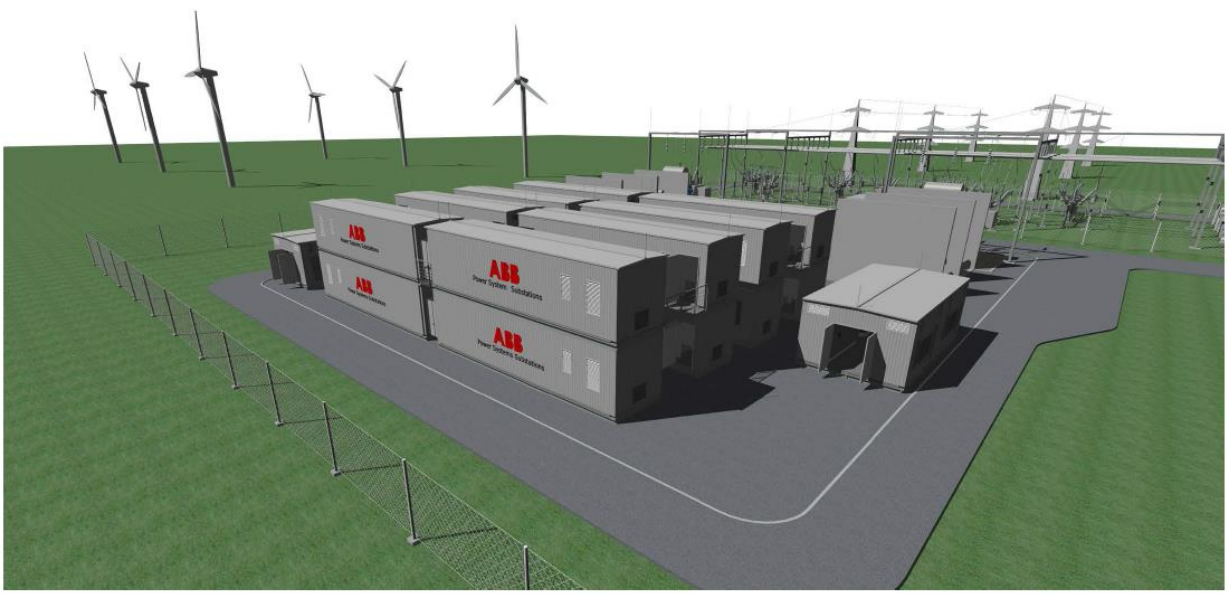
ABB's *EssPro Grid* is a battery energy storage system that can be used in projects ranging from hundreds of kilowatts to tens of megawatts. It can be used for a range of applications such as frequency regulation, spinning reserve, capacity firming, peak shaving, power quality, uninterruptable power supply, load levelling and voltage support.

BESS components

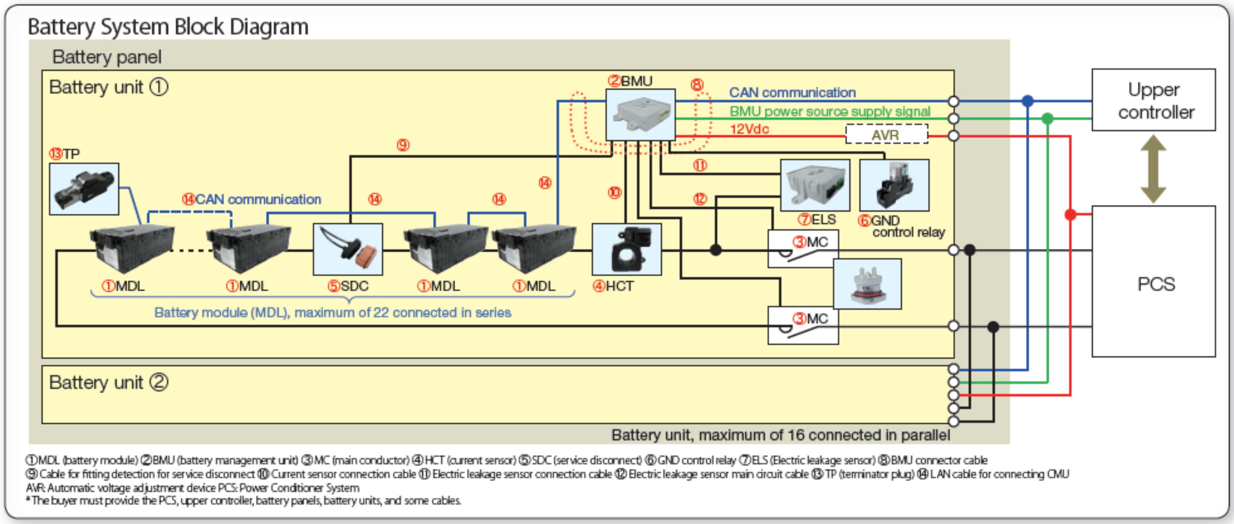
Power Converter 	Control System 
Protection Equipment 	Switchgear 
Transformers 	Batteries  



Example of a 1 MW, 15 min. EssPro Grid layout



Example of a 20 MW, 60 min. EssPro Grid layout



Source: Toshiba

Technical comparison of various battery chemistries

Zinc-Air

The pioneer of this technology, Fluidic Energy, claims that their "Zinc-Air based energy storage platform has substantial raw material cost advantages over lead acid batteries (1/4th the cost) and lithium ion batteries (1/17th the cost)". Fluidic Energy is already working with the Asian Development Bank in Indonesia where it is supplying batteries to a mini-grid project[11].

Lithium-ion

A variety of materials are used for the battery cathodes, e.g. iron phosphate (LFP), Manganese oxide (LMO), Cobalt oxide (LCO), Nickel cobalt aluminum (NCA) and Nickel manganese cobalt (NMC), and the anodes, e.g. graphite or Titanium oxide (LTO).

Table 4: Lithium-ion battery chemistries

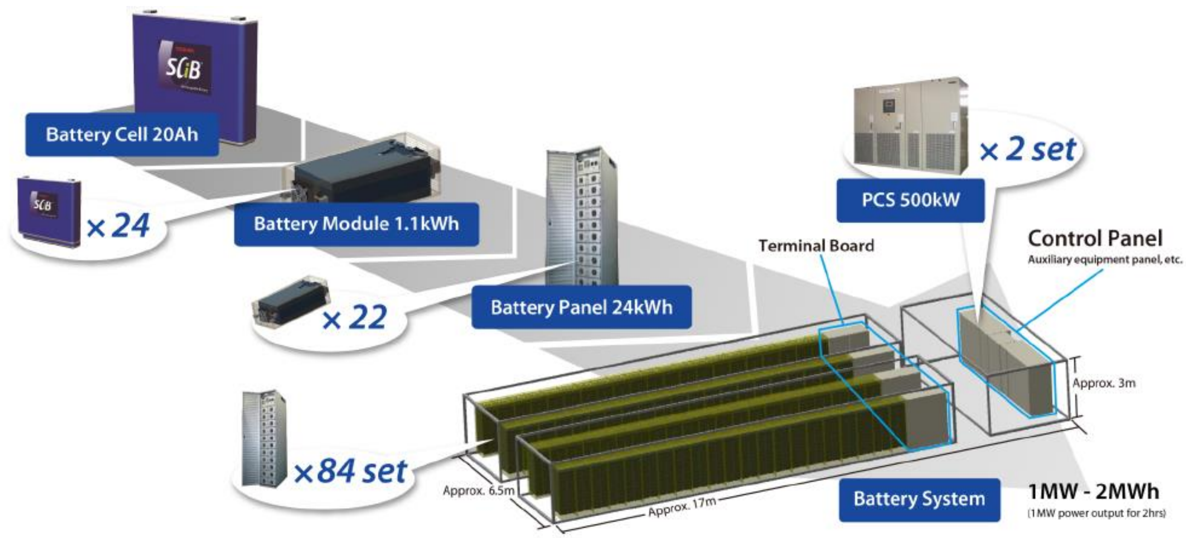
Cathode	**Anode**	**Energy Density (Wh/kg)**	**Number of cycles**
LFP	Graphite	85-105	200-2,000
LMO	Graphite	140-180	800-2,000
LMO	LTO	80-95	2,000-25,000
LCO	Graphite	140-200	300-800
NCA	Graphite	120-160	800-5,000
NMC	Graphite, Silicone	120-140	800-2,000

Source: IRENA, Battery storage for renewables: market status and technology outlook, January 2015

One of the most promising lithium ion batteries for grid-scale applications uses Manganese oxide (LMO) in the cathode and Titanium oxide (LTO) in the anode. While the energy density is lower than other lithium ion chemistries, the increase in 100% depth-of-discharge cycles is significant.

[11] https://www.adb.org/projects/50227-001/main

Toshiba's "SCiB" cells are an example of a Lithium-Titanate-Oxide (LTO) battery, with the anode made up of LTO nanocrystals. The cells are well suited to high power applications such as frequency response due to a fast charge/discharge rate (6 minutes to reach 80% State of Charge level) and long life (recovery capacity remains around 90% after 10,000 cycles).



SCiB cell stacking to form a grid-scale BESS [Source: Toshiba]

Sodium-Sulphur

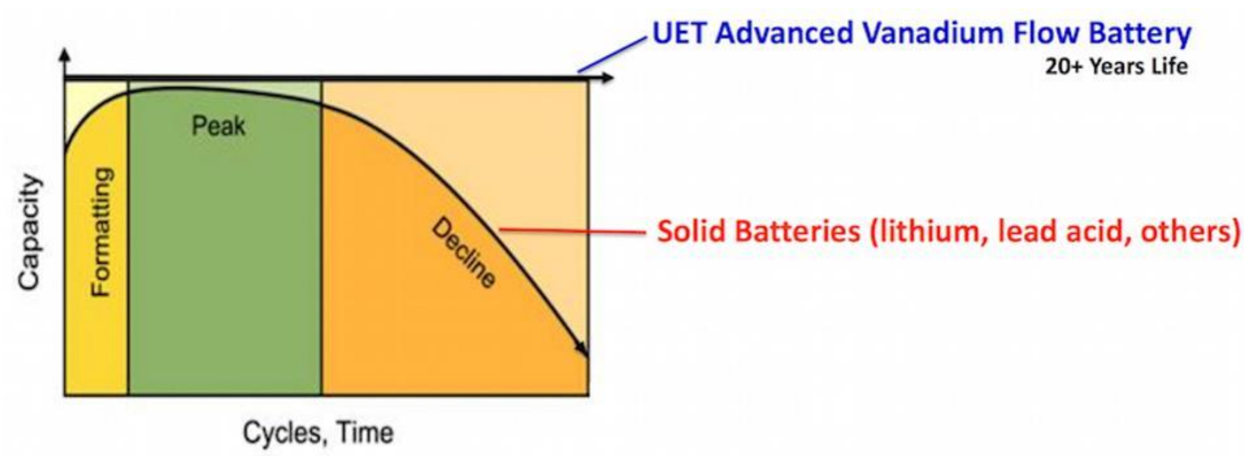
NaS batteries provide long discharge times (six hours plus) and long life, rated at 15 years. The batteries' advantages also include high energy density and high charge-discharge efficiency. NAS batteries are economical too, as their principal materials—sodium, sulfur, and ceramic—are plentiful and inexpensive. NGK Insulators is the world's only commercial supplier of NaS batteries.

NGK Insulators supplied 252 containerized sodium sulfur battery units for a demonstration project designed to balance the grid on Kyushu Island in Japan. [Source: http://www.powermag.com/battery-storage-goes-mainstream-2/?pagenum=4]

Flow Batteries

Flow batteries have long been considered as the logical choice for grid-scale applications because of their long durations and lifespans, and because they see less degradation from repeated charging cycles than other technologies. However, cost-effective commercial solutions have been lacking until recently when Primus Power announced that it has started production of its second-generation "EnergyPod 2" zinc bromide flow battery, which offers a five-hour discharge duration, a 20-year lifespan, and costs 50% less than the typical lithium-ion battery system. However, the round-trip efficiency of 70% is still lower than the 85% efficiency of a typical lithium-ion battery system.

The 25 kW/125 kWh "EnergyPod 2" has dimensions of 1.8 x 2.1 x 2.2 m and weighs 4,200 kg. Unlike lithium-ion based systems, EnergyPod 2 has no fire concerns and energy capacity does not fade over time [Source: http://primuspower.com/en/product/]



Unlike lithium-ion based systems, flow batteries do not degrade over time. However, worn out pumps need replacing [Source: http://www.iva.se/globalassets/rapporter/vagval-el/201604-iva-vagvalel-ellagring-rapport-english-e-ny.pdf]

Market estimates of the cost of storage

Lazard's levelized Cost of Storage study (Dec. 2016) analyzes the levelized costs associated with the leading energy storage technologies given a single assumed capital structure and cost of capital, and appropriate operational and cost assumptions derived from a robust survey of Industry participants.

Lazard's LCOS study incorporates capital costs for the entirety of the energy storage system ("ESS"), which is composed of the storage module ("SM"), balance of system ("BOS"), power conversion system ("PCS") and related EPC costs.

The primary use case for a grid-scale wind farm-coupled ESS is defined as *transmission system*. The *frequency response* use case is also relevant due to lack of sufficient spinning reserves in the NTDC system and will also be considered in the analysis.

Transmission System Use Case Cost

Large-scale energy storage system to improve transmission grid performance and assist in the integration of large scale variable energy resource generation (e.g., utility-scale wind, solar, etc.)

Specific operational uses: provide voltage support and grid stabilization; decrease transmission losses; diminish congestion; increase system reliability; defer transmission investment; optimize renewable-related transmission; provide system capacity and resources adequacy; and shift renewable generation output

		Transmission									
		Zinc		Flow Battery (V)		Flow Battery (Z-Br)		Lithium		Sodium	
	Units	Low	High	Low	High	Low	High	Low	High	Low	High
Power Rating	MW	100	100	100	100	100	100	100	100	100	100
Duration	Hours	8	8	8	8	8	8	8	8	8	8
Usable Energy	MWh	800	800	800	800	800	800	800	800	800	800
100% DOD Cycles/Day		1	1	1	1	1	1	1	1	1	1
Operating Days/Year		350	350	350	350	350	350	350	350	350	350
Project Life	Years	20	20	20	20	20	20	20	20	20	20
Annual Used Energy	MWh	280,000	280,000	280,000	280,000	280,000	280,000	280,000	280,000	280,000	280,000
Project Used Energy	MWh	5,600,000	5,600,000	5,600,000	5,600,000	5,600,000	5,600,000	5,600,000	5,600,000	5,600,000	5,600,000
Initial Installed Cost	$/kWh	261	680	487	1,174	699	647	440	1045	468	1368
Recplacement Capital Cost	$/kWh										
After Year 5		0	0	0	0	0	420	0	0	0	0
After Year 10		200	293	32	63	36	389	189	338	270	792
After Year 15		0	0	0	0	0	379	0	0	0	0
O&M Cost	$/kWh	7	24	12	35	21	19	5	11	7	21
Charging Cost	$/MWh	35	35	35	35	35	35	35	35	35	35
Efficiency	%	64%	64%	68%	70%	70%	73%	92%	93%	82%	82%
Levelized Cost of Storage	$/MWh	262	438	314	690	434	549	267	561	301	784

The study assumes 7000 100% depth-of-discharge cycles over the course of the life of the energy storage system. Some chemistries such as Lithium-Titanate-Oxide (LTO) cells produced by Toshiba are capable of maintaining over 80% of their capacity after 15,000 charge/discharge cycles at a 3C charge/discharge rate in a "high energy" configuration or maintaining over 90% of their capacity after

20,000 charge/discharge cycles at a 5C charge/discharge rate in a “high power” configuration. However, such cycle lifetime figures are based on test environments with temperatures at 25 or 35 degrees Celsius. The ambient temperature in Jhimpir is often over 40 and can reach as high as 50 degrees Celsius. Therefore a certain amount of parasitic load for cooling should be accounted for which would reduce the BESS efficiency. Therefore, an efficiency of 85% is used for LTO batteries in the feasibility analysis.

<u>Frequency regulation Use Case Cost</u>

Frequency is a crucial parameter in an AC electric power system. Deviations from the nominal frequency are a consequence of imbalances between supply and demand; an excess of generation yields an increase in frequency, while an excess of demand results in a decrease in frequency.

The power mismatch is, in the first instance, balanced by changes in the kinetic energy stored within the rotating mass of large, synchronous generators. Specially designated *primary reserve* generators with automatic governor control (AGC) take over the task of providing balancing energy within seconds. If the frequency deviation is large-enough or lasts long-enough, for example due to the tripping of a large generator, then additional *secondary reserve* generators which are already synchronized with the system, i.e. *spinning reserve* take over the frequency regulation burden within minutes. In addition to compensating for outages of large generators, spinning reserve is also used in compensating for errors in load forecasts and variable (solar & wind) generation forecasts.

Eventually, non-spinning reserves (also known as operational reserves or *tertiary reserve*) are brought online and synchronized with the system which enables *secondary reserve* to return to standby mode.

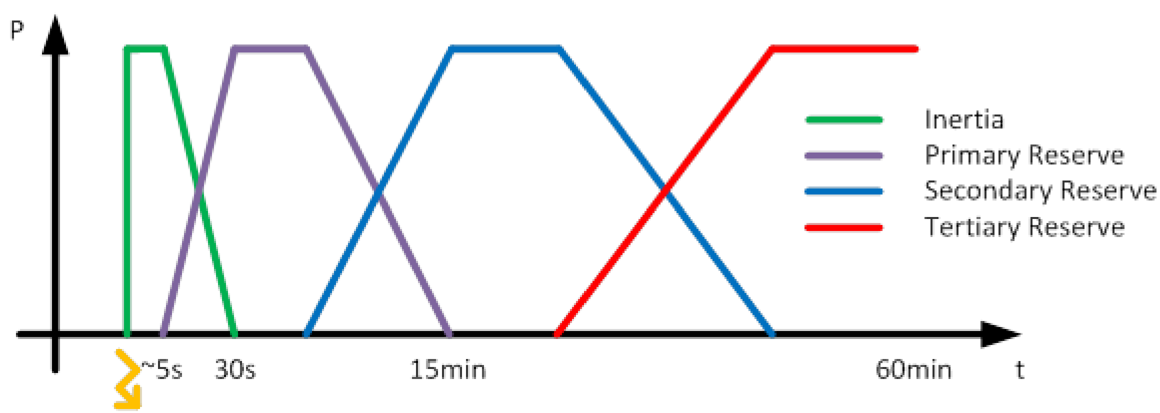


Figure 1: Frequency regulation requirements in Germany

In a power system with reduced system inertia and a high level of variable generation, frequency deviations are likely to become more frequent and more severe. To counteract this, energy storage systems can be used to provide frequency response services in a much shorter timeframe than conventional network assets. A battery energy storage system (BESS) in a “high power” configuration can designed to balance power by raising or lowering output to follow the moment-by-moment changes in load to maintain frequency to be held within a tolerance bound.

National Grid, the UK's Transmission System Operator, has tendered for 210 MW of a novel frequency response ancillary service called "Enhanced Frequency Response" with the following operational requirements.

- Response must take place within 1 s of a frequency deviation occurring
- The service provider must be able to deliver the service in either direction (export/import to/from grid)
- The service provider must be able to provide 100% capacity for a minimum of 15 minutes
- The provider must maintain an operational availability of 95% to qualify for the full payment

This is in contrast with existing frequency response services which can have timescales of up to 10 seconds, or 30 seconds (depending on the service). Such operational constraints are especially suitable for battery energy storage systems. However, using an energy storage system in this way presents additional challenges because the systems are constrained by both energy and power, and due to the fact that their degradation is heavily affected by their operating state of charge and cycling requirements.

		Frequency Regulation			
		Lithium		Flywheels	
	Units	Low	High	Low	High
Power Rating	MW	10	10	10	10
Duration	Hours	0.5	0.5	0.5	0.5
Usable Energy	MWh	5	5	5	5
100% DOD Cycles/Day		4.8	4.8	4.8	4.8
Operating Days/Year		350	350	350	350
Project Life	Years	10	10	10	10
Annual Used Energy	MWh	8,400	8,400	8,400	8,400
Project Used Energy	MWh	84,000	84,000	84,000	84,000
Initial Installed Cost	$/kWh	1,024	1,706	4,140	9,200
Recplacement Capital Cost	$/kWh				
After Year 5		0	0	0	0
After Year 10		0	0	0	0
After Year 15		0	0	0	0
O&M Cost	$/kWh	20	32	83	184
Charging Cost	$/MWh	47	47	47	47
Efficiency	%	89%	89%	82%	85%
Levelized Cost of Storage	$/MWh	190	277	598	1,251

Energy Storage Modelling and Simulation

The process of expanding transmission systems relies heavily on modelling. The simplest approach, known as the *copper plate approach,* assumes an unconstrained electrical grid and is mostly used in economic models. The most complex grid model is the *AC power flow model* in which active and reactive power flows are modelled. This model requires detailed grid data – each node needs to be defined either as a PQ or as a PV bus, demand and generation data have to be additionally specified by their reactive power or voltage behavior and information of the impedance of power lines is necessary.

In order to assess the feasibility of an energy storage asset connected to the *Jhimpir-2* substation, various use cases with different revenue streams have earlier been identified. These use cases need different battery configurations, i.e., high power vs. high energy and therefore different costs.

Methodology

The energy storage model comprises of two parts – the network model and the asset model.

- Step one consists of building the AC power flow model and analyzing the node voltages as well as transformer and line loadings in different scenarios of power generation, load and network availability with the objective of identifying the maximum power evacuation capacity (from Jhimpir-2) in which network assets are not overloaded and that the voltages at the nodes stay within the limits prescribed by the grid code[12].
- In step two, a multi-period asset optimization model is developed. The model is a mixed-integer linear program (MIP) with an objective function that maximizes power evacuation out of Jhimpir-2. The model provides the asset dispatch plan, i.e. the optimal charge/discharge cycling of the energy storage based on historical wind power generation data[13] from a single calendar year. The optimization model takes into account network outages and grid tripping events[14], as well as plant operational constraints related to Lithium ion-based battery energy storage systems used in grid-scale applications.

As the network outages are based on limited data, a probability distribution function of network outages is created and a Monte Carlo Simulation (with ten scenarios) is used for each BESS configuration, e.g. C, C/2, etc.

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[12] The voltages at the buses in the extra-high voltage network must maintained between 1.08 and 0.95 per unit during normal steady-state operations

[13] Wind generation data provided by the Hawa Energy wind farm

[14] Network outage data provided by the FFC wind farm

AC Power Flow Model

This model has been developed with the purpose of determining the optimal size and configuration of a Pilot energy storage facility at the Jhimpir-2 two substation based on network operational constraints.

However, some general takeaways from this Study are –

- Total transfer capacity (TTC) between the Northern and Southern sections of the NTDC extra-high voltage network should be reduced. This is needed in order to reduce line loadings on medium length (150-300 km) and long length (> 300 km) transmission lines, as well as to reduce line losses and reactive power flow that cause voltage problems
- Wind power generation has the lowest LCOE[15] at 60 $/MWh. Therefore the full capacity of 2460 MW should be given priority grid access. However, in terms of *security-constrained* economic dispatch (SC-ED[16]), wind power generation in the Southern Wind Corridor would need to be capped at 70% of installed capacity, or 1722 MW
- Wind power curtailment occurs during 1322 hours, which is 15.1% of the year. The total energy curtailed is 576,761 MWh, which at an average tariff of 110 USD/MWh would cost electricity consumers USD 63.44 million annually in surcharges
- **Conclusion:**
    - Significant network expansion is needed in the Southern half of the transmission grid if power is to be reliably and cheaply supplied from new thermal and wind power plants, especially to regional loads.
    - Without network expansion, wind farm curtailments will increase
    - Sectionalizing the grid in terms of setting TTC limits and reducing large-scale bulk power flows over critical transmission paths would benefit NPCC dispatchers as the control areas would be smaller

Total Transfer Capacity (TTC)

The data for the network model (obtained from the Planning Department at NTDC) comprises of two scenarios – the 2019/2020 summer peak (maximum load) and the 2019/2020 winter off-peak (minimum load).

The data shows that 1500 MW of power is transferred across this boundary during both summer and winter scenarios. As a result, the total transfer capacity (TTC) across the 500 kV AC lines (in red) was restricted to 1500 MW in the AC power flow model.

By dividing the NTDC extra-high voltage network into two sections – a Northern section and a Southern section, and by explicitly setting the TTC across that boundary, the bus at Shikarpur can be set in the model as the *slack* bus. In other words, the Shikarpur 500 kV bus is guaranteed to maintain its voltage at the value assigned to it.

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[15] Levelized cost of electricity ($/MWh)

[16] The SC-ED adds network constraints and other power system operations requirements to the basic economic dispatch (ED) algorithm

Therefore, in order to assess the operational security of the Southern Grid, it is sufficient to assess the voltages and asset loading levels in the Southern grid with the voltage at Shikarpur set to the maximum and minimum voltage levels permissible in the Grid Code.

Figure 2: The dotted line divides the grid into two control areas - North and South

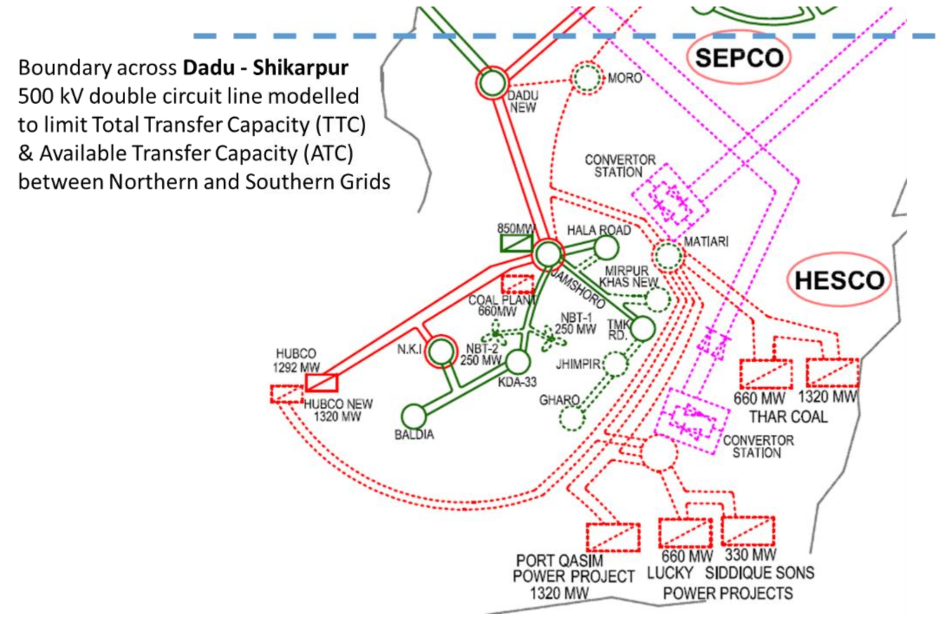
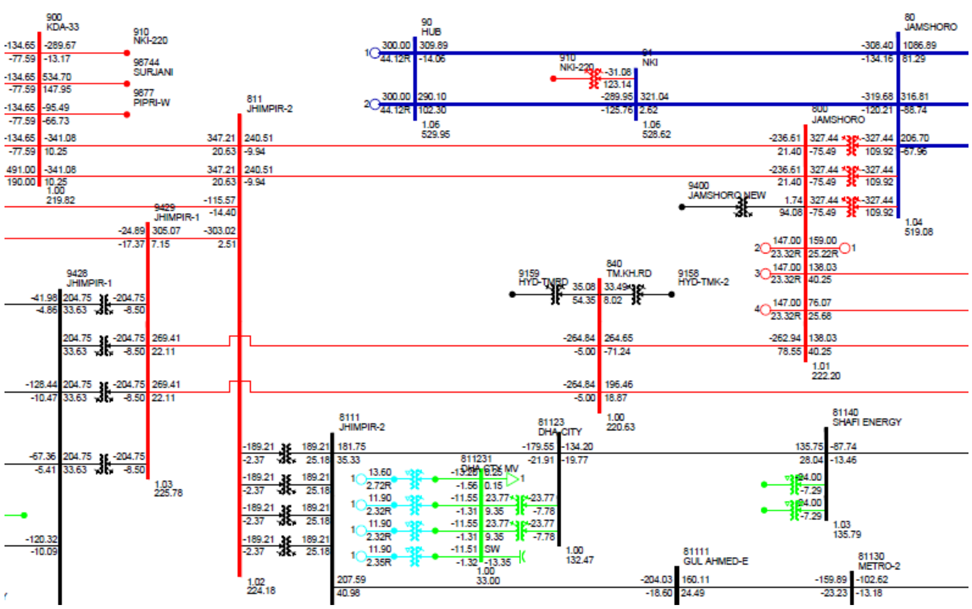


Figure 3: Single Line Diagram showing the Jhimpir-1 (9429) and Jhimpir-2 (811) substations



Data used in the model

NOTE: In the tables below, power generation is negative and loads are positive

Table 5: synchronous generators modelled

name	min_q_kvar	max_q_kvar	min_p_kw	max_p_kw
KE Port Qasim	-180000	100000	-370000	-100000
Hub Co 1	-160000	120000	-323000	-100000
Hub Co 2	-160000	120000	-323000	-100000
Port Qasim CPP	-409000	217000	-617000	-200000
Engro CPP 1	-247500	105600	-310000	-100000
Engro CPP 2	-247500	105600	-310000	-100000
Jamshoro 1	-65000	50000	-170000	-60000
Jamshoro 2	-65000	50000	-170000	-60000
Jamshoro 3	-65000	50000	-170000	-60000
Jamshoro 4	-65000	50000	-170000	-60000
Thatta	-9105	11651	-19740	-6267
Kotri GTPS 1	-18000	10000	-40000	-20000
Kotri GTPS 2	-18000	10000	-32000	-15000
Kotri Site	-7437	5812	-12600	-4000
Nooriabad	-6197	4840	-10500	-3330

Table 6: transformers modelled

name	MVA	hv_kV	lv_kV	tap_min	tap_max	tap_step_%
Gharo New 9255/9256	250	221.694	132	-18	15	0.625
Jamshoro New 800/9400	320	211.75	132	-312	687	0.02004009
Jamshoro 80/800 1	450	500	220	-499	499	0.02004009
Jamshoro 80/800 2	450	500	220	-499	499	0.02004009
Jamshoro 80/800 3	450	500	220	-499	499	0.02004009
Dadu 70/700 1	450	475	220	-250	749	0.02004009
Dadu 70/700 2	450	475	220	-250	749	0.02004009
Jhimpir-1 9429/9428 1	250	225.5	132	-20	12	0.625
Jhimpir-1 9429/9428 2	250	225.5	132	-20	12	0.625
Jhimpir-1 9429/9428 3	250	225.5	132	-20	12	0.625
Jhimpir-1 9429/9428 4	250	225.5	132	-20	12	0.625
Jhimpir-2 811/8111 1	250	231	132	-24	8	0.625
Jhimpir-2 811/8111 2	250	231	132	-24	8	0.625
Jhimpir-2 811/8111 3	250	231	132	-24	8	0.625
Jhimpir-2 811/8111 4	250	231	132	-24	8	0.625

Hala Rd 820/9090	250	214.5	132	-12	20	0.625

Table 7: wind power plants modelled

name	min_p_kw	max_p_kw	min_q_kvar	max_q_kvar
Gharo New Cluster	-150000	0	-49303	49303
Jimpir1 UEPL Cluster	-180000	0	-59163	59163
Jimpir1 Master Cluster	-200000	0	-65737	65737
Jimpir1 Tricon Cluster	-200000	0	-65737	65737
Jimpir1 Hawa Cluster	-200000	0	-65737	65737
Jimpir1 Sachal Cluster	-200000	0	-65737	65737
Norinco-2	-50000	0	-16434	16434
Tricom	-50000	0	-16434	16434
Sinowell	-50000	0	-16434	16434
Jimpir2 Cacho Cluster	-400000	0	-131474	131474
Jimpir2 DHA City Cluster	-410000	0	-134760	134760
FWEL 1	-50000	0	-16434	16434
FWEL 2	-50000	0	-16434	16434
BWEPL GUJJU	-14000	0	-4602	4602
FFC	-50000	0	-16434	16434
Zorlu	-56800	0	-18669	18669
TGF	-50000	0	-16434	16434
Sapphire	-50000	0	-16434	16434
Master Green	-50000	0	-16434	16434

AC Power flow Results

Caveats

- As RYK – Moro is a very long line, power transfer will need to be capped at the stability limit and the line will likely be loaded below 40%. However, there are also likely to be additional sources of power generation feeding the load at RYK which have not been considered in this analysis in which the focus is on the Southern Grid
- The HVDC lines carrying 4000 MW from Thar to Punjab have not been included in the model since the power exports have no impact on bus voltages or trafo/line loadings south of Shikarpur which is the control area being modelled. Furthermore, a number of power stations that would deliver power on those links have being marked out-of-service in the data
- The Study does not take into account N-1 contingencies. Such scenarios would reduce power transfer and increase curtailments. However, in order to draw meaningful conclusions from any Contingency Analysis, the likely/credible contingency scenarios need to be provided by NPCC
- The Study also does not take into account HVDC line trips and any remedial action schemes (RAS) that may instantaneously cut thousands of MWs at Lahore or Faisalabad or transfer large volumes of bulk power onto the AC network
- The Study only takes into account Peak Load. In order to increase accuracy, loads should be provided as an hourly time series, similar to wind power generation

Grid Code

The Grid Code (in operating condition 4.9) sets the following limits on bus voltages for both normal operations and contingency conditions

Voltage Level	**Normal Condition**		**Contingency Condition**	
	Max (1.08)	**Min (0.95)**	**Max (1.1)**	**Min (0.9)**
500 kV	540	475	550	450
220 kV	238	209	245	198
132 kV	143	125	145	119

Modelling Results

BASE CASE

	Wind Generation		**Thermal Gen**		**Bus Voltages (per unit)**					
	Dispatch	power factor	Dispatch	Outages	Shikarpur	Dadu	KDA-33	Jamshoro	Jhimpir-1	Jhimpir-2
1	90%	0.99	Pmax		1.02	0.9562	0.9364	0.9817	0.9658	0.9586
2	80%	0.99	Pmax		1.02	0.9662	0.9733	0.9915	1.0025	0.9944
3	70%	0.99	Pmax		1.02	0.9782	0.9876	0.9968	1.0169	1.0082
4	90%	0.95	Pmax		1.02	0.9641	1.0100	0.9948	1.0687	1.0478
5	90%	0.99	Pmin		1.02	0.9924	0.9662	1.0086	1.0105	0.9985
6	80%	0.99	Pmin		1.02	0.9947	0.9752	1.0117	1.0196	1.0071

	Trafo loading [%]		
Scenario	Jamshoro	Jhimpir-1	Jhimpir-2
1	104.0964	81.5164	79.6887
2	83.7059	67.3522	68.3408
3	65.4651	55.2612	59.0367
4	100.7905	78.0529	74.5784
5	42.9518	78.1607	76.5275
6	67.4917	66.3245	67.4917

	Line Loading [%]								
	Jamsho – Dadu	Dadu – Matiari	RYK – Moro*	Moro – Matiari	Jhimp2 - KDA33	Jamshoro - Jhimp2	T.M.K Rd - Jhimpir1	Jhimpir2 - Jhimpir1	Jhimp1 - T.M.K
	153 km 500 kV	172 km 500 kV	335 km 500 kV	192 km 500 kV	60 km 220 kV	80 km 220 kV	75 km 220 kV	30 km 220 kV	78 km 132 kV
1	100.4002	86.9874	79.4070	76.6171	27.3348	58.1328	48.8371	27.3307	66.0841
2	92.0315	80.0048	78.6554	71.5768	26.2994	45.7659	40.8256	22.5126	64.9105
3	83.8354	73.2234	78.1784	66.7262	25.9199	35.1125	33.9552	18.5366	65.4254
4	100.0999	86.5529	78.7720	76.2277	29.1248	53.5930	46.6293	28.5079	57.7691
5	34.9074	30.2261	76.8274	36.4321	51.3889	39.6717	40.5543	37.0996	62.8728
6	28.2141	25.0417	76.6611	32.6316	50.9142	29.2917	33.8866	33.0334	63.7342

EDGE CASES

Table 8: Bus voltages (per unit) for edge cases

	Wind Generation		Thermal Gen		Bus Voltages (per unit)					
	Dispatch	power factor	Dispatch	Outages	Shikarpur	Dadu	KDA-33	Jamshoro	Jhimpir-1	Jhimpir-2
1	100%	0.99	Pmin		1.08	1.0359	0.9850	1.0388	1.0286	1.0165
2	100%	0.95	Pmin		1.08	1.0309	1.0100	1.0310	1.0726	1.0498
3	90%	0.99	Pmin		1.08	1.0314	0.9731	1.0307	1.0174	1.0051
4	90%	0.99	Pmax		1.08	0.9899	0.9570	0.9946	0.9861	0.9786
5	80%	0.99	Pmax		1.08	0.9999	0.9858	1.0047	1.0153	1.0066
6	70%	0.99	Pmax		1.08	1.0074	0.9961	1.0112	1.0255	1.0165
7	100%	0.99	Pmax	P Qasim CPP	1.08	0.9928	0.9085	0.9893	0.9373	0.9315
8	50%	0.99	50%		1.08	1.0319	0.9793	1.0311	1.0174	1.0073
9	20%	0.99	Pmax		1.08	1.0262	0.9757	1.0243	1.0008	0.9967
10	5%	0.99	Pmax		1.08	1.0263	0.9570	1.0226	0.9795	0.9785
11	100%	0.99	Pmin		0.95	0.9502	0.9123	0.9874	0.9578	0.9474
12	100%	0.95	Pmin		0.95	0.9565	1.0100	0.9983	1.0702	1.048
13	90%	0.95	Pmin		0.95	0.9575	1.0100	0.9990	1.0681	1.0467
14	90%	0.99	Pmin		0.95	0.9548	0.9509	0.9941	0.9955	0.984
15	90%	0.99	Pmax		0.95	0.9140	0.9050	0.9633	0.9347	0.9281
16	80%	0.99	Pmax		0.95	0.9269	0.9540	0.9768	0.9834	0.9756
17	70%	0.99	Pmax		0.95	0.9352	0.9760	0.9840	1.0051	0.997
18	90%	0.99	Pmax	P Qasim CPP	0.95	0.9263	0.9117	0.9411	0.9346	0.9413
19	50%	0.99	50%		0.95	0.9572	0.9784	0.9983	1.0165	1.0065
20	20%	0.99	Pmax		0.95	0.9517	0.9550	0.9911	0.9804	0.9766
21	5%	0.99	Pmax		0.95	0.9487	0.9030	0.9838	0.9261	0.9262

Analysis of Bus Voltages

- In scenarios of high wind power generation (>= 70%) and voltage at Shikarpur set to 0.95 per unit, thermal generation needs to be throttled down to avoid low voltages at Dadu
- When thermal generation is set to P_{min}, low voltages are observed at KDA-33 and Jhimpir-2 in the 100% wind power generation scenario. In this case, power factor control of wind turbines boosts the bus voltages above the minimum permissible value and curtailment is not required.
- However, fast modulation of the thermal plants (from P_{max} down to P_{min}) may not be possible as coal-fired plants are generally designed to be run for long periods at a single set-point. It is possible that if load is also expected to drop off, then economic dispatch may require a large power station running on imported coal to be shut-down for 12-24 hours. However, taking the largest generator (Port Qasim CPP) offline has an adverse effect on voltages on all buses when Shikarpur is at 0.95 and on KDA-33, Jhimpir-1 and Jhimpir-2 when Shikarpur is at 1.08

Transformer and transmission line loading

Transformers cores become increasingly saturated with magnetic flux (B-H curve) due to excessive primary voltage at high loading levels. This results in voltage wave distortion and the damage to the transformer's insulation when operating at overloaded levels results in asset's operating life is reduced. Loading of transformers up to 80% has been considered safe in this analysis.

NOTE: The scenarios that are problematic in terms of bus voltages, i.e. scenarios 7, 11, 15-18 and 21 are marked with a strike-through in the following tables.

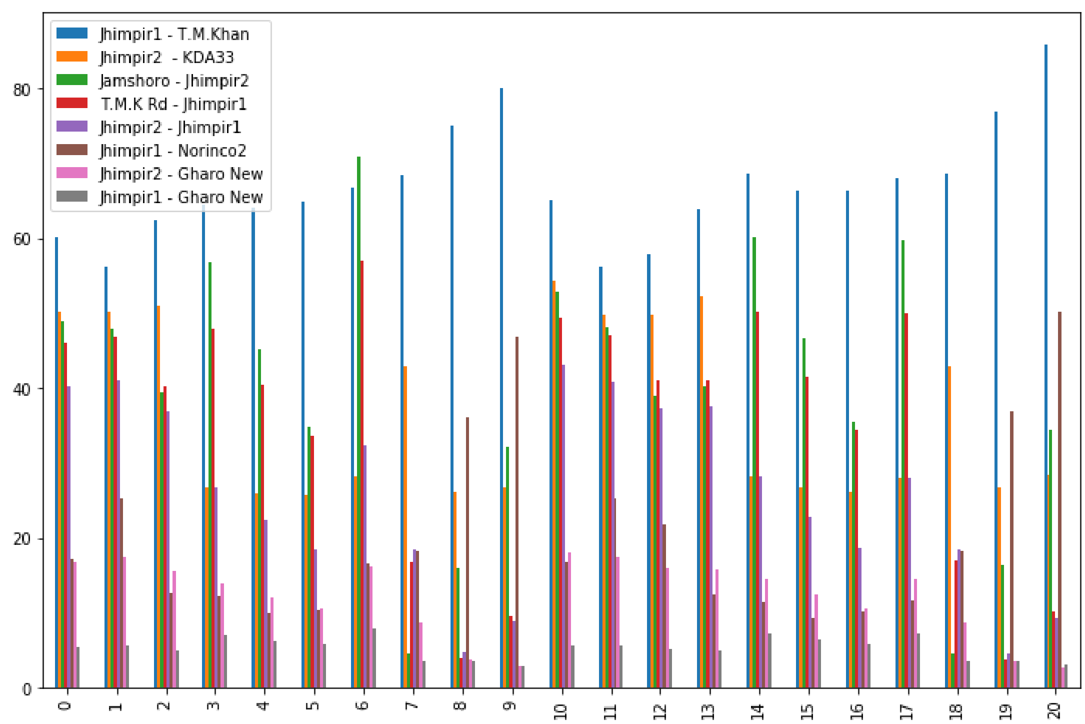
Table 9: Transformer loading

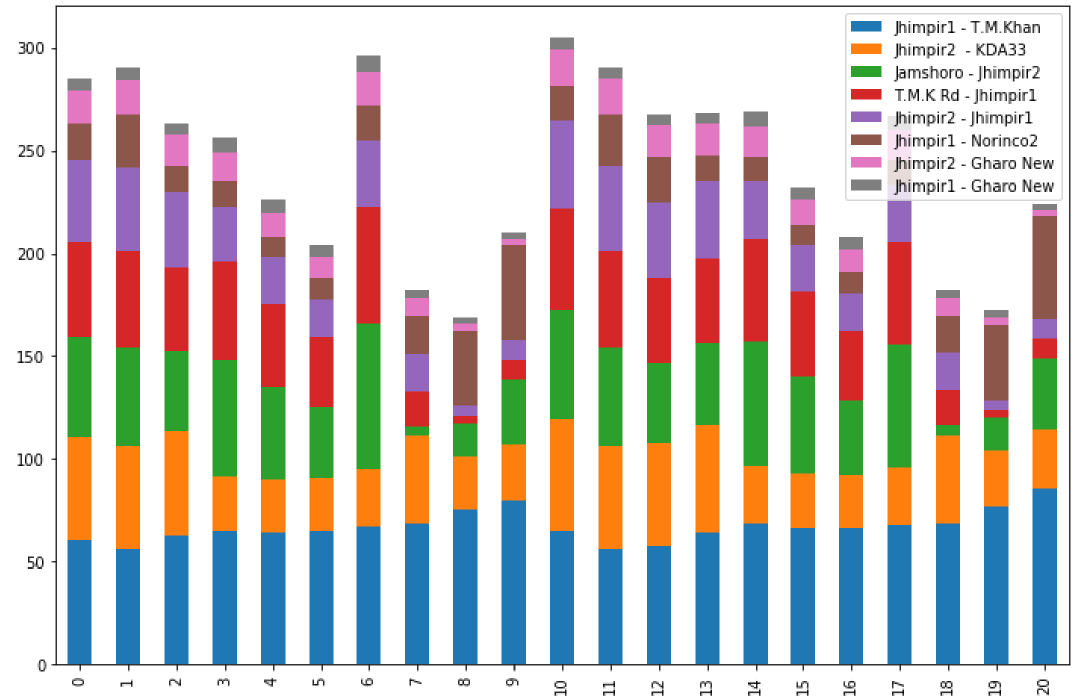
	Wind Generation		**Thermal Gen**		**Vn p.u.**	**Trafo loading [%]**		
Scenario	Dispatch	power factor	Dispatch	Outages	Shikarpur	Jamshoro	Jhimpir-1	Jhimpir-2
1	100%	0.99	Pmin		1.08	59.813	87.9741	83.5046
2	100%	0.95	Pmin		1.08	60.9367	88.3646	82.4957
3	90%	0.99	Pmin		1.08	44.9622	77.6727	76.0314
4	90%	0.99	Pmax		1.08	102.3322	79.9539	78.0741
5	80%	0.99	Pmax		1.08	82.7603	66.5831	67.5258
6	70%	0.99	Pmax		1.08	64.7566	54.8459	58.5617
~~7~~	~~100%~~	~~0.99~~	~~Pmax~~	~~PQ CPP~~	~~1.08~~	~~125.0898~~	~~96.0328~~	~~91.0847~~
8	50%	0.99	50%		1.08	19.8892	32.7558	42.294
9	20%	0.99	Pmax		1.08	26.4085	4.1299	17.1722
10	5%	0.99	Pmax		1.08	57.0686	20.4676	4.3852
~~11~~	~~100%~~	~~0.99~~	~~Pmin~~		~~0.95~~	~~63.6349~~	~~94.0912~~	~~89.5578~~
12	100%	0.95	Pmin		0.95	60.8591	88.5332	82.6353
13	90%	0.95	Pmin		0.95	43.6493	78.0939	74.6513
14	90%	0.99	Pmin		0.95	43.3934	79.2562	77.6434
~~15~~	~~90%~~	~~0.99~~	~~Pmax~~		~~0.95~~	~~106.9649~~	~~84.0321~~	~~82.2865~~
~~16~~	~~80%~~	~~0.99~~	~~Pmax~~		~~0.95~~	~~85.0035~~	~~68.5611~~	~~69.6603~~
~~17~~	~~70%~~	~~0.99~~	~~Pmax~~		~~0.95~~	~~66.2502~~	~~55.8391~~	~~59.6982~~
~~18~~	~~90%~~	~~0.99~~	~~Pmax~~	~~PQ CPP~~	~~0.95~~	~~106.3378~~	~~83.4865~~	~~81.7221~~
19	50%	0.99	50%		0.95	15.6745	32.7776	42.3281
20	20%	0.99	Pmax		0.95	25.2808	3.9619	17.5234
~~21~~	~~5%~~	~~0.99~~	~~Pmax~~		~~0.95~~	~~57.0686~~	~~22.0227~~	~~4.6311~~

Table 10: Line loading

	Line Loading [%]							
	Jhimpir1 - T.M.Khan	Jhimpir2 - KDA33	Jamshoro - Jhimpir2	T.M.K Rd - Jhimpir1	Jhimpir2 - Jhimpir1	Jhimpir1 - Norinco2	Jhimpir2 - Gharo New	Jhimpir1 - Gharo New
	78 km S/C	60 km D/C	80 km D/C	75 km D/C	30 km S/C	32 km S/C	95 km S/C	75 km S/C
1	60.13	50.28	48.85	46.09	40.23	17.18	16.90	5.38

2	56.16	50.09	47.93	46.88	40.97	25.28	17.38	5.53
3	62.42	51.02	39.42	40.30	36.89	12.75	15.52	4.94
4	64.55	26.74	56.87	47.92	26.81	12.33	13.96	6.98
5	64.03	25.97	45.24	40.35	22.34	9.94	12.09	6.31
6	64.83	25.70	34.84	33.68	18.49	10.37	10.49	5.76
7	66.77	28.16	70.87	57.02	32.41	16.62	16.28	7.80
8	68.53	42.91	4.63	16.90	18.42	18.24	8.78	3.61
9	75.03	26.23	15.99	3.92	4.73	36.05	3.65	3.54
10	79.94	26.75	32.21	9.58	8.90	46.81	2.96	3.01
11	65.15	54.41	52.80	49.32	43.05	16.78	18.00	5.70
12	56.28	49.86	48.16	47.04	40.91	25.29	17.38	5.57
13	57.80	49.72	38.97	41.13	37.35	21.76	15.91	5.10
14	63.90	52.21	40.23	41.11	37.57	12.46	15.79	5.04
15	68.58	28.27	60.13	50.27	28.15	11.42	14.60	7.29
16	66.31	26.84	46.67	41.54	22.87	9.32	12.38	6.49
17	66.26	26.23	35.49	34.33	18.61	10.13	10.61	5.88
18	68.05	28.08	59.71	49.97	27.98	11.55	14.52	7.25
19	68.59	42.94	4.63	16.91	18.42	18.25	8.78	3.61
20	76.87	26.80	16.46	3.72	4.63	36.89	3.59	3.59
21	85.87	28.34	34.46	10.14	9.35	50.26	2.74	3.13





<u>Analysis of Transformer and Line Loading levels</u>

- Transformer overloading occurs at high generation levels. In order to avoid transformer overloading, thermal generation is operated at P_{min} and wind power generation capped at 90%, or thermal generation is operated at P_{max} and wind power generation capped at 70%
- In scenarios where thermal generation is operated at P_{min}, the transformers at Jhimpir-1 and Jhimpir-2 are at risk, whereas in scenarios where thermal generation is operated at P_{max}, the transformer at Jamshoro is most at risk.
- The Jamshoro transformer comes under pressure due to its location as a transit point for power flows from Jhimpir making their way to the 500 kV super-grid, as well as due to 240 MW of thermal generation connected at Jamshoro
- Line loadings are not a problem as the lines are short (<100 km) and neither voltage drop nor stability issues dominate
- The Jhimpir1 - T.M.Khan line has the highest loading levels, with loading exceeding 80% in scenario 21

Inter-area power flow

The loading limit is capped by different overriding phenomenon at different line lengths – thermal limits on short lines, voltage drop on medium lines and electrical phase shift / stability limits on long lines.

At Surge Impedance Loading (SIL), the capacitive charging current of the line from the ground exactly offsets the inductive impedance of the line and as a result only active power pulsates along the line. Below the SIL, transmission lines generate net capacitive (charging) current that needs to be absorbed by the system if the voltages at the ends are to be kept below the upper limit. Typically, for very long lines (> 250 km), the line is loaded close to the SIL. The For example, while the thermal limit on a long 500 kV line may be 3000 MW, the SIL would be much lower, at 850-1000 MW.

At a length of 193 km, the Shikarpur – Dadu line can be considered a typical medium length line. For such lines, voltage drop limits typically dictate the amount of power that can be safely transferred. In order to minimize the reactive power flow between the two control areas, the line can be loaded to a level that reduces the voltage drop between the two buses, Shikarpur and Dadu.

NOTE: In the table below, positive reactive power (Q) is inductive consumption, negative reactive power (Q) is capacitive consumption

Table 11: Shikarpur - Dadu 500 kV double circuit line

	Shikarpur - Dadu 500 kV double circuit line					
Scenario	**P into Shikarpur**	**P into Dadu**	**Q into Shikarpur**	**Q into Dadu**	**Q from line**	**loading percent**
1	-110.29	112.21	237.62	-683.27	-446.25	22.30
2	-112.01	114.36	291.20	-750.53	-439.34	23.90
3	122.16	-120.02	263.67	-705.50	-441.84	23.13
4	-1828.02	1867.88	1064.04	-1073.33	-9.29	72.54
5	-1617.48	1648.39	896.94	-1008.91	-111.97	64.43
6	-1398.57	1421.98	761.23	-958.96	-197.73	56.75
7	-1457.81	1485.57	936.39	-1080.03	-143.65	61.68
8	543.07	-538.97	231.05	-651.57	-420.52	27.31
9	-228.98	232.21	354.48	-782.11	-427.63	26.50
10	156.71	-156.46	-189.68	-183.80	-373.47	8.63
11	-94.70	94.79	-180.89	-194.88	-375.77	7.60
12	-108.11	108.26	-238.77	-138.93	-377.70	9.20
13	122.98	-122.76	-269.38	-107.90	-377.29	10.39
14	128.29	-128.09	-243.78	-132.64	-376.42	9.67
15	-1806.61	1845.02	519.67	-459.80	59.87	69.34
16	-1604.26	1633.28	332.63	-380.96	-48.33	60.32
17	-1389.35	1410.52	192.96	-330.89	-137.92	51.64
18	-1238.81	1256.34	240.88	-415.39	-174.51	47.62
19	547.65	-544.49	-288.48	-56.32	-344.80	21.72

20	-223.84	224.36	-181.24	-190.52	-371.77	10.31
21	156.74	-156.49	-189.49	-183.97	-373.46	8.63

Analysis of power flow between the two control areas

- Scenarios 4–7:
  a. Synchronous generation is at a maximum and wind generation is also high, resulting in a large active power transfer from the Southern Grid to the Northern Grid. The voltage drop between the two control areas is also very high, close to 1.08. This results in a large reactive power transfer in the opposite direction, i.e. from the Northern Grid to the Southern Grid.
  b. There is little reactive current addition (leading MVArs) or cancelling effect (lagging MVArs) from the line. Therefore almost all the reactive power generated by the large voltage drop needs to be consumed at Dadu.
- Scenarios 8–10:
  a. Active power generation in the Southern Grid is comparatively low and the voltage at Dadu is higher, around 1.03. Therefore the line which is carrying less active power and less reactive power is lightly loaded and generating MVArs. These MVArs flow outwards and need to be consumed in the two control areas.
- Scenarios 11–14:
  a. Active power generation in the Southern Grid is low since thermal generation is operating at P_{min}. The voltage on both sides of the boundary is very low, because even though Shikarpur is at the Grid Code's lower limit of 0.95, the voltage drop is also small. This leaves Dadu at 0.9565 per unit also perilously close to the lower limit.
  b. As a result of the low active power transfer and the low voltage drop, the line loading is very low – between 7.6% at maximum wind power generation and 10.39% when the wind turbines operate at the lowest permissible power factor of 0.95.
- Scenarios 15–18:
  a. Wind generation varies between 90% and 5%. Thermal generation is at P_{max} and operating at a low voltage set point, producing large quantities of reactive power which further depresses the voltage at Dadu to below permissible limits
  b. In scenario 18, the 617 MW imported coal-fired power station at Port Qasim is taken offline. Without the contribution of MVArs from the coal plant, the bus voltages in the entire region fall below the lower limit of 0.95
- Scenarios 19–21:
  a. Wind generation is at 50% or below results in a lightly loaded line generating over 300 MVAr of reactive power that flows towards the two ends of the line. As the voltage drop in the line is low, the bus voltages in the Southern Grid are at acceptable levels in scenarios 19 and 20
  b. In scenario 21, wind power production is only at 5% and the bus voltages at Dadu, KDA-33 and Jhimpir-1 fall below the lower limits.

Power Flows in and out of Jhimpir-1 and Jhimpir-2

Table 12: active and reactive power flows in/out of Jhimpir

P outflow [MW]		Q outflow [MVAr]	
Jhimpir-1	Jhimpir-2	Jhimpir-1	Jhimpir-2
-977.97	-700.4	-68.47	30.51
-977.94	-701.76	-266.15	-114.67
-880.38	-628.04	-78.41	19.63
-880.31	-616.91	-69.93	18.42
-782.79	-545.36	-87.46	18.53
-685.15	-473.01	-94.95	20.03
-977.62	-688.1	-36.54	36.06
-489.64	-330.73	-93.17	6.12
-195.91	-107.58	-61.2	20.84
-48.81	3.25	-28.99	31.4
-977.7	-699.3	-44.64	24.13
-977.7	-701.78	-265.54	-113.48
-880.37	-629.44	-257.36	-105.19
-880.33	-627.68	-72.56	9.27
-880.15	-616.47	-54.11	26.46
-782.73	-544.89	-80.24	12.3
-685.13	-472.8	-91.36	8.02
-880.15	-616.51	-56.18	25.37
-489.64	-330.75	-93.06	5.4
-195.9	-107.55	-58.57	21.27
-48.8	3.43	-20.24	32.23

Analysis of Jhimpir power flows

- Jhimpir-1 feeds power to Jamshoro, Hala Rd and Mirpurkhas via T.M.Khan Rd
- Jhimpir-2 feeds power to KDA-33 and Jamshoro
- Net active power flow (P) out of Jhimpir-1 is generally higher than power flow out of Jhimpir-2 Since the two buses are connected, the direction of net power flow is from Jhimpir-1 to Jhimpir-2 and onwards into the HESCO network

Acceptable wind power generation scenarios for optimal design of Energy Storage

In order to determine the maximum transmission capacity out of Jhimpir, maximum generation levels need to be identified from a network operations perspective. These levels are then cross-referenced against economic criteria to arrive at a practical transmission limit.

Table 13: power generation capacity in the Southern Grid

Load	**Wind Generation**		**Thermal Generation**	
Max [MW]	P Min [MW]	P Max [MW]	P Min [MW]	P Max [MW]
3,235.5	0	2460.80	988.56	3047.84

The following power generation scenarios are acceptable in terms of Grid Code limits for bus voltages, transformer loadings and line loadings

Table 14: acceptable power generation scenarios

	Wind Generation		**Thermal Gen**	**Vn p.u.**	**Trafo loading [%]**		
Scenario	Dispatch	power factor	Dispatch	Shikarpur	Jamshoro	Jhimpir-1	Jhimpir-2
3	90%	0.99	Pmin	1.08	44.9622	77.6727	76.0314
6	70%	0.99	Pmax	1.08	64.7566	54.8459	58.5617
8	50%	0.99	50%	1.08	19.8892	32.7558	42.294
9	20%	0.99	Pmax	1.08	26.4085	4.1299	17.1722
10	5%	0.99	Pmax	1.08	57.0686	20.4676	4.3852
13	90%	0.95	Pmin	0.95	43.6493	78.0939	74.6513
14	90%	0.99	Pmin	0.95	43.3934	79.2562	77.6434
19	50%	0.99	50%	0.95	15.6745	32.7776	42.3281
20	20%	0.99	Pmax	0.95	25.2808	3.9619	17.5234

- When the voltage at Shikarpur is at 1.08 p.u. and thermal generation is at P_{max}, wind power generation is capped at 70%
- When the voltage at Shikarpur is at 1.08 p.u. and thermal generation is at P_{min}, wind power generation is capped at 90%
- When the voltage at Shikarpur is at 0.95 p.u. and thermal generation is at P_{max}, wind power generation is capped at 20%
- When the voltage at Shikarpur is at 0.95 p.u. and thermal generation is at 50%, wind power generation is capped at 50%
- When the voltage at Shikarpur is at 0.95 p.u. and thermal generation is at P_{min}, wind power generation is capped at 90%

Economic Dispatch

The majority of newly built thermal generation in the Southern Grid are to be coal-fired. Such large power stations are built to operate for long periods at the maximum power level (P_{max}) which is also the level at which the plant has the highest efficiency. Operating such plants at the minimum power level (P_{min}) may not be economically feasible due to the lower efficiency at that operating level. Operating at lower levels also reduces the amount of reactive power that can be provided by the synchronous generators for voltage stability in the surrounding region. Therefore it is safe to assume that in periods of high load, thermal generation will be run at maximum capacity.

Example using Port Qasim CPP

	Efficiency	Coal usage [tons/h]	Coal price at gate [$/ton]	Hourly Fuel Cost [$]
P_{min} [200 MW]	40%	231.375	90	20,823.75
P_{max} [617 MW]	48%	192	90	17,353.125
Cost Differential				3,470.63
Equivalent wind farm gen at a tariff of 110 $/MWh [MW]				31.55

Limits on power evacuation capacity from Jhimpir for energy storage modelling

The following table provides an indication of power evacuation limits in the boundary conditions for voltage at the grid interconnection point. During normal conditions, the voltage at Shikarpur will be closer to 1.02 p.u.

Scenario	Voltage at Shikarpur	Thermal Generation in Southern Grid	Jhimpir wind power generation
Base Case	1.02 p.u	3047.84 MW	1722.56 MW (70%)
Upper Limit	1.08 p.u.	3047.84 MW	1722.56 MW (70%)
Lower Limit	0.95 p.u.	3047.84 MW	492.16 MW (20%)

Based on the power flow studies, a power evacuation limit of 60% of wind power generation has been conservatively used for optimally sizing the energy storage at Jhimpir-2 substation. As 810 MW of wind power is planned, power evacuation capacity of 486 MW is set as a constraint in the energy storage dispatch model.

Wind Farm Generation Modelling

The wind generation data is based on hub height wind mast data received from the “Hawa Energy” wind farm in Jhimpir. It was converted to wind power generation using the power curve of the GE 1.7-103 wind turbine

Figure 4: GE 1.7-103 wind turbine – power generated (kW) vs. wind speed (m/s)

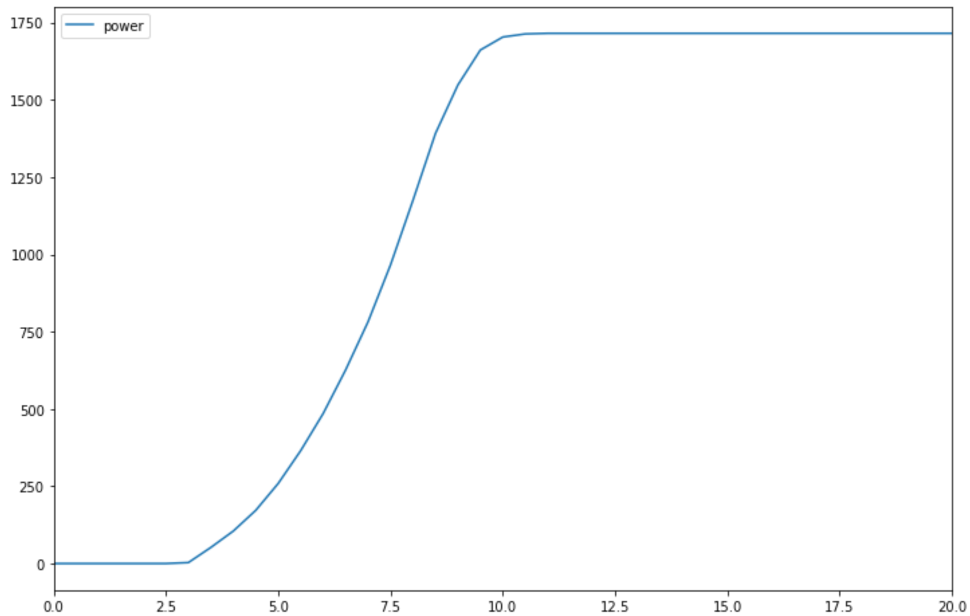
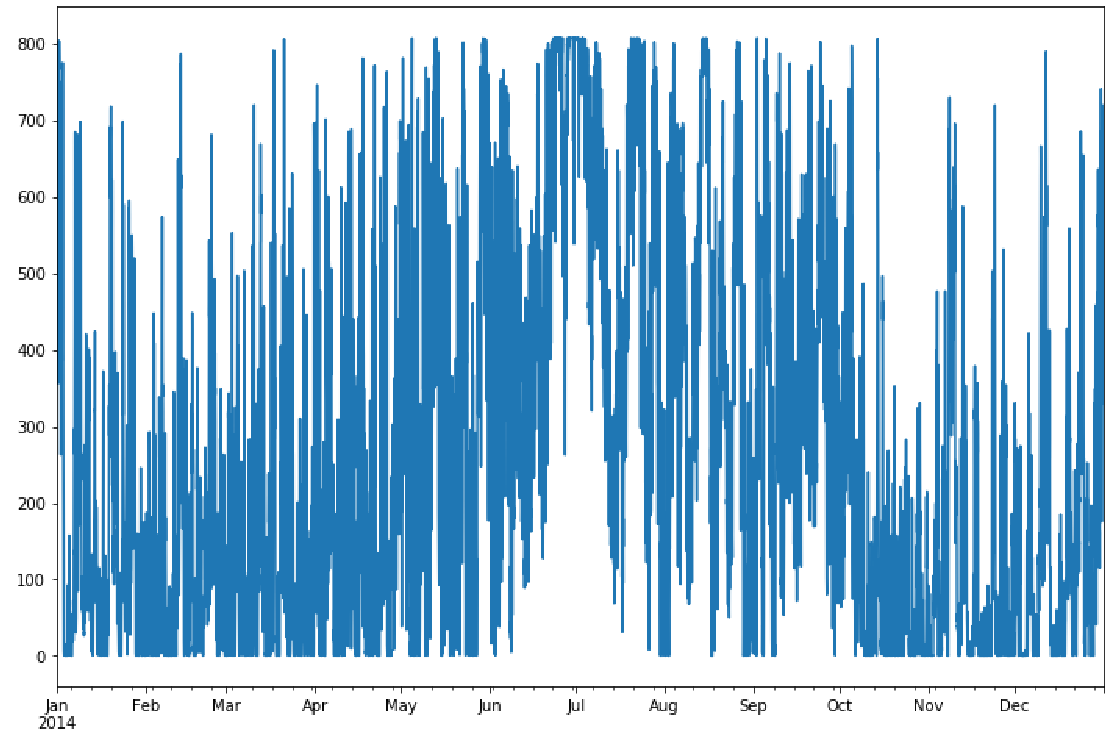


Table 15: wind power generation statistics from 2014 based on the Hawa Energy wind mast scaled up for Jhimpir-2

Jhimpir-2 Wind Power Generation Capacity [MW]	810
Hours in year	8760
Mean generation [MW]	261.42
Standard deviation [MW]	244.96
Minimum [MW]	0.00
25% [MW]	41.59
50% [MW]	192.63
75% [MW]	426.47
Maximum [MW]	807.77
Hours with gen above 60%	**1163**

Figure 5: annual distribution of wind power generation scaled to Jhimpir-2 WPPs

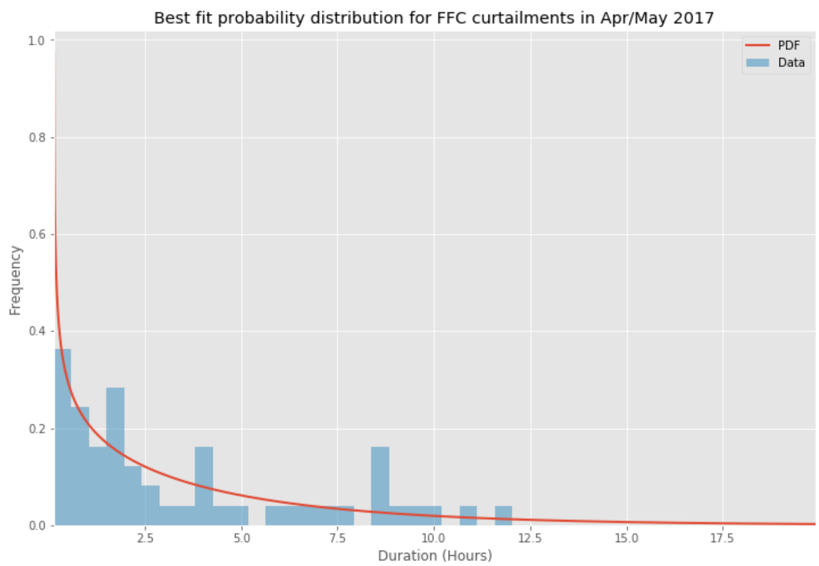


The high season for wind power is summer, which also happens to be the time of maximum load.

Probability distribution function of network outages and grid tripping events

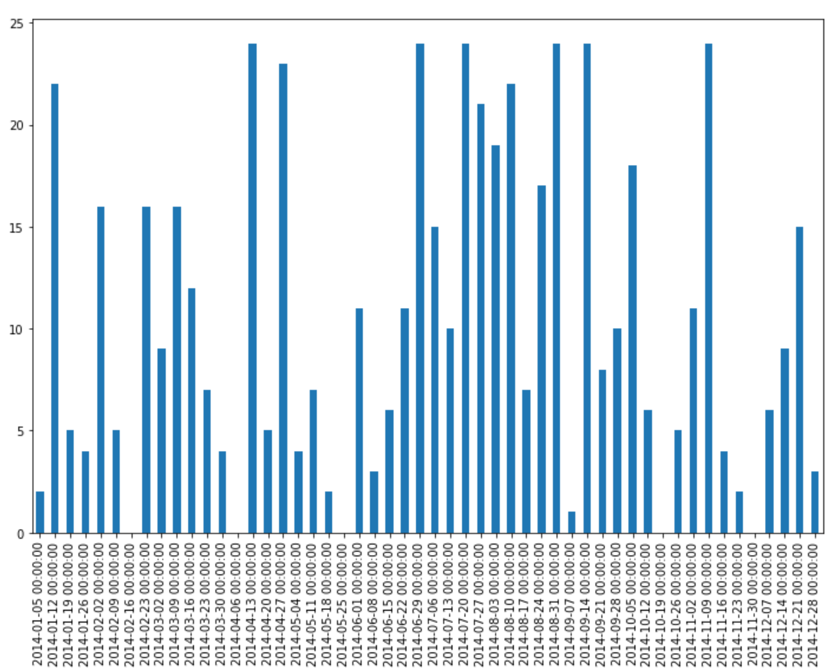
The probability distribution function is calculated by using a kernel estimation procedure. The best fit function to the data (lowest standard error) was the Generalized Gamma function.

Figure 6: Best fit probability density function to network outages in May 2017 as experienced by FFC wind farm



The durations of the network outage events are random variables that are drawn from the calibrated probability density function. The occurrence of each outage is based on a Poisson spike process.

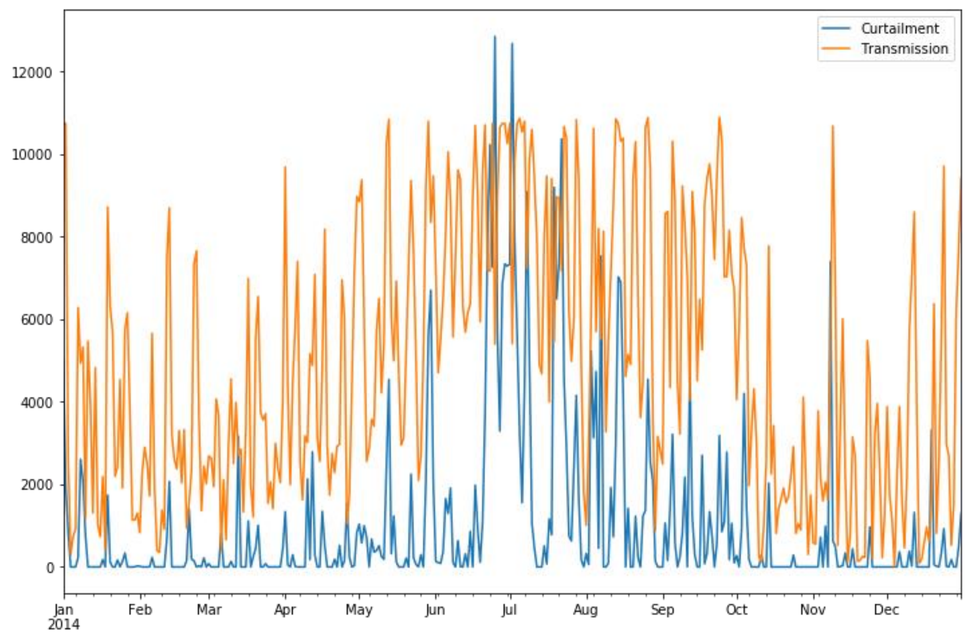
Figure 7: Sample of number of hours of network outage per week for a given scenario



Energy Storage Model

The scenario generator combines “perfect foresight” of annual wind power generation at Jhimpir-2 (max. 810 MW) with network outages that are random variables in terms of duration (hours) and occurrence of an outage. Whenever there is an outage, transmission capacity is set to zero.

Figure 8: Wind power daily volume evacuated vs. curtailed in a particular scenario



Optimization Algorithm

Within each scenario, the dispatch plan of the storage asset is calculated using a convex optimization algorithm. The objective function maximizes power evacuation by making optimal use of the storage asset whilst subject to the operational constraints of the asset. The GLPK solver is used to solve the problem.

Input data: constants

BESS_Efficiency = 0.85

Wind_Power_Generation [time series of 8760 hourly values]

Input data: scenario-wise changes

Maximum_BESS_Charge_Rate = C, where C in [100, 200]

Maximum_BESS_Discharge_Rate = C, where C in [100, 200]

Maximum_Transmission_Capacity [hourly time series: 0 MW in hours that have grid outages, 486 MW otherwise]

Decision Variables:

BESS SOC_t [MWh] (State-of-charge of the battery in each hour)

BESS $Charge_t$ [MW] (Power injected into the battery in each hour)

BESS $Discharge_t$ [MW] (Power withdrawn from the battery in each hour)

Objective Function:

Maximize $\{ \sum_{t=0}^{T=8760} (\boldsymbol{Transmission_t + BESS\ discharging_t - Curtailment_t})\ [\boldsymbol{MWh}]\ \}$

Constraints:

$$WindGen_t[MW] - Transmission_t[MW] - BESS\ charge_t[MW] = Curtailment_t[MW],\ \ \forall\ t\ \in T$$

$$Transmission_t[MW] + BESS\ discharge_t[MW] \leq Outage_t[0,1] * MaxTransCapacity\ [486\ MW],\ \ \forall\ t\ \in T$$

$$isCharging_t[0,1] + isDischarging_t[0,1] = 1$$

$$BESS\ charge_t[MW] \leq\ isCharging_t[0,1] * MaxChargeRate\ [MW]$$

$$BESS\ discharge_t[MW] \leq\ isDischarging_t[0,1] * MaxDischargeRate\ [MW]$$

$$BESS\ SOC_t[MWh] = BESS\ SOC_{t-1}[MWh] + BESS\ efficiency\ [0.85] * BESS\ charge_{t-1}[MW] -\ BESS\ discharge_t[MW]$$

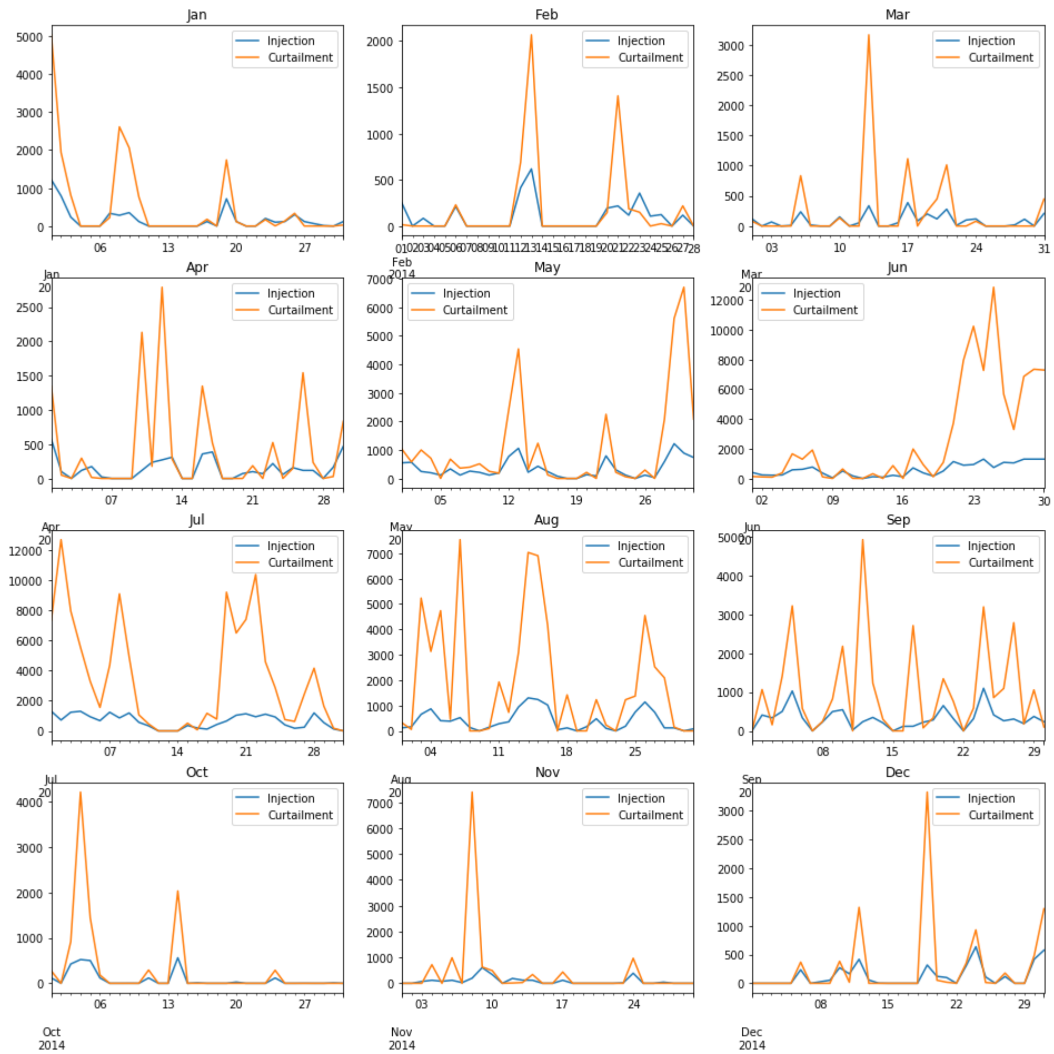
Model Results – Dispatch Plan

100 MW / 100 MWh configuration

Table 16: Dispatch plan in one scenario for a single day using a 100 MW/100 MWh battery configuration

	Curtailment	Injection	State of Charge	Transmission	Wind Power	Withdrawal
01-01-14 0:00	109.902	100	0	486	695.9021	0
01-01-14 1:00	328.191	0	85	401	729.1908	85
01-01-14 2:00	89.6424	100	0	486	675.6424	0
01-01-14 3:00	248.193	0	85	401	649.1934	85
01-01-14 4:00	191.117	100	0	486	777.1174	0
01-01-14 5:00	381.96	0	85	416	797.9603	70
01-01-14 6:00	216.845	100	15	486	802.8454	0
01-01-14 7:00	391.015	0	100	401	792.0152	85
01-01-14 8:00	3.36622	100	15	486	589.3662	0
01-01-14 9:00	0	0	100	355.954	355.9543	100
01-01-14 10:00	0	0	0	398.652	398.6524	0
01-01-14 11:00	6.85594	100	0	486	592.8559	0
01-01-14 12:00	318.254	0	85	401	719.2539	85
01-01-14 13:00	721.987	17.6471	0	0	739.6337	0
01-01-14 14:00	208.108	100	15	486	794.108	0
01-01-14 15:00	396.628	0	100	401	797.6275	85
01-01-14 16:00	217.679	100	15	486	803.6791	0
01-01-14 17:00	378.69	0	100	401	779.6899	85
01-01-14 18:00	180.207	100	15	486	766.2067	0
01-01-14 19:00	402.385	0	100	401	803.3855	85
01-01-14 20:00	196.086	100	15	486	782.0865	0
01-01-14 21:00	371.935	0	100	401	772.9349	85
01-01-14 22:00	120.037	100	15	486	706.0372	0
01-01-14 23:00	36.8924	100	100	486	622.8924	0

Figure 9: Energy stored in the battery vs. energy curtailed in one scenario for a 100 MW/100 MWh battery

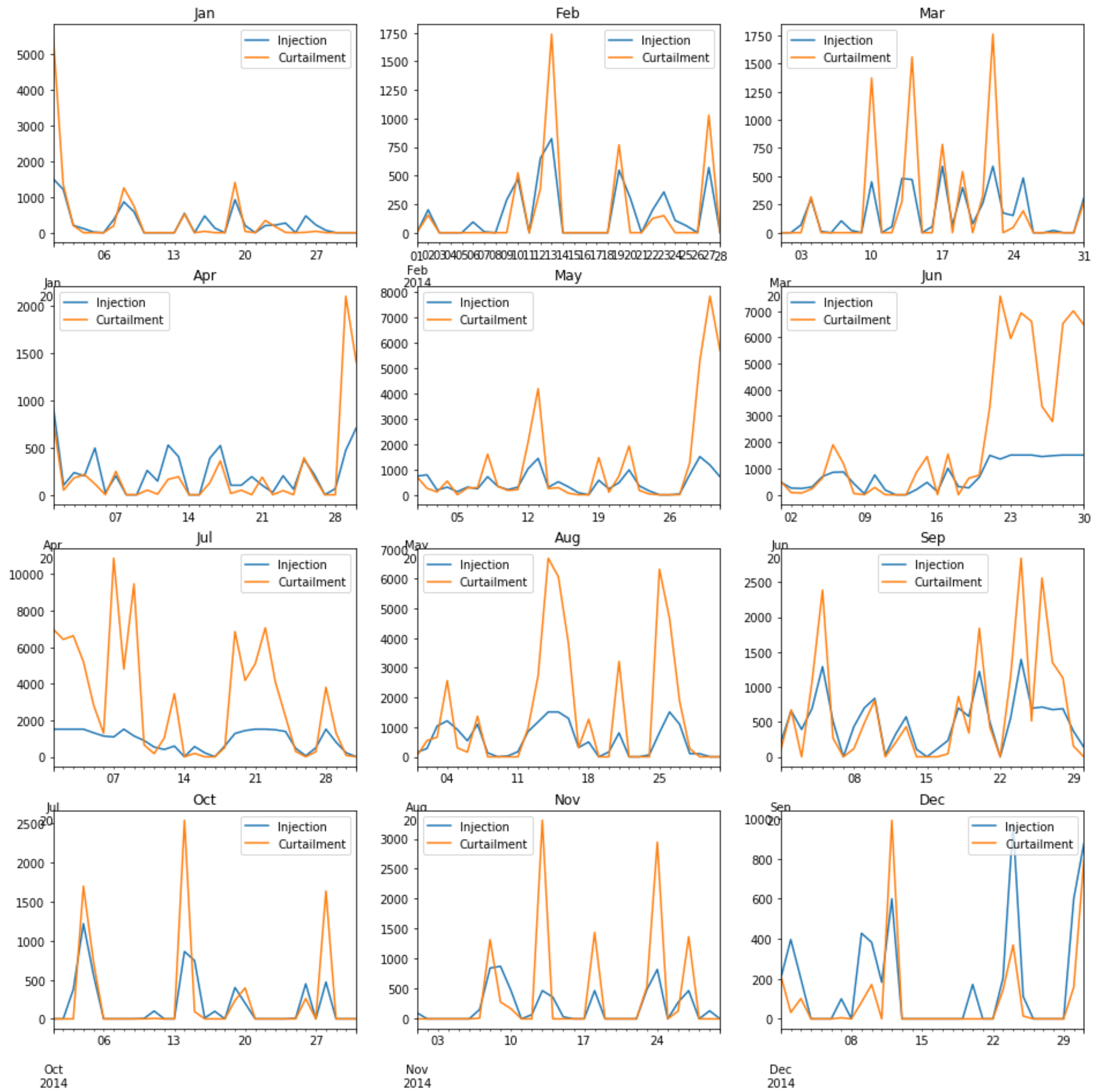


100 MW / 400 MWh configuration

Table 17: Dispatch plan in one scenario for a single day using a 100 MW/400 MWh battery configuration

	Curtailment	Injection	State of Charge	Transmission	Wind Power	Withdrawal
01-01-14 0:00	151.079	58.8235	0	486	695.9021	0
01-01-14 1:00	143.191	100	50	486	729.1908	0
01-01-14 2:00	89.6424	100	135	486	675.6424	0
01-01-14 3:00	63.1934	100	220	486	649.1934	0
01-01-14 4:00	191.117	100	305	486	777.1174	0
01-01-14 5:00	411.96	0	390	386	797.9603	100
01-01-14 6:00	216.845	100	290	486	802.8454	0
01-01-14 7:00	406.015	0	375	386	792.0152	100
01-01-14 8:00	3.36622	100	275	486	589.3662	0
01-01-14 9:00	0	0	360	355.954	355.9543	100
01-01-14 10:00	12.6524	0	260	386	398.6524	100
01-01-14 11:00	6.85594	100	160	486	592.8559	0
01-01-14 12:00	619.254	100	245	0	719.2539	0
01-01-14 13:00	353.634	0	330	386	739.6337	100
01-01-14 14:00	208.108	100	230	486	794.108	0
01-01-14 15:00	211.628	100	315	486	797.6275	0
01-01-14 16:00	417.679	0	400	386	803.6791	100
01-01-14 17:00	393.69	0	300	386	779.6899	100
01-01-14 18:00	180.207	100	200	486	766.2067	0
01-01-14 19:00	217.385	100	285	486	803.3855	0
01-01-14 20:00	396.086	0	370	386	782.0865	100
01-01-14 21:00	719.994	52.9412	270	0	772.9349	0
01-01-14 22:00	120.037	100	315	486	706.0372	0
01-01-14 23:00	36.8924	100	400	486	622.8924	0

Figure 10: Energy stored in the battery vs. energy curtailed in one scenario for a 100 MW/400 MWh battery



Monte Carlo Simulation Results

Table 18: 100 MW / 100 MWh

Scenario	Power Evacuation WITH Storage [MWh]	Power Evacuation WITHOUT Storage [MWh]	Curtailment WITH Storage [MWh]	Curtailment WITHOUT Storage [MWh]	Delta Power Evacuation [MWh]	Annual Savings[17] [$]
1	1871156	1844221	392105	445811	26934	2,962,822
2	1861990	1835453	400497	454579	26537	2,919,101
3	1877988	1851501	382621	438531	26487	2,913,621
4	1860821	1834663	402152	455369	26157	2,877,347
5	1867726	1841363	395809	448668	26362	2,899,861
6	1861485	1835173	400725	454859	26312	2,894,324
7	1885876	1858721	376045	431311	27155	2,987,097
8	1889577	1862915	371095	427117	26662	2,932,820
9	1889270	1862669	372695	427363	26601	2,926,142
10	1876299	1848969	385844	441063	27330	3,006,304
AVG	**1874219**	**1847565**	**387958.8**	**442467.1**	**26653.7**	**2,931,944**

Table 19: 100 MW / 200 MWh

Scenario	Power Evacuation WITH Storage [MWh]	Power Evacuation WITHOUT Storage [MWh]	Curtailment WITH Storage [MWh]	Curtailment WITHOUT Storage [MWh]	Delta Power Evacuation [MWh]	Annual Savings [$]
1	1896432	1857319	355408	432712	39112	4,302,338
2	1885505	1847209	365342	442822	38295	4,212,557
3	1883045	1842956	369498	447075	40088	4,409,786
4	1867058	1828371	384156	461660	38686	4,255,558
5	1896447	1855549	356337	434483	40898	4,498,825
6	1901380	1861885	350873	428147	39495	4,344,507
7	1880893	1840754	370601	449278	40139	4,415,350
8	1875400	1835500	376456	454532	39900	4,389,058
9	1877018	1836885	373316	453146	40132	4,414,570
10	1893877	1854568	358169	435463	39309	4,324,025
AVG	**1885705.5**	**1846099.6**	**366015.6**	**443931.8**	**39605.4**	**4,356,657.4**

[17] Based on an average tariff of 110 $/MWh

Table 20: 100 MW / 400 MWh

Scenario	Power Evacuation WITH Storage [MWh]	Power Evacuation WITHOUT Storage [MWh]	Curtailment WITH Storage [MWh]	Curtailment WITHOUT Storage [MWh]	Delta Power Evacuation [MWh]	Annual Savings [$]
1	1885250	1833883	348420	456148	51366	5,650,342
2	1906486	1853928	327090	436103	52558	5,781,394
3	1881268	1829679	350433	460353	51589	5,674,835
4	1911252	1859665	321896	430366	51586	5,674,566
5	1878634	1828865	352306	461166	49769	5,474,633
6	1896027	1843865	337381	446167	52161	5,737,794
7	1900190	1848228	332538	441803	51961	5,715,781
8	1917713	1865130	314997	424901	52582	5,784,109
9	1893370	1842535	338087	447496	50834	5,591,830
10	1904347	1854563	329837	435469	49784	5,476,262
AVG	**1897454**	**1846034**	**335298.5**	**443997.2**	**51419**	**5,656,155**

Financial Analysis

The CAPEX for lithium ion cells and balance of plant (BOP) such as inverters and control systems are based on the latest lithium ion mega-project – Tesla's 100 MW/129 MWh project for South Australia signed on July 6th 2017.

CAPEX	**Unit Cost**	**Battery Configuration**		
	$/kWh	C: 100 MW/100 MWh	C/2: 100 MW/200 MWh	C/4: 100 MW/400 MWh
Battery packs	250	$25 million	$50 million	$100 million
BOP (incl. inverters)	320	$32 million	$32 million	$32 million
TOTAL		$57 million	$82 million	$132 million

Levelized Cost of Storage (LCOS) with Frequency Response (FR) & Energy Storage (ES)

CAPEX			
BESS with C/2 configuration: 100 MW/200 MWh (100 MWh for each Use Case)			$82 million
Energy Storage capacity usage by Use Case			
Cycling (charge/discharge cycles)	100 MWh		
Frequency Response (FR)	100 MWh	FR Payment charge ($/MW-y)	65,000[18]
Revenues			
UC 1: Curtailment reduction	26,654 MWh	Curtailment costs saved ($/y) based on 110 $/MWh average WPP tariff	$2,931,940
UC 2: WPP paying BESS for delivering Frequency Response on its behalf	810 MW	FR Revenues ($/y)	$6,500,000
Total Revenues ($/y)	$11,031,940		
Expenses			
Total Expenses ($/y)	$695,000		
Current $ Level Cost of Storage: 205 $/MWh (20.5 $c/kWh)			
Constant $ Level Cost of Storage: 146 $/MWh (14.6 $c/kWh)			

[18] Ancillary Services are presently not provided by IPPs as a dedicated service and there are no tariffs from NEPRA, nor is there a competitive market. In order to provide the feasibility of using a BESS to provide "primary and secondary control" on behalf of WPPs, the marginal price from the most recent German PRL auction discounted by 50% was used.

Levelized Cost of Storage (LCOS) with Energy Storage (ES only)

CAPEX			
BESS with C/2 configuration: 100 MW/200 MWh			$82 million
Energy Storage capacity usage by Use Case			
Cycling (charge/discharge cycles)	200 MWh		
Revenues			
UC 1 only: Curtailment reduction	39,605 MWh	Curtailment costs saved ($/y) based on 110 $/MWh average WPP tariff	$4,356,657
Total Revenues ($/y)	$4,356,657		
Expenses			
Total Expenses ($/y)	$695,000		
Current $ Level Cost of Storage: 301 $/MWh (30.1 $c/kWh)			
Constant $ Level Cost of Storage: 214 $/MWh (21.4 $c/kWh)			

NOTE: The Excel sheet containing the Financial Model is provided in Appendix C

Environmental Impact

There are numerous environmental issues to consider with lithium ion batteries. Lithium can pose significant disposal hazards. While many lithium compounds used in industrial processes are harmless, even a small amount of elemental lithium reacts violently, sparking flames in contact with water. This makes it critical to prevent leaching from landfills into groundwater. Flammable organic solvents in lithium batteries can be ignited by a spark, also making them potentially dangerous in landfills.

Most of the potential negative impacts to the environment can be avoided by following international best practices. It is assumed that the first operator of the Pilot BESS would be a foreign company experienced in large utility-scale battery operations. Therefore it is expected that the foreign operator would provide its expertise in establishing standard operating procedures (SOPs) based on international best practices.

Land Usage

A two hundred MWh battery energy storage system would require approximately five acres of land. This is based on other lithium-ion battery projects such as the eighty MWh project at Southern California Edison's Mira Loma substation which uses one and a half acres of land. The land should be allocated in close proximity to the Jhimpir-2 substation.

Figure 11: Tesla's 80MW substation in Mira Loma, California

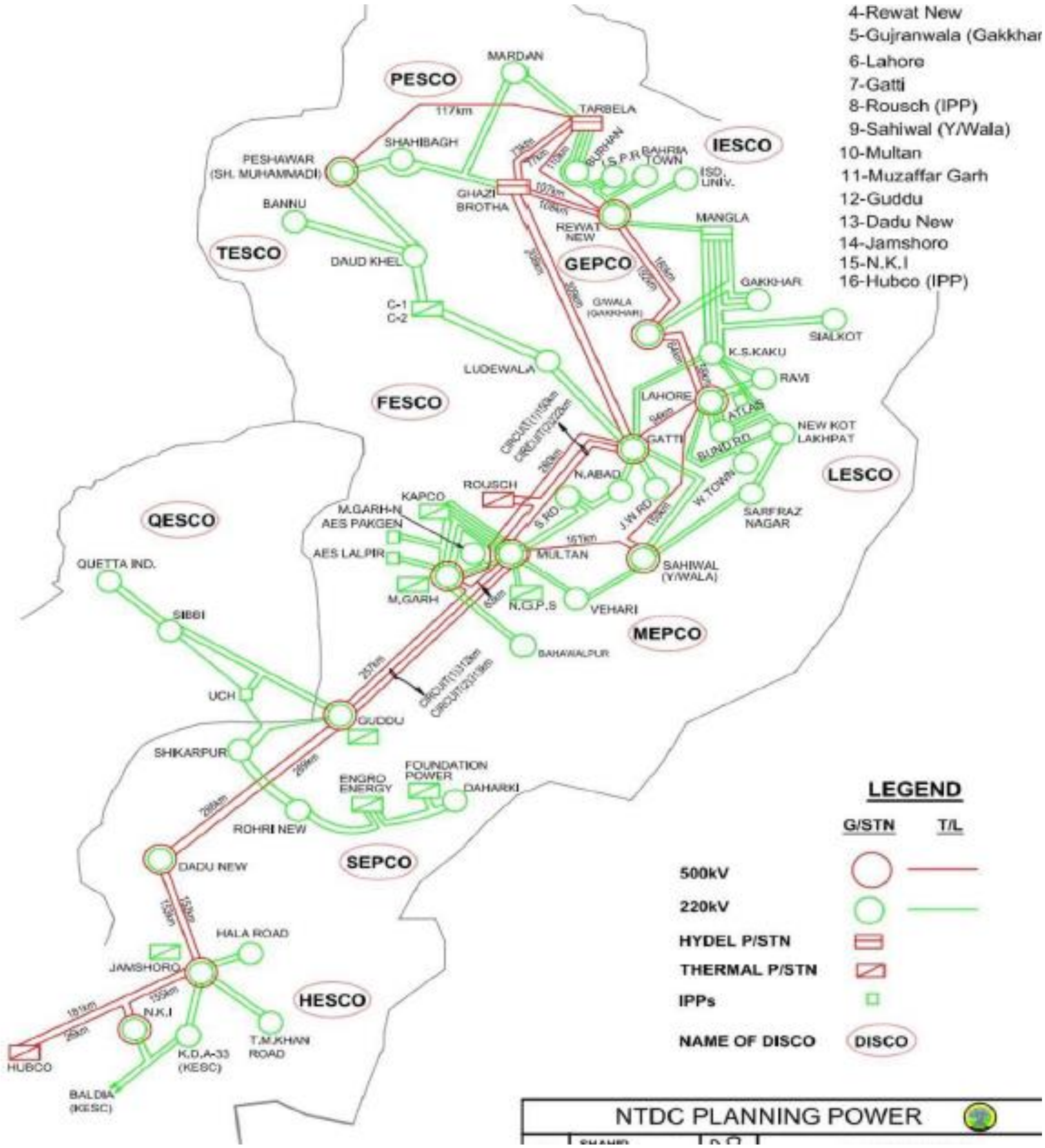
Appendix A – Curtailment events reported by FFC WPP in April and May 2017

SN	Date	Start Time	End date	End Time	Duration	Event	WPP power output	Lost energy [MWh]
1	02-Apr-17	9:40	02-Apr-17	18:28	8:48	Grid tripping	0	440.00
2	03-Apr-17	8:35	03-Apr-17	17:57	9:22	Grid tripping	0	468.33
3	04-Apr-17	9:41	17-Mar-17	18:06	8:25	Grid tripping	0	420.83
4	05-Apr-17	9:35	05-Apr-17	10:07	0:32	Curtailment	16	18.13
5	05-Apr-17	10:08	05-Apr-17	11:42	1:34	Grid tripping	0	78.33
6	05-Apr-17	11:43	05-Apr-17	18:27	6:44	Curtailment	16	228.93
7	05-Apr-17	18:28	05-Apr-17	22:55	4:27	Curtailment	25	111.25
8	06-Apr-17	18:02	06-Apr-17	18:45	0:43	Curtailment	20	21.50
9	06-Apr-17	18:46	06-Apr-17	20:38	1:52	Curtailment	30	37.33
10	12-Apr-17	17:43	12-Apr-17	18:59	1:16	Curtailment	25	31.67
11	14-Apr-17	17:22	14-Apr-17	19:45	2:23	Curtailment	25	59.58
12	22-Apr-17	6:19	22-Apr-17	6:41	0:22	Grid tripping	0	18.33
13	22-Apr-17	7:13	22-Apr-17	9:10	1:57	Curtailment	5	87.75
14	25-Apr-17	14:18	25-Apr-17	14:38	0:20	Grid tripping	0	16.67
15	25-Apr-17	14:39	25-Apr-17	18:50	4:11	Curtailment	15	146.42
16	26-Apr-17	8:21	26-Apr-17	10:12	1:51	Curtailment	36	25.90
17	26-Apr-17	10:13	26-Apr-17	10:25	0:12	Curtailment	46	0.80
18	27-Apr-17	16:00	27-Apr-17	19:05	3:05	Curtailment	34	49.33
19	28-Apr-17	16:22	28-Apr-17	19:01	2:39	Curtailment	25	66.25
20	29-Apr-17	18:45	29-Apr-17	19:28	0:43	Curtailment	21	20.78
							TOTAL	**2348.13**

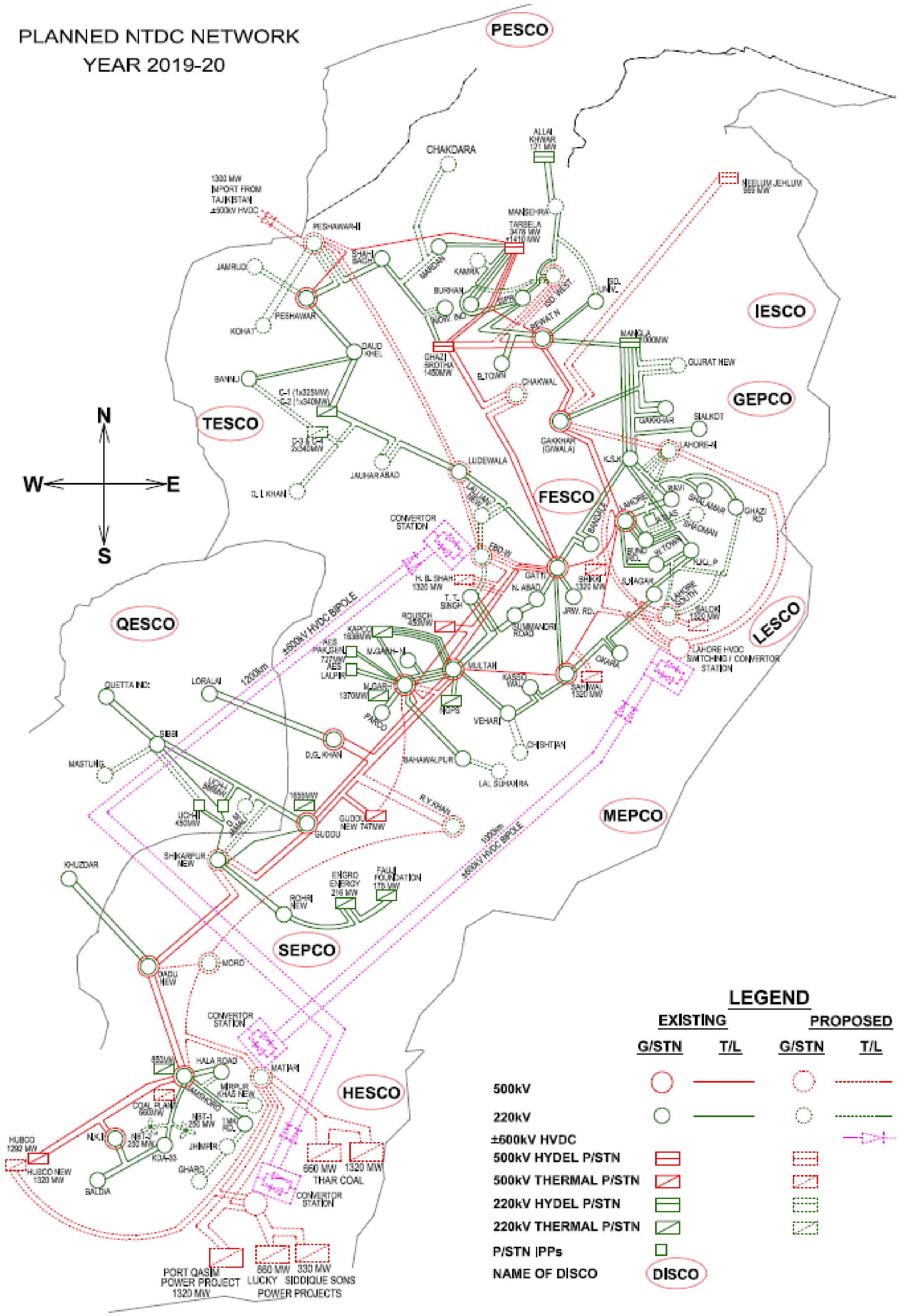
SN	Date	Start Time	End date	End Time	Duration	Event	WPP power output	Lost energy [MWh]
1	02-May-17	16:50	02-May-17	20:47	3:57	Curtailment	30	79.00
2	03-May-17	16:24	03-May-17	19:10	2:46	Curtailment	30	55.33
3	04-May-17	14:27	04-May-17	15:03	0:36	Grid tripping	0	30.00
4	04-May-17	15:21	04-May-17	15:48	0:27	Curtailment	20	13.50
5	05-May-17	16:15	05-May-17	19:50	3:35	Curtailment	35	53.75
6	06-May-17	9:20	06-May-17	18:00	8:40	Curtailment	10	346.67
7	06-May-17	18:01	06-May-17	19:16	1:15	Curtailment	25	31.25
8	07-May-17	6:00	07-May-17	16:45	10:45	Curtailment	5	483.75
9	07-May-17	16:46	07-May-17	16:57	0:11	Curtailment	10	7.33
10	07-May-17	16:58	07-May-17	17:06	0:08	Grid tripping	0	6.67
11	07-May-17	17:07	07-May-17	18:00	0:53	Curtailment	10	35.33
12	07-May-17	18:01	07-May-17	19:55	1:54	Curtailment	25	47.50
13	08-May-17	7:28	08-May-17	9:30	2:02	Curtailment	20	61.00
14	08-May-17	13:02	08-May-17	20:25	7:23	Curtailment	10	295.33
15	09-May-17	9:51	09-May-17	11:39	1:48	Curtailment	16	61.20
16	09-May-17	12:57	09-May-17	18:35	5:38	Curtailment	16	191.53
17	14-May-17	12:50	14-May-17	20:33	7:43	Curtailment	25	192.92
18	15-May-17	13:33	15-May-17	22:02	8:29	Curtailment	25	212.08
19	16-May-17	15:28	16-May-17	20:38	5:10	Curtailment	25	129.17
20	18-May-17	10:35	18-May-17	20:38	10:03	Curtailment	30	201.00
21	19-May-17	10:33	20-May-17	9:35:00	23:02	Curtailment	25	575.83
22	21-May-17	14:53	22-May-17	24:00:00	9:07	Curtailment	30	182.33
23	22-May-17	13:50	22-May-17	20:21	6:31	Curtailment	30	130.33
24	22-May-17	22:05	22-May-17	23:55	1:50	Curtailment	30	36.67
25	23-May-17	9:52	23-May-17	10:58	1:06	Curtailment	30	22.00
26	23-May-17	10:59	23-May-17	23:00	12:01	Curtailment	25	300.42
27	25-May-17	16:44	25-May-17	17:10	0:26	Grid tripping	30	8.67
28	25-May-17	18:14	25-May-17	20:18	2:04	Curtailment	15	72.33
29	25-May-17	20:19	25-May-17	21:00	0:41	Curtailment	25	17.08
30	27-May-17	14:05	27-May-17	18:04	3:59	Curtailment	30	79.67
31	28-May-17	2:48	28-May-17	3:41	0:53	Grid tripping	0	44.17
32	28-May-17	6:33	28-May-17	6:42	0:09	High Frequency	0	7.50
33	28-May-17	6:42	28-May-17	8:07	1:25	Grid tripping	0	70.83
34	30-May-17	4:17	30-May-17	8:17	4:00	Grid tripping	0	200.00
							TOTAL	**4282.15**

Appendix B – Network Diagrams

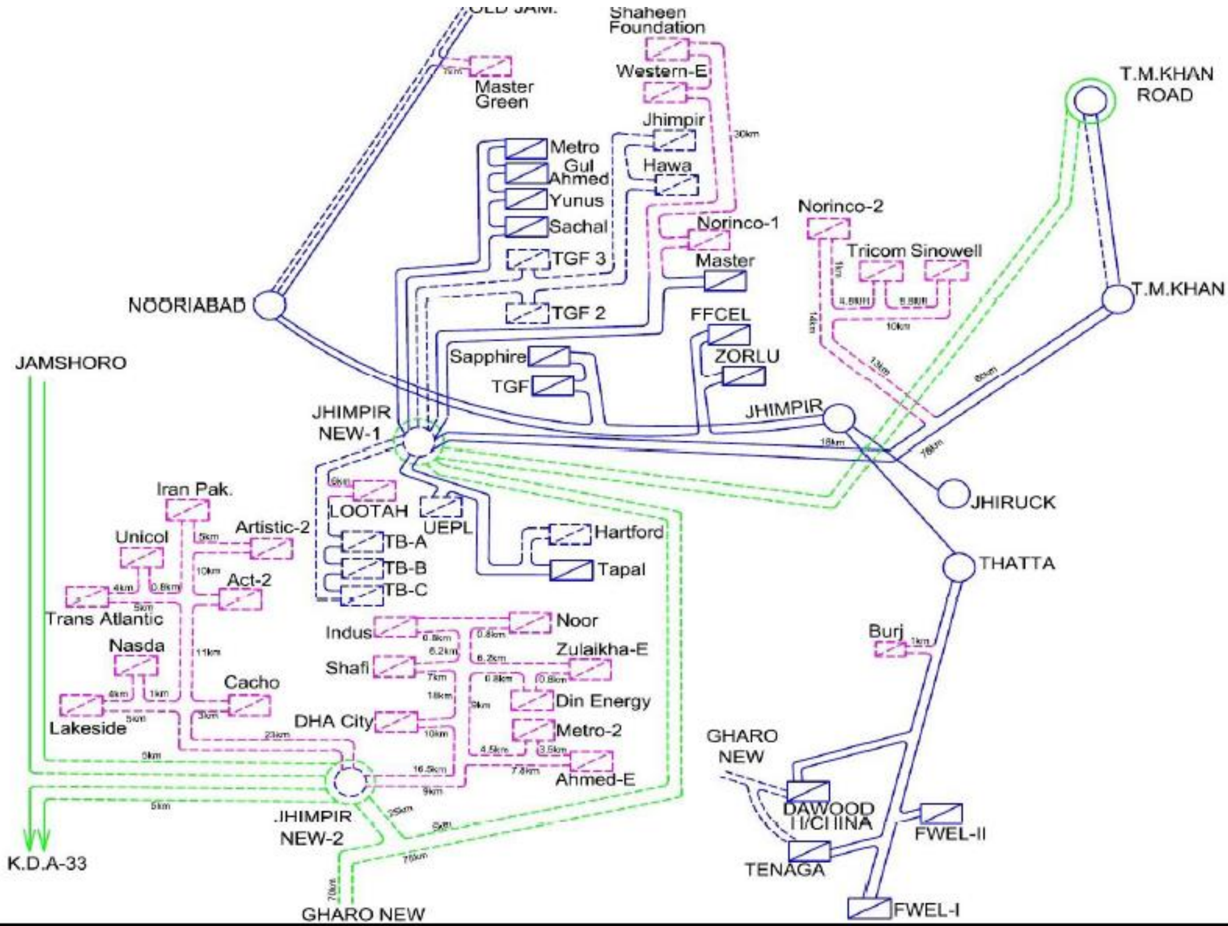
NTDC EHV network 2014



PLANNED NTDC NETWORK YEAR 2019-20



Planned network connection of wind farms in Jhimpir



Appendix C – Financial model

BESS financial model.xlsx