

Resiliency and Environmental Sustainability

An Evaluation and Quantification of NJ TRANSITGRID Benefits

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NJ TRANSITGRID Benefits Evaluation Acronyms

AMPD	Air Markets Program Data
AVERT	US EPA Avoided Emissions and Generation Tool
BPU	New Jersey Board of Public Utilities
C&I	Commercial and Industrial
CAIDI	Customer Average Interruption Duration Index
СНР	Combined Heat and Power
CO2	Carbon Dioxide
DEIS	Draft Environmental Impact Statement
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Agency
EPA	U.S. Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
FTA	Federal Transit Administration
GhG	Greenhouse Gas
H2	Hydrogen Gas
HBLR	Hudson-Bergen Light Rail
HHV	Higher Heating Value
ICE	Interruption Cost Estimate Calculator
IEEE	Institute of Electrical and Electronics Engineers
LHV	Lower Heating Value
Li-ion	Lithium-Ion
LMP	Locational Marginal Price
LOEE	Loss of Energy Expectation
M&E	Morris & Essex Line
MMBtu	1 Million Btu (British Thermal Units)
MOU	Memorandum of Understanding
MW	Megawatts
MWh	Megawatt Hour
NEC	Northeast Corridor
NERC	North American Electric Reliability Corporation
NJ TRANSIT	New Jersey Transit Corporation
NJ TRANSITGRID	NJ TRANSITGRID Traction Power System
NREL	National Renewable Energy Laboratory
O&M	Operation & Maintenance
OWEDA	New Jersey Offshore Wind Economic Development Act
PEP	Purchased Electric Power (Tariff)
PURPA	Public Utility Regulatory Policies Act
PV	Photovoltaic
REC	Renewable Energy Certificate
RNG	Renewable Natural Gas
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SOC	State-Of-Charge
PJM	Pennsylvania-New Jersey-Maryland Interconnection
IPCC	International Panel on Climate Change
WACC	Weighted Average Cost of Capital





NJ TRANSITGRID Benefits Evaluation Executive Summary

The purpose of this document is to evaluate and quantify the full value of the NJ TRANSITGRID Traction Power System (NJ TRANSITGRID) project. This value includes enhanced resiliency through the provision of highly reliable power and significant environmental benefits through replacement of the current greenhouse gas (GhG) intensive grid-supplied energy. NJ TRANSITGRID will use the cleanest, most efficient and sustainable technologies currently available (including solar, fly wheel storage, and gas generation) to meet its advanced power quality and resiliency needs. The *NJ TRANSITGRID Benefits Evaluation* is provided in three parts:

- *Part 1: Overview of NJ TRANSITGRID Benefits* This section defines the goals of the project and presents the technical and economic background necessary to understand the full scope of the project benefits.
- Part 2: Environmental Benefits Analysis This section describes the development of a
 detailed model of NJ TRANSITGRID and its use in quantifying the environmental benefits
 discussed in Part 1. The model is intended to highlight and explain important elements of
 the proposed design including when it will run and the measure of the environmental
 benefits that result from its use. This model provides direct measures that substantiate
 and validate NJ TRANSITGRID environmental benefits.
- Part 3: Reliability and Flexibility Benefits Analysis This section describes a reliability model of NJ TRANSITGRID used to quantify and value the reliability and flexibility benefits to the grid. In addition to a quantification of the benefits that accrue directly to the New Jersey Transit Corporation (NJ TRANSIT) system, other benefits such as grid stress release and reduction of peak load power on local circuits are also examined. A novel concept for the development of a market for these benefits is discussed as a potential way to monetize these benefits, bring needed support to the local grid, and enhance the economic feasibility of the program making its economic and societal benefits available to all stakeholders.

Part 1: Overview of NJ TRANSITGRID Benefits

Part 1 establishes that NJ TRANSITGRID is firmly within the goals of Governor Murphy's Executive Order 28 to support New Jersey's *Clean Energy Economy* as well as the complementary goals of enhancing infrastructure resiliency. The design for NJ TRANSITGRID emerged with a vision of a new highly efficient power plant controlled by NJ TRANSIT that would energize critical components in a core segment of the NJ TRANSIT and Amtrak service territory. The new plant would operate under normal or "blue-sky" conditions and provide for substantial continuation of service under emergency or "black-sky" conditions that may include a regional grid failure.

By establishing a power source independent of the grid and new wire connections to its traction power system, NJ TRANSITGRID sets the stage for a generation of innovation leading to the use of increasingly efficient and cleaner energy production. The resulting environmental





NJ TRANSITGRID Benefits Evaluation Executive Summary

benefits will help the State of New Jersey and contribute to the global effort for immediate and significant reductions in its GhG emissions. NJ TRANSITGRID also provides another important clean energy component by providing increased flexibility to the power system to manage the variability and uncertainty of renewable generation. Analysis shows that although solar, wind and battery technologies are making great advancements, natural gas-powered resources are still crucial to our vital infrastructure. By providing a firm commitment to support renewables and innovative energy storage, including flywheels and solar, while operating at peak efficiencies, NJ TRANSITGRID is a vital bridge to a cleaner energy future.

Part 2 – Environmental Benefits Analysis

The model developed for evaluation and quantification of environmental benefits of NJ TRANSITGRID is divided in four main components. The first component describes projected energy production, which is key to the calculation of how often and when the power plant will run. A supply curve is developed to estimate how often the plant will run based on price signals provided by the wholesale energy market. The market will only call or purchase energy when that energy being produced is less expensive than other energy being produced at that time. Using this supply curve, an hourly dispatch and generation schedule is developed. Then a baseline estimate of emissions is determined using operations data for the power plant.

The second component of the model estimates the displacements of GhG. As NJ TRANSITGRID is more efficient and less polluting than most power plants, there is a net environmental benefit gained by replacing power from Regional Fossil Generation Fleet including other natural gas-powered plants and highly polluting coal plants.

The third component of the model evaluates enhanced benefits that will result from the use of more progressive energy systems such as an expanded solar and energy storage system. Cogeneration or the use of waste heat energy to provide thermal energy to a nearby off-taker, and cleaner and more sustainable alternative fuels such as Renewable Natural Gas (RNG) and Hydrogen Gas (H2) that can displace the use of natural gas.

The fourth component includes a high-level summary and comparison of results including Emission Factor by Generation Source (a summary of the volumes of GhG emissions by technology); Annual GhG Displacement by Generation Source (a summary of the displacements and avoided emissions that result from NJ TRANSITGRID production; and Enhanced Benefits (a summary of potential additional avoided emissions that result from NJ TRANSITGRID operations using developing technologies).

Part 3 – Reliability & Flexibility Benefits Analysis

An Internal Reliability Model and External Reliability Model are developed to quantify and value the reliability and flexibility benefits to the power grid that result from the operation of NJ TRANSITGRID. The Internal Reliability Model tests the ability of the new system to respond to contingencies at its three internal connections including the Amtrak portion of the Northeast





NJ TRANSITGRID Benefits Evaluation Executive Summary

Corridor (NEC) line, the Morris & Essex (M&E) line via the Mason Substation and to the Hudson-Bergen Light Rail (HBLR) line via a new NJ TRANSITGRID East Hoboken Substation. The External Reliability Model assumes that only the connection at the Mason Substation will be feasible as a connection via switches and the existing distribution network wires to reconnect blocks of external utility customers during contingencies.

For both models, the methodology proceeds in three steps. The first is to assign a baseline reliability measure to the substations that are connected to NJ TRANSITGRID. The second step is to then quantify the probability that NJ TRANSITGRID will be available to energize the connections at a time when the grid may fail. The third step uses the baseline reliability measure developed in Step 1 and the capacity available developed in Step 2 to quantify the amount of energy that NJ TRANSITGRID will be able to provide in the event of grid outages. For the internal model, this results in increased reliability for NJ TRANSITGRID passengers with fewer delays and stoppages. A key component of the External Reliability Model is an estimation of the fair market price for reliability and flexibility services that NJ TRANSITGRID could offer to the utility for its connected customers.





Part 1: Overview of NJ TRANSITGRID Benefits





NJ TRANSITGRID Benefits Evaluation Part 1: Overview of NJ TRANSITGRID Benefits

Introduction

Consistent with the Clean Energy goals of Governor Murphy's Executive Order 28, New Jersey Transit Corporation (NJ TRANSIT) is taking decisive actions to become the first transit agency in the nation to invest in its own resilience and sustainability related to its electric power supply. NJ TRANSITGRID is a first-of-its-kind transit microgrid designed to provide highly reliable power in a core segment of the NJ TRANSIT and Amtrak critical service territory. The project will be the most modernized and efficient traction power system in the United States. NJ TRANSITGRID will deploy efficient and environmentally sound technologies, including energy storage and solar photovoltaic (PV) generation, to produce power for NJ TRANSIT and Amtrak operations, replacing the current use of GhG intensive grid-supplied energy.

The innovative design of NJ TRANSITGRID will allow it to evolve with developments in new clean energy technology and continue to produce even cleaner power to reach the goals of Governor Murphy's Executive Order 28. Absent these investments, NJ TRANSIT would continue to be captive to grid-supplied power in terms of reliability, environmental quality and GhG emissions related to energy production and transmission. This project is consistent with the Governor's goals and actively advances those goals in a way that sets an example for other public agencies.

NJ TRANSIT is already an inherently 'green' mass transit operation. Each rider who gets out of their car to ride a commuter train, light rail or a bus every day decreases their carbon foot print by almost half.¹ This reduction of GhG is amplified when in times of increased reliance on public transit such as during severe weather events like Superstorm Sandy, region-wide power losses such as the 2003 Northeast blackout and homeland security emergencies. Likewise, on heavy road congestion days and traffic-alert days when higher than usual volumes of car and truck traffic crowd the state's highways, bridges and tunnels NJ TRANSIT serves a vital purpose to keep people and goods moving and must remain reliable and operational during critical times.

The following report highlights the various advantages and critical operational benefits NJ TRANSITGRID will bring to NJ TRANSIT and its ridership that relies on it to get them to their work, home and entertainment every day and presents a rationale and methodology for the evaluation and quantification of some of the environmental and economic benefits associated with the NJ TRANSITGRID project. While the resiliency benefits to be derived from NJ TRANSITGRID are well understood, this paper will demonstrate the alignment of grid resilience with New Jersey's Clean Energy goals and how NJ TRANSITGRID will advance the directives of Governor Murphy's Executive Order 28 to support New Jersey's Clean Energy Economy.





NJ TRANSITGRID Benefits Evaluation Part 1: Overview of NJ TRANSITGRID Benefits

Background

NJ TRANSITGRID was initially undertaken by NJ TRANSIT and the New Jersey Board of Public Utilities (BPU) in cooperation with the U.S. Department of Energy (DOE) and the Federal Transit Administration (FTA) following the massive public transportation disruptions that occurred in the wake of Superstorm Sandy in October 2012. In August 2013, a Memorandum of Understanding (MOU) was signed between the state and federal partners to advance a project with the overall objective to ensure reliable provision of electric power to key public transportation assets providing services along New Jersey's Hudson River coastline and the Newark area.

In February 2014, the U.S. DOE Sandia National Laboratory published a report of its feasibility analysis of the proposed NJ TRANSITGRID project including details of a planned traction power microgrid supplied by natural gas-fired generation, and several distributed generation systems for facilities not connected to the transit microgrid. In September 2018, a Design Criteria Manual and 20% design drawings were developed by the Jacobs Engineering Group (Jacobs) and represent the most current version of the NJ TRANSITGRID technical specifications. Additional studies of the project's feasibility included a July 2017 study by Levitan & Associates of the potential economic return on investment (Economic Screening Analysis) and a May 2019 Draft Environmental Impact Statement (DEIS) prepared by the FTA and in cooperation with NJ TRANSIT.²

The proposed project would include a natural gas-fired electric power generating plant (referred to as the Main Facility), and the electrical lines, substations and other emergency generators to distribute the power to required areas. The Main Facility would utilize combined-cycle technology resulting in power generation capacity of 104 to 140 megawatts (MW). The preferred site for the Main Facility is in Kearny, Hudson County, New Jersey. The electrical lines would be located in Kearny, Jersey City, Hoboken, Bayonne, Weehawken, Union City, and North Bergen, New Jersey; specifically, within or adjacent to the existing Morris & Essex Rail Line between Newark, NJ and Hoboken Rail Yard; and the Hudson Bergen Light Rail Line.

NJ TRANSITGRID: Resilient Power Supply for Vital Transportation Infrastructure

From the initial 2013 MOU through to the completion of the 20% engineering designs, the primary objective of NJ TRANSITGRID has been to improve the resiliency of the electricity supply to key NJ TRANSIT and Amtrak infrastructure, including traction power systems and their auxiliary and supporting services (i.e., signal and control power, power for track switches and switch heaters, power for movable bridges and tunnels, etc.).

NJ TRANSITGRID, once built, will be able to use its Main Facility to energize the connected rail lines under blue-sky" conditions and provide for substantial continuation of service under black-sky conditions that may include a regional grid failure. The NJ TRANSITGRID power system will be connected in parallel to PJM transmission circuits and therefore also be able to





Part 1: Overview of NJ TRANSITGRID Benefits

participate in wholesale energy markets (meaning, among other things, that it could share its efficient power with others).³ The resiliency benefits to be derived from the NJ TRANSITGRID Project are well understood and have been extensively documented elsewhere.⁴

These resiliency benefits stem from the ability of the traction power microgrid to stay energized and actively connected to the rail systems during events ranging from intermittent brown outs that adversely affect safety, surveillance and control equipment to wide-spread utility outages. In such black-sky conditions, NJ TRANSITGRID will provide continuity of operation to the commuter trains, allow the securing and storing of valuable equipment and the performance of critical emergency activities to prepare for and recover from blackouts, flooding events, emergencies and damaging winds. In addition, NJ TRANSIT's ability to operate during times of emergency helps to keep essential emergency and human service support personnel reasonably accessible and out of their cars at critical times when emergency services often need enhanced access to the road network.

New Jersey's Clean Energy Economy

From Resiliency to Economic and Environmental Sustainability

In addition to these vital resiliency benefits, there are other highly valuable societal and regional environmental and economic benefits that will result immediately from implementation of the NJ TRANSITGRID. These benefits include decreased and avoided emissions of criteria air pollutants and GhG from power generation. This results when the newer, more efficient and cleaner NJ TRANSITGRID turbines replace power currently supplied to the NJ TRANSIT and Amtrak systems by older, less efficient production in the PJM energy stack - including legacy coal-fired power plants.

There are also the decreased and avoided general societal economic costs and savings to New Jersey utility ratepayers that will result from the deployment of NJ TRANSITGRID. These benefits stem from the deferral or avoidance of distribution and transmission system upgrades (that otherwise would have been necessary absent the project), decrease in line losses, reduced utility Operations & Maintenance (O&M) costs, generator fuel savings, and reduced line congestion. NJ TRANSIT will also benefit economically from controlling its own power production, using more efficient power generation and zero fuel-cost PV generation.

There will be, as well, mid-term and long-term societal and regional environmental and economic benefits provided by NJ TRANSITGRID through support of increased deployment and use of renewable energy in the state. On May 23, 2018, Governor Murphy signed Executive Order 28 calling for the completion of the 2019 New Jersey Energy Master Plan with a comprehensive blueprint for the total conversion of the State's energy production profile to 100% clean energy sources on or before January 1, 2050. This plan will put into place a process towards a carbon-





Part 1: Overview of NJ TRANSITGRID Benefits

neutral power generation fleet in New Jersey providing net-zero carbon dioxide (CO₂) emissions to slow and eventually reverse the pace of global climate change.

Grid Flexibility and Deep Decarbonization

The goal of net-zero by 2050 in the power generation sector expressed in Executive Order 28 is consistent with the findings and recommendations of the 2018 International Panel on Climate Change (IPCC) Special Report that indicates reaching net-zero in world-wide emissions of CO_2 is required to limit global warming to no more than 1.5° C above pre-industrial levels.⁵ Pathways to climate stabilization that pass through net-zero by 2050 will require many structural and procedural changes in the power producing sector of the economy including significant improvements in energy efficiency, the electrification of energy end use (such as the replacement of conventional cars and trucks with electric vehicles) and a rapid decarbonization of electrical power generation.⁶ Decarbonization, defined as a reduction in CO_2 emissions from current levels, will require the widespread adoption of zero-carbon emitting power sources coupled with the use of cleaner and more efficient fossil-fuel generation to provide the operational flexibility required of future power systems characterized by highly variable renewable resources. The NJ TRANSITGRID project puts NJ TRANSIT on a path that is consistent with these goals.

New Jersey is already a leader in the adoption of Clean Energy. New Jersey has one of the highest production rates of PV power in the country⁷ and in April 2018 New Jersey passed legislation enabling the establishment of community solar programs, which promises to add another 150 MW of distributed PV production by 2022. New Jersey is also on track to create one of the first, and largest, state programs for the promotion of an offshore wind industry. In January 2018, Governor Murphy Signed Executive Order 8 to fully implement the Offshore Wind Economic Development Act (OWEDA) in order to meet a goal of obtaining 3,500 MW from offshore wind by the year 2030.

Higher penetrations of renewable power from solar and wind requires increased flexibility from the power system to manage the variability and uncertainty of the generation. Grid flexibility in this context refers to closely aligning supply and demand – a task made increasingly more difficult by the addition of renewable power whose supply is difficult to forecast and may or may not align with the demand profile. This mismatch between supply and demand leads to requirements for fast up or down ramping of dispatchable resources to meet the system load when renewable supply cannot. ⁸ Increased flexibility in the grid will avoid overbuilding of renewable capacity to ensure reliability. Such overbuilding can lead to curtailment of production, lower capacity factors, and reduced return on investment for utilities and energy developers.⁹ The NJ TRANSITGRID project is a good example of the type of project designed to provide such flexibility and efficient balancing of resources to support the adoption of increased levels of clean renewable energy.





Part 1: Overview of NJ TRANSITGRID Benefits

All power systems have some level of flexibility designed to balance supply and demand. Much of the flexibility needed by power systems is provided by thermal and hydro generators. Operational requirements of such plants—the ability to ramp quickly, operate across a wider output range, and start up and shut down more quickly—are essential for managing system variability. New plants, particularly combined- and simple-cycle gas turbines (like NJ TRANSITGRID) show extremely flexible characteristics as they have the ability to operate at low minimum output with good efficiency, high ramp rates, and low start times.¹⁰

Likewise, energy storage assets such as the flywheels that are part of the NJ TRANSITGRID project, contribute to grid flexibility by providing high-quality ancillary regulation services such as voltage and frequency regulation. Flywheels recycle energy from the grid in response to changes in demand and grid frequency. When generated power exceeds load, the flywheels store the excess energy. When load increases, the flywheels return the energy to the grid. The flywheel system can respond nearly instantaneously to an independent system operator's control signal at a rate 100 times faster than traditional generation resources.¹¹ The operational flexibility of NJ TRANSITGRID using gas turbines and flywheels will only increase in efficiency, environmental benefit, and overall value as renewables make up a greater share of the electricity supply.

NJ TRANSITGRID Innovation

As may be seen from the previous discussion, the increased penetration of renewables to meet Clean Energy goals, with their near zero marginal costs of operation, coupled with the need for increased grid flexibility to support them, may alter the traditional way the energy resources available to power system operators is understood and valued. The Massachusetts Institute of Technology (MIT) Energy Initiative has suggested in recent work a conceptual realignment and redefinition of the attributes of generating technologies to allow for a better assessment of the value of their production output in support Clean Energy goals. The attributes include: fuel-saving variable renewable energy resources such as wind power and PV; fast-burst balancing resources to meet instantaneous regulation demand; and firm low-carbon resources necessary to meet energy demand through fast up or down ramping or low-power generation.¹² The NJ TRANSITGRID unique and forward-looking solution provides a combination of all three attributes in the form of high-efficiency natural gas generation (potential for firm-low carbon resource), PV generation (fuel saving resource), and flywheel energy storage (fast burst resource).

NJ TRANSITGRID is being designed to take advantage of anticipated advancements in technology and market availability that offer cleaner alternatives for the application of firm low-carbon resources, such as the use of RNG or H2 fuel cells¹³, each of which will lead to deep reductions in the output of GhG. Although some of these potential benefits rely on contingencies (e.g., the future availability of new critical technology or a continuation in the decline in costs of





Part 1: Overview of NJ TRANSITGRID Benefits

renewable resources) the proposed major realignment of the underlying NJ TRANSIT and Amtrak infrastructure as part of the NJ TRANSITGRID project allows NJ TRANSIT to assert control over its own power supply, in a way that allows it to use cleaner and more efficient power. By doing so it can take advantage of general trends in the economics and technology of clean power to quicken the pace of innovation and capture the benefits of a cleaner, more efficient and resilient grid for the state of New Jersey.

Could NJ TRANSITGRID go to Net-Zero Emissions in the Short Term?

As indicated, NJ TRANSITGRID is being designed to take advantage of anticipated midterm to long-term technical innovations that will provide a path to net-zero by 2050 for the New Jersey power generation sector. However, this statement may raise the question on why NJ TRANSITGRID would not just go to net-zero power production right away? Why not go immediately to net-zero power production using large-scale renewable energy resources (such as grid-scale PV) coupled with energy storage?¹⁴

The simplest answer to this question may be understood in the economics of constructing such a large-scale renewable power system that would be sufficient to offset the planned natural gas-fired power production of NJ TRANSITGRID. The power generating equipment will consist of two 22.5 MW natural gas-fired combined cycle turbines and three 22.5 MW simple cycle combustion turbines. The total annual energy output for these components is estimated to be 698,062 MW hours (MWh) per year assuming 100% capacity factor operation of the two combined cycle units (525,600 MWh/year) and 7 hours per day (average) for the three simple cycle combustion turbines (172,462 MWh/year). To produce this much energy using only solar power would entail construction of a PV power plant with a capacity of nearly 390 MWac¹⁵ requiring perhaps 2,600 acres of land (4.1 square miles)¹⁶ and at an estimated cost of \$600 - 800 Million to construct.¹⁷

This economic analysis of net-zero replacement of the NJ TRANSITGRID natural gasfired power generation, however, only considers grid-connected scenarios. To achieve the stated resiliency goals of the project, the solar and energy storage components would have to be able to operate disconnected from the grid during black-sky conditions. This scenario would add additional costs as large installations of energy storage components would have to be used to replace the energy, ancillary services and flexibility benefits that would otherwise be provided by the gas turbines.

The traction power system for the NJ TRANSIT and Amtrak service lines, along with all their auxiliary and supporting services require a complex power delivery system that relies on specialized equipment and critical voltage and frequency regulation. The electrified railways systems have no on-board power or fuel supply. Power is supplied to these trains with an overhead wire conductor (the overhead electric catenary system) while the running rails act as





Part 1: Overview of NJ TRANSITGRID Benefits

the return wire. Traction power substations located along the rail track right-of-way convert electric power to the required voltages, current types and frequencies. Although the solar panels of a large PV system could, in theory, provide the total energy required, the additional ancillary services needed in grid-connected and islanded modes to balance the system and provide frequency regulation must be provided by energy storage systems, such as flywheels and batteries, coupled with the PV power plant.

These ancillary services balance the supply and demand for power in the rail transmission and distribution systems and maintain system frequency within acceptable levels. For example, the electrified rail system encounters frequent high rates of change in power generation due to transient loads. It is estimated that additional step loads or instantaneous changes in demand for power on the system (resulting from a failure of power sources or electrical components, or a large consumer load start-up) are expected to be as high as 10.8 MW per second, while load rejection or the sudden loss of load (due to braking, for example) could be as high as 18.8 MW per second. The gas turbine power plant as designed, using some auxiliary energy storage components, has been finely tuned to address such contingencies. It is due to their ability to provide low-running spinning reserves and quick response flexibility to rapid changes in demand that gas turbines play such a crucial role in modern electricity supply systems.

Large-scale PV power plants cannot provide this type of flexibility and rapid cycling – in fact, the high variability of large-scale renewable energy output would only increase the requirements for flexibility in the system. Absent the use of dispatchable resources, the energy storage components must therefore provide such balancing, quick ramping and frequency regulation for NJ TRANSITGRID in islanded operation. Battery storage, however, is not amenable to this type of service. Although the cost of battery technology has decreased rapidly over the past few years, particularly for the lithium-ion (Li-ion) battery, making grid-scale energy storage economical in a growing range of uses, such a rapid cycling of charging and discharging of the batteries due to the frequent load/unload requirement of the system would quickly destroy the batteries making their repeated and costly replacement inevitable.

Flywheel energy storage systems, on the other hand, can provide the rapid cycling for frequency regulation without deleterious effects and provide the instantaneous supply of the large bursts of power on the order of 10-20 MW per second to match the anticipated step loads. The technical feasibility for this level of operation has already been demonstrated in grid-connected pilot projects. For example, Beacon Power opened a 5 MWh (20 MW over 15 mins) flywheel energy storage plant in Stephentown, New York in 2011 using 200 flywheels and a similar 20 MW system at Hazle Township, Pennsylvania in 2014.¹⁸ The installed costs of flywheel energy storage systems are estimated between \$1,500 - \$6,000 per kWh, therefore a flywheel energy storage system for NJ TRANSITGRID capable of providing the required short-term frequency support could cost between \$5-30 Million.¹⁹





Part 1: Overview of NJ TRANSITGRID Benefits

As flywheel energy storage systems are unsuitable for uses other than short-term storage (due in part to self-discharge rates of 15% or higher)²⁰ energy storage for NJ TRANSITGRID in islanded operation to support the PV power plant would most likely be provided by Li-ion batteries. For the 390 MWac PV power plant required to replace the natural gas-fired power components of NJ TRANSITGRID, the utility-scale energy storage system is estimated to require a battery size of 230 MWdc.²¹ Given the wide variety of uses required of the Li-ion batteries in island mode, storage duration amongst the battery arrays may vary between 0.5 - 4 hours.

For short durations (0.5 - 1 hours), energy storage would be used primarily to balance generation and load and smooth some short-term variations in voltage and current for frequency response not handled directly by the flywheel energy storage systems. For longer storage durations (2- 4 hours), the storage could shift energy supply to periods of low power production and mitigate variable energy output during peak operations.

This 230 MWdc battery storage system would require between 28 - 224 forty-foot containers (depending on the mix of storage duration per battery array) and cost between \$125 - \$425 Million dollars to install (using an estimate of \$380/kWh to \$895/kWh for 4-hour duration and 0.5-hour duration, respectively).²² This energy storage system, should it be built, would far exceed any existing utility-scale PV-plus-storage application. The only such U.S.-based utility-scale system recorded in the U.S. DOE Energy Storage Database is a 13-MW PV plus 52-MWh energy storage system in Kauai, Hawaii.²³

Quantification of NJ TRANSITGRID Benefits

In the sections that follow, the environmental and resiliency benefits of the proposed project are quantified. Part 2 of this report presents a detailed model of NJ TRANSITGRID to highlight and explain important elements of the proposed design including when it will run and the measure of the benefits that result from its use. Three dispatch schemes for generation and sale of excess energy by NJ TRANSITGRID are used to anticipate the total displacement of generation by conventional generation technologies of the U.S. Regional Fossil Generation Fleet, as well as specific steam coal baseload plants in Pennsylvania and natural gas-fired peaker generation plants in New Jersey.²⁴ Part 3 of this report presents an Internal Reliability Model and External Reliability Model to quantify and value the reliability and flexibility benefits of NJ TRANSITGRID. Additionally, a novel concept for the development of a market for reliability and flexibility benefits on local circuits is discussed. This market anticipates the use of NJ TRANSITGRID spare capacity by the utility in response to proper price signals to respond to contingencies. This market would allow the utility to reallocate distributed generation resources for utilization on local circuits under specified circumstances to respond to losses of power from the grid.





Part 1: Overview of NJ TRANSITGRID Benefits

Taken together, these technical discussions in Part 2 and Part 3 provide a quantification of the important benefits that NJ TRANSITGRID will provide to all NJ TRANSIT passengers as well as all residents of the State of New Jersey.

Model Development

The mathematical modeling and simulation software package MATLAB was used to model the NJ TRANSITGRID Main Facility and then simulate the dynamic behavior of that system for Part 2 and Part 3. The MATLAB scripts along with its graphical output is provided in the *Technical Appendix*.

⁴ For example, see: Section ES.2 (Purpose and Need for the Project) in the May 2019 DEIS. The generalized benefits of resiliency to the NJ TRANSIT system during a power outage are the subject of a pre-Sandy (June 2012) study published by NJ TRANSIT and Rutgers University: Resilience of NJ TRANSIT Assets to Climate Impacts. Available at: <u>https://rucore.libraries.rutgers.edu/rutgers-lib/47313/PDF/1/play/</u>

⁵ Intergovernmental Panel on Climate Change (2018). Global warming of 1.5° C: Summary for Policy Makers. According to the IPCC Special Report: ...Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate, they are larger if global warming exceeds 1.5° C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5° C, especially if the peak temperature is high (e.g., about 2° C).

https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_version_stand_alone_LR.pdf

⁶ Kriegler, E., et al. (2014). The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Clim. Change 123, 353–367.

⁷ According to the Energy Information Agency (EIA) as of January 2019, New Jersey has the 8th highest production of PV by state across all power producing sectors and the 2nd highest for distributed (non-utility) generation of PV. See: EIA Electric Power Monthly: <u>https://www.eia.gov/electricity/monthly/</u> Table 1.17.A Solar Photovoltaic by Census Division by Sector (Accessed 4/10/19).

⁸ Cochran, J. et al. (2015). Flexibility in 21st Century Power Systems. National Renewable Energy Laboratory (NREL) Technical Report NREL/TP-6A20-61721. <u>https://www.nrel.gov/docs/fy14osti/61721.pdf</u>. See Figure 1: Greater Need for Flexibility. The net load on power systems that results from the addition of large-scale wind and solar generation ...can lead to



¹ The Federal Transit Administration estimates that, on a national level, the average transit system emits 0.45 lbs. CO2 per passenger mile compared with a single occupancy private vehicle at 0.96 lbs. CO2 per passenger mile. See: Federal Transit Administration (2010). Public Transportation's Role in Responding to Climate Change: <u>https://www.epa.gov/sites/production/files/2016-</u>04/documents/public transportations role in responding to climate change.pdf

² Information regarding the NJ TRANSITGRID project may be found at the project website: <u>https://njtransitresilienceprogram.com/nj-transitgrid-overview/</u>

³ PJM Interconnection (headquartered near Philadelphia) is the regional transmission organization (RTO) that operates the competitive wholesale electricity market and manages the high-voltage electricity grid to ensure reliability for more than 61 million people in all or parts of 13 states (including New Jersey) and the District of Columbia.



NJ TRANSITGRID Benefits Evaluation Part 1: Overview of NJ TRANSITGRID Benefits

steeper ramps, deeper turn downs, and shorter peaks in system operations... creating the need for more flexibility in the system.

⁹ Cochran, J. et al. (2012). Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A00-53732. www.nrel.gov/ docs/fy12osti/53732.pdf

¹⁰ Electric Power Research Institute. (2015). The Integrated Grid: A Benefit-Cost Framework. Report No. 3002004878. See discussion on flexibility resources on pp 8-8, 8-9.

¹¹ Lazarewicz, M.L. and Ryan, T. (2010) Grid-Scale Frequency Regulation Using Flywheels. Beacon Power Corp. <u>https://www.sandia.gov/ess-ssl/EESAT/2003_papers/Lazarewicz.pdf</u>

¹² Sepúlveda, N. A., Jenkins, J. D., de Sisternes, F. J., & Lester, R. K. (2018). The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. Joule, 2(11), 2403–2420. https://doi.org/10.1016/j.joule.2018.08.006

¹³ H2 is a gas which forms when two hydrogen atoms bond together and become a hydrogen molecule. H2 is also called molecular hydrogen. It is the most common form of Hydrogen because it is stable with a neutral charge.

¹⁴ Although New Jersey and other nearby states on the Atlantic coast have recently implemented plans to procure grid-scale offshore wind power, it is not expected that any of the planned offshore wind farms will be operational before 2023.

¹⁵ The estimated capacity of the PV power plant was calculated with use of the *PVWatts Calculator* provided by NREL at the web site: <u>https://pvwatts.nrel.gov/pvwatts.php</u>.

¹⁶ The estimate for required land area was derived from generation-based area estimates given in: Ong, S.; Campbell, C.; Denholm, P.; Margolis, R. & Heath, G. (2013). Land-Use Requirements for Solar Power Plants in the United States. National Renewable Energy Laboratory (NREL) Technical Report NREL/TP-6A20-56290. <u>https://www.nrel.gov/docs/fy13osti/56290.pdf</u>. See Table ES-1. Summary of Land-Use Requirements for PV and CSP Projects in the United States. Estimates used are for Generation-weighted average land use (acres/GWh/yr). As indicated in the report, the use of generation-based results (i.e. acres/GWh/yr) ...provides a more consistent comparison between technologies that differ in capacity factor and enables evaluation of land-use impacts that vary by solar resource differences, tracking configurations, and technology and storage options.

¹⁷ Costs of construction were derived from estimates in: Fu, R.; Feldman, D.; & Margolis, R.; (2018) U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018. National Renewable Energy Laboratory (NREL) Technical Report NREL/TP-6A20-72399. <u>https://www.nrel.gov/docs/fy19osti/72399.pdf</u>. See Figure 27: Q1 2018 benchmark by location: 100-MW utility-scale PV systems, EPC only. The estimated cost for construction of a utility-scale 1-axis tracking system power plant using union labor in New Jersey is estimated at \$1.22/Wdc (\$1.5875/Wac) or \$1.587 Million per MWac. (Conversion between Wac and Wdc uses a DC to AC ratio (inverter loading ratio) of 1.3.)

¹⁸ See Beacon Power Operating Plants: <u>https://beaconpower.com/stephentown-new-york/</u> & <u>https://beaconpower.com/hazle-township-pennsylvania/</u>.

¹⁹ Energy pricing for flywheel energy storage systems estimated from: IRENA (2017). Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi.





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https://www.irena.org/-

/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

According to the analysis the energy installation costs for flywheel systems are expected to decline to between \$1,000 - \$3,900/kWh as cycle and calendar lifetimes substantially improve.

²⁰ Ibid. See page 20.

²¹ Using a DC to AC ratio (also known as the inverter loading ratio or ILR) of 1.3 and an inverter/storage size ratio of 1.67. See: Fu, R.; Remo, T.; & Margolis, R.; (2018) 2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark National Renewable Energy Laboratory (NREL) Technical Report NREL/TP-6A20-71714. https://www.nrel.gov/docs/fy19osti/71714.pdf.

²² Ibid. See page 11.

²³ Ibid. See Introduction.

²⁴ A "base load power plant" is a power generating station that usually provides a continuous supply of electricity to the power system. A "peaker power plant" is a power generating plant that may only run a few hours a day for a few days a week or month to provide power to the system at times of highest or "peak" demand.





Part 2: Environmental Benefits Analysis





NJ TRANSITGRID Benefits Evaluation Part 2 – Environmental Benefits Analysis

Abstract

A detailed model has been developed of the NJ TRANSITGRID Main Facility for use in quantifying the environmental benefits discussed in Part 1 of this report. The model is intended to highlight and explain important elements of the proposed NJ TRANSITGRID Main Facility design including when it will run and the measure of the benefits that result from its use. Three dispatch schemes for generation and sale of excess energy by NJ TRANSITGRID are used to anticipate the total displacement of generation by conventional generation technologies of the Regional Fossil Generation Fleet, as well as specific steam coal baseload plants in Pennsylvania and natural gas fired peaker generation plants in New Jersey.

The NJ TRANSITGRID power plant uses energy efficient technology that results in low rates of emission of GhG per megawatt-hour (MWh) of energy production. The 22.5 MW Simple Cycle engines of the NJ TRANSITGRID Main Facility emit 0.645 tons/MWh of CO_2 . The 60 MW combined cycle baseload power plant emits 0.484 tons/MWh of CO_2 . The 127.5 MW Full-power plant emits 0.569 tons/MWh of CO_2 . These low emission factors result in overall estimated annual reductions of CO_2 emissions of the Regional Fossil Generation Fleet ranging from 185,452 to 296,172 tons.

When compared to the baseload steam coal power plants in Pennsylvania that have high capacity factors and very high emission factors, the reductions in emissions are even greater ranging between 293,283 to 496,987 tons of CO₂ per year. The natural gas power plants located in New Jersey near to the NJ TRANSITGRID location are low capacity factor generating plants that provide a model for NJ TRANSITGRID operations as a capacity resource to the PJM market subject to the economic dispatch of the PJM operator. When operating at lower capacity factors, emission reductions are still significant but relatively lower ranging from 52,039 to 97,391 tons of CO₂ annually.

With NJ TRANSIT in control of the design and operation of its own generation resources through the implementation of NJ TRANSITGRID, several options to enhance the emission benefits even more may become available once they become technically and economically feasible. These options include: 1) use of energy storage systems in coordination with the planned solar array, 2) cogeneration and thermal dispatch of the heat energy exhaust of the three peaking engines, and 3) the use of alternative fuels for the combustion turbine engines. Each are considered in detail below. The implementation of these technologies each result in increased displacements of CO₂ from the Regional Fossil Generation Fleet. For example, the planned 0.6 MW solar array could be used to charge up the 10 MW flywheel energy storage system during off-peak hours and then deliver the stored energy during the peak demand hours when less efficient power plants are being dispatched. A 0.6 MW, 2.5 MW and 3.5 MW solar plant each





Part 2 – Environmental Benefits Analysis

matched with the 10 MW flywheel energy storage system could displace an additional 2,923 tons, 5,265 tons, and 6,506 tons of CO_2 , respectively.

Enhanced environmental benefits result from the use of RNG and High-Volume H2 Turbines. Emission displacements range from 92,514 tons of CO_2 from the use of up to 20% RNG in the natural gas supply to 231,286 tons of CO_2 by using up to 50% H2 in modified turbines. Use of the three peaker engines for combined heat and power (CHP) that can provide thermal energy from waste heat can provide an additional 177,117 tons of CO_2 emission reductions.

Depending on its status as an electric power supplier in New Jersey, NJ TRANSITGRID may be required to include a certain percentage of renewable energy production in its total kilowatt-hours sold through the purchase and retirement of Renewable Energy Certificates (RECs) that are used to support the development of renewable energy projects, such as solar or wind.





Part 2 – Environmental Benefits Analysis

Introduction

Part 2 of this report describes the development of a detailed model of the NJ TRANSITGRID Main Facility and its use in quantifying the environmental benefits discussed in Part 1. The model is intended to highlight and explain important elements of the proposed NJ TRANSITGRID Main Facility design including when it will run and the measure of the benefits that result from its use. The main purpose of NJ TRANSITGRID is to provide resiliency to key transport infrastructure. The purpose of this section is to estimate decreased emissions of GhG that result along with increased resiliency benefits due to the forward-thinking and innovative design of the Main Facility.

An important aspect of the model is the development of energy dispatch schemes that describe and predict how energy will be produced and distributed by NJ TRANSITGRID. The energy generated by the NJ TRANSITGRID Main Facility is expected to partially power NJ TRANSIT load on its M&E line and NJ TRANSIT and Amtrak loads on the NEC. The remainder of the capacity after these scheduled loads are served will be available to sell to the wholesale electricity market managed by the PJM Interconnection or for retail sale to the local electric utility, PSE&G. Therefore, to test the model and estimate benefits, historic load data for the M&E and NEC lines, as well as pricing data for electricity and natural gas for the one-year period of analysis between March 2018-March 2019 is used. A one-year period of analysis was selected for its ability to capture important variations in load demand.

Sources and Data

For purposes of consistency, the engineering and economic design parameters of the most current NJ TRANSITGRID design documents have been used in the model. The description of the Main Facility generally follows the equipment selection and configuration provided in the Application for Preconstruction Permit for the NJ TRANSITGRID Traction Power System Project, Kearny, New Jersey prepared by BEM Systems, Inc. (November 2018). Additional technical information regarding the power plant was derived from the Jacobs September 2018 20-percent design information and the July 2017 *Economic Screening Analysis* prepared by Levitan & Associates.

Data regarding emissions from the U.S. fossil generation fleet was retrieved form the U.S. Environmental Protection Agency (EPA) Air Markets Program Data (AMPD) web site. The data query web tool provided makes accessible all EPA Clean Air Markets Programs data at the unit (engine), plant and utility region and national levels.¹ Additional information regarding the technical operation of the generation fleet was retrieved from the U.S. Energy Information Agency (EIA) Form EIA-860 detailed data. The Form EIA-860 survey collects generator-level specific information about existing and planned generators and associated environmental equipment at electric power plants.²





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Figure 2-1: Incremental Heat Rate of the NJ TRANSITGRID Main Facility

Model Description

Parameters of the Physical Plant

The proposed design of the NJ TRANSITGRID Main Facility includes the use of five 22.5 MW simple-cycle natural gas fired combustion turbine engines. Two of the simple-cycle combustion turbine engines will be used in combination with a single 15 MW steam turbine to provide combined cycle power. Use of a multiple stage combined cycle power plant has the advantage in that the first simple cycle gas turbine (22.5 MW) can be brought online quickly to provide immediate power. As the load increases, the second simple-cycle gas turbine is brought on-line followed by the 15 MW steam turbine to complete the combined cycle, which will improve fuel efficiency and provide further power. Once the combined cycle power plant has reached full baseload capacity of 60 MW (including the two 22.5 MW baseload engines and the one 15 MW





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steam turbine) three additional 22.5 MW simple cycle combustion turbine peaker engines are available to meet additional load (the sequence of the firing of the turbines is illustrated in *Figure 2-1*).

The engines to be used in the NJ TRANSITGRID Main Facility will be one of the GE LM2500 family of advanced aeroderivative turbines, or similar technology, that have a high electrical efficiency. The heat rate, which is the measure of the input heat energy per unit of output electric power, is estimated at 10,365 Btu/kWh at the higher heating value (HHV) - equivalent to a thermal efficiency of a 32.92%.³ The use of the steam turbine to create combined cycle power allows the Main Facility to achieve higher efficiencies of up to 42.98% by lowering the heat rate to 7,938 Btu/kWh at the baseload full capacity of 60 MW. At the Main Facility's full 127.5 MW capacity (including 60 MW of baseload combined cycle power and three 22.5 MW peaker engines), the plant's average heat rate is 9,225 Btu/kWh achieving a full power efficiency of approximately 37%.

Jacobs provides estimates for the heat rates of the gas turbine as load varies from 0 to 100%.⁴ As the load on the gas turbine is reduced, the heat rate is also reduced. The most efficient operating point for the gas turbines is at full load. As gas engine efficiency is typically quoted by manufacturers based upon the lower heating value (LHV) of the gas, the heat rate estimates for the LM2500 engines are provided by Jacobs from manufacturer information in terms of LHV.

However, as natural gas suppliers typically quote the HHV value of the fuel, and it is the HHV that is used when kWh unit charges are applied for the fuel, the heat rate and thermal energy values used in this evaluation are taken at the HHV. The quoted HHV value for the engine at full power (10,365 Btu/kWh) implies a conversion ratio (LHV to HHV) used by Jacobs of 0.904, which is in line with rules-of-thumb for this conversion for natural gas. This conversion ratio has been applied to arrive at the HHV values for other output levels of the engine. The HHV incremental heat rate of the Main Facility, presented as load varies and different combinations of turbines are brought on-line, is shown in *Figure 2-1*.

Operating Costs

It is intended that NJ TRANSITGRID will always serve a certain amount of load to the M&E and NEC lines. Any energy or ancillary services that may be produced by the Main Facility in excess of this must-serve load is available for export to wholesale and retail markets through its interconnection. One of the principal drivers of NJ TRANSITGRID energy dispatch beyond its must-serve baseload will be the costs of operations and potential revenue that may be gained from variable production levels.

The costs of electrical energy generation can generally be divided into two broad areas: ownership or sunk costs and operating or avoidable costs. The sunk costs include the expenses to build, finance and insure the plant. Fixed operation costs are expenses that must be met





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regardless of whether the engines are generating power. Variable operating costs depend on the amount of energy produced and principally include the price of the fuel (natural gas) and O&M of the generation equipment. As the sunk costs are non-recoverable, the economic decision to run the engines is based on the ability of the power plant to generate enough revenue to meet or exceed the average variable costs.





The price of natural gas used in this analysis is based on the benchmark Henry Hub natural gas spot price which is typically quoted in dollars per Million Btu (\$/MMBtu). The variation in the spot price over the period of analysis for this evaluation (March 2018 – March 2019) is shown in *Figure 2-2*. As may be seen in the chart, the spot price of natural gas can be volatile in the short term. During the period of analysis, the minimum price of natural gas was \$2.54/MMBtu (02/05/2019), the maximum price was \$4.70/MMBtu (11/21/2018), and the average price over the one-year period was \$3.09/MMBtu.⁵

The O&M costs have been estimated at \$5.71 per MWh of generation. This estimate is originally provided by Jacobs and subsequently used by Levitan & Associates in their July 2017 financial analysis. The quoted unit cost estimate, although it may apply to differing configurations of plant design than assumed for this evaluation, is used in the model for consistency. The O&M





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expenses are not expected to fluctuate much on a per-unit basis from hour-to-hour or day-to-day as long-term contracts with labor and service vendors generally remove short-run price risk.

<u>Revenue</u>

For consistency with the prior financial analysis by Levitan & Assoc., this evaluation assumes that the Main Facility will participate in the PJM wholesale market as an energy-only resource selling self-scheduled blocks of power on the real-time balancing market.⁶ The price paid to generators by the market operator is based on the location of the energy injection into the transmission grid and is referred to as the Locational Marginal Price (LMP). This evaluation makes use of the real-time historical LMP values available through PJM to calculate potential revenue.⁷

The system-wide energy price component of the LMP is set by the marginal resource during each fifteen-minute block and can vary widely from hour-to-hour. The marginal resource in the wholesale market for electric power the highest-cost generating units that are required at any one time to meet variable system demand. In the economic dispatch process used in wholesale power markets, electricity from generating units that are the least expensive to operate are dispatched to the system first, and the most expensive plants are dispatched last. Therefore, the lowest variable-cost units are brought online first; as the load increases through peak (high-demand) hours, increasingly expensive units are brought online.

In addition to this base energy price, the LMP is also composed of costs associated with line congestion and transmission losses. As the system-wide energy price is set by the marginal resource, which is often a natural-gas fired combustion power plant, the LMP also reflects the variable cost of natural gas.

The PJM pricing node is where a physical injection or withdrawal of energy is modeled and for which an LMP is calculated and used for financial settlements. The Kearny pricing node (ID # 1348263388) is in the PSE&G zone adjacent to the proposed location of the NJ TRANSITGRID power plant and serves as the injection point for the Kearny Generating Station, a peaking power plant located in an industrial area of Kearny, New Jersey, known as South Kearny.

Figure 2-3 presents the average LMP at each hour of the day during the period of analysis at the Kearny pricing node. This chart shows that the variability of the LMP is related to peak hours of load usage during the morning and late afternoon/early evening, and the increased LMP on weekdays as opposed to weekends and holidays. Due to this pattern it can be expected that profitable operation of the Main Facility for external sales would be more likely at times of peak demand.





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Figure 2-3: Average Hourly LMP at the Kearny Pricing Node

Model Components

The model is divided into four main components as follows. Each is described in turn in the report.

- 1. NJ TRANSITGRID Production
 - <u>Bid Curve</u>: An incremental cost curve or offer curve that consists of hourly MW-Price pair segments for the entire period of analysis.
 - <u>Hourly Dispatch & Generation Schedule</u>: The 8760 hourly results of the bid curve incorporating the hourly/daily/seasonal variation are summarized into 24 average hourly blocks for weekdays and for weekends. The dispatch blocks are then paired back with the must-serve NJ TRANSIT load to form the 8760-hour generation schedule to use in the emissions analysis.
 - <u>Emissions</u>: Estimation of GhG (GhG) emissions under each of the 8760 dispatch/generation schemes.
- 2. Emissions Displacements
 - <u>Regional Fossil Generation Fleet</u>: Calculation of reduced emissions in the regional fossil generation fleet due to the use of NJ TRANSITGRID both for internal energy and for export to the wholesale market.





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- <u>Natural Gas Peaker Plant:</u> Evaluation of emission displacements assuming a natural gas peaker plant is the marginal resource.
- <u>Steam Coal Baseload Plant</u>: Evaluation of displacements assuming a baseload steam coal plant is the marginal resource.
- 3. Enhanced Benefits
 - <u>Solar power and energy storage system</u>: Evaluation of additional emission displacements that result from use of solar power with 10 MW flywheel energy storage system.
 - <u>Cogeneration</u>: Evaluation of additional emission displacements that result from the use of waste heat energy of the three peaker combustion turbine engines to provide thermal energy to a nearby off-taker.
 - <u>Alternative Fuels</u>: Evaluation of emission reductions that result from use of alternative fuels such as RNG and H2 that displace the use of natural gas in the combustion turbines.
- 4. Summary Results
 - <u>Emission factor by generation source</u>: Summary of the volumes of GhG emissions per MW of production by technology evaluated by the model.
 - <u>Annual GhG displacement (tons) by generation source</u>: Summary of the displacements and avoided emissions that result from NJ TRANSITGRID production.
 - <u>Enhanced benefits</u>: Summary of potential additional avoided emissions that result from NJ TRANSITGRID operations using developing technologies.

The U.S. EPA AVERT Model

The U.S. EPA Avoided Emissions and Generation Tool (*AVERT*) is used to estimate the annual net volume of emissions that may be displaced in the regional fossil generation fleet through NJ TRANSITGRID operation. *AVERT* is the U.S. EPA's most sophisticated fleet emissions displacement modelling tool. It utilizes emissions and operation data provided by U.S. power plant operators to EPA and the U.S. EIA every year. This information is used in the model to simulate generation behavior of each unit in the system and identify a cohort of marginal resources, taking into account historic capacity factors, increasing efficiencies at higher levels of output, higher emissions from units that are just warming up, and seasonally changing emissions for units with seasonal environmental controls. Both the U.S. EPA AMPD and Form EIA-860 data





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are key underlying sources for the *AVERT* power sector inventory used to calculate the annual avoided emissions.⁸

To use AVERT, the hour-by-hour generation for each of the annual NJ TRANSITGRID generation schemes over the period of analysis is input into the AVERT model interface. The statistical analysis engine of *AVERT* uses this information to identify marginal resources throughout the region at each hour and estimate the amount of generation displaced by NJ TRANSITGRID operation. This displaced generation, generally from power plants that are less efficient and thereby more polluting that NJ TRANSITGRID, results in displaced GhG emissions.

The NJ TRANSITGRID Production Model

This section provides a summary of the methodology used to model the NJ TRANSITGRID dispatch and energy generation schemes as a basis for estimating plant GhG emissions.

Bid Curve

The bid curve is an incremental cost curve or offer curve that consists of hourly MW-Price pair segments for the entire period of analysis. The bid curve is meant to model the break-even price for NJ TRANSITGRID generation given each hour's variable operating costs and potential revenue. Each hour has two bid prices. The first is baseload mode that is capped at 60 MW of production from the combined cycle power plant. The second is full power mode that includes the full 127.5 MW capacity.

The model uses the hourly/daily/seasonal variation in historic LMP, natural gas spot prices, variable O&M costs, and the NJ TRANSIT load to set hourly bids for each mode into the wholesale/retail markets. The bid prices reflect average variable costs only and do not take into consideration owner sunk costs or fixed operating costs. The purpose is to construct a dispatch model that might reflect actual operating conditions to measure emissions. It is not meant to provide a financial model of the Main Facility that incorporates economic profit considerations.

The first step in construction of the bid curve is to determine the hourly must-serve NJ TRANSIT load composed of the historical load demand for the M&E and NEC lines. Then the available excess capacity for the 60 MW combined cycle power plant and the 67.5 MW peaker engine plant is calculated. As the baseload and peaker plants each have different heat rates, the hourly variable costs per MW of energy production for each mode of operation is calculated separately using this equation:

(incremental heat rate * gas price) + variable operating cost (Eq. 2-1)





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The net revenue per MW of energy produced for each hourly block is then calculated by subtracting the hourly variable costs calculated in Eq. 1 from the hourly LMP.

For example, in the 12:00 hour on Thursday, June 7 of the period of analysis, the combined load on the M&E and NEC lines is 35.91 MW. The available baseload capacity on the 60 MW combined cycle power plant is therefore 24.09 MW and the available capacity on the three peaker engines is the full 67.5 MW. The per MW bid for baseload power is the heat rate of the combined cycle plant (7938 Btu/kWh) multiplied by the spot gas price at that time (\$3.02 /MMBtu) plus the variable O&M (\$5.71/MWh), which is equal to \$29.68/MWh.

Similarly, the per MW bid for full power is the heat rate of the full power plant (9223 Btu/kWh) multiplied by the spot gas price (\$3.02 /MMBtu) plus the variable O&M (\$5.71/MWh), which is equal to \$33.56/MWh. The historical PJM LMP at the Kearny pricing node in the 12:00 hour on Thursday, June 7 of the period of analysis was \$34.74. The total net revenue for the 12:00 hour for the baseload dispatch scheme therefore is the difference of the LMP and baseload bid price (\$34.74 - \$29.68) multiplied by the available baseload energy for that hour (24.09 MW), which is \$121.81. Similarly, the total net revenue for the full power dispatch scheme is \$107.79.



Figure 2-4: NJ TRANSITGRID Cost and PJM LMP (June 2018)

Figure 2-4 presents the LMP recorded at the Kearny pricing node during a two-week period in June 2018, which includes the day used in the example in the preceding paragraph. The





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average variable operating costs for the Main Facility at baseload (60 MW) and full power (127.5 MW) are plotted onto the chart for comparison. As can be seen, in this two-week time segment, the costs remain relatively stable compared to the highly volatile LMP, which may swing far above the cost to produce a MWh of energy, and also may fall far below.

Hourly Dispatch & Generation Schedule

The 8760 hourly results of the bid curve incorporating the hourly/daily/seasonal variation are summarized into 24 average hourly blocks for weekdays and for weekends. The dispatch blocks are then paired back with the must-serve NJ TRANSIT load to form the 8760-hour generation schedule to use in the emissions analysis.

The first step is to calculate annual averages for each weekday and weekend hour of the day for the NJ TRANSIT load, the available baseload and full power capacity, and the net revenue for PJM dispatch of the excess energy. The hourly averages of the baseload-only dispatch is presented in *Figure 2-5*. Due to the supply of baseload to the NEC and M&E lines, excess capacity up to the 60 MW baseload generation is not available for external sale between the weekday hours of 7:00 a.m. – 10:00 a.m. and 4:00 p.m. – 8:00 p.m. During hours in which excess capacity up to 60 MW is available for sale to the PJM real-time market, the hours characterized by positive revenue include the weekday hours 11:00 a.m. – 3:00 p.m., and the weekday hours immediately preceding and following the baseload dispatch to the NEC and M&E lines (5:00 a.m. and 9:00 p.m.). Weekend hours where expected income would exceed costs include the block of time between 11:00 a.m. – 9:00 p.m., except for 1:00 p.m.

The hourly averages of the full power dispatch up to 127.5 MW is presented in *Figure 2-***6**. As power generation is not restricted to baseload levels, there is excess capacity available for external sale at every weekday and weekend hour. The hours characterized by positive revenue include the weekday hours 6:00 a.m. – 8:00 p.m. except for 8:00 a.m. Weekend hours where expected income would exceed costs include the block of time between 4:00 p.m. – 7:00 p.m.





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Figure 2-6: Average Hourly Capacity & Revenue (Full-power Dispatch)

Using this information, three different block-loading dispatch schemes were selected where all excess power would be available for sale to the PJM wholesale market. The three dispatch schemes are summarized in *Table 2-1* and *Table 2-2*. The goal of Dispatch 1 (Maximize Revenue) is to maximize the revenue gained from operation of the engines. The goal of Dispatch 2 (Break-even) is to generate the maximum amount of electricity without losing money on the average variable costs expenditures.⁹ The goal of Dispatch 3 (Full-power) is to assess the benefits




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of the Main Facility generation at its maximum output.¹⁰ The total energy generated during the one-year period of analysis for Dispatch 1, Dispatch 2 and Dispatch 3 is 644,848 MWh, 847,668 MWh, and 1,119,853 MWh, respectively. The results of the three dispatch schemes are presented in *Figure 2-7* (Weekdays) and *Figure 2-8* (Weekends).

0= No Dispatch 1 = Baseload Dispatch 2= Full-power Dispatch					
	Avg. Net Revenue			Dispatch Sc	heme
Hour	Baseload	Full-power	1	2	3
0	(\$85,426)	(\$316,771)	0	1	2
1	(\$94,889)	(\$336,802)	0	1	2
2	(\$116,451)	(\$385,569)	0	1	2
3	(\$121,228)	(\$394,368)	0	1	2
4	(\$106,398)	(\$361,531)	0	1	2
5	(\$50,976)	(\$240,075)	0	1	2
6	\$33,591	\$31,380	2	2	2
7	\$0	\$40,459	2	2	2
8	\$0	(\$27,752)	2	2	2
9	\$0	\$5,917	2	2	2
10	\$0	\$23,783	2	2	2
11	\$32,287	\$33,561	2	2	2
12	\$44,859	\$77,142	2	2	2
13	\$49,116	\$86,878	2	2	2
14	\$51,507	\$97,604	2	2	2
15	\$73,874	\$182,168	2	2	2
16	\$0	\$181,283	2	2	2
17	\$0	\$184,737	2	2	2
18	\$0	\$100,737	2	2	2
19	\$0	\$66,563	2	2	2
20	\$0	\$57,027	2	2	2
21	\$20,630	(\$16,224)	1	2	2
22	(\$17,354)	(\$159,248)	0	2	2
23	(\$66,871)	(\$276,240)	0	1	2

Table 2-1: Dispatch Schemes (Weekdays)





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Table 2-2: Dispatch Schemes Summary	
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	Dispatch		Annual Ener	rgy Delivery (N	lWh)	PJM Sales
No.	Goal	NEC	M&E	PJM	Total	Profit/Loss (\$)
1	Maximize revenue	231,660	47,038	366,150	644,848	\$1,248,973
2	Break-even	231,660	47,038	568,970	847,668	\$0
3	Full-power	231,660	47,038	841,155	1,119,853	(\$3,078,337)

Figure 2-7: NJ TRANSITGRID Weekday Hourly Dispatch Blocks







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Figure 2-8: NJ TRANSITGRID Weekend Hourly Dispatch Blocks

Emissions

Due to its high energy production efficiencies, operating the NJ TRANSITGRID Main Facility to supply some of its own load and offer excess capacity into the wholesale and retail markets will generally reduce the volumes of GhG emitted by the regional commercial electricity generating fleet. This will be especially true during times of peak demand that typically coincide with poor air quality as more expensive (i.e. less efficient and thereby more polluting) resources are brought online.

According to the manufacturer information for the selected 22.5 MW combustion turbine engines, the expected emissions rate for CO_2 is 29,017 pounds per hour (lbs./hr) at full power or an emissions factor (the rate of emissions per unit of energy produced) of 0.645 tons of CO_2 per megawatt-hour (tons/MWh).¹¹ For the more efficient combined cycle power plant that includes a steam turbine to provide an additional 7.5 MW per simple cycle engine, the CO_2 emission factor is reduced to 0.484 tons/MWh. At full power using the combined cycle power plant to provide baseload of 60 MW plus the three 22.5 MW peaker engines, the CO_2 emission factor is 0.569 tons/MWh. These results are summarized in **Table 2-3**.





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Table 2-3: NJ TRANSITGRID CO₂ Emission Factors

Operation Mode	Power	CO ₂ Emission Factor
Simple Cycle	22.5 MW	0.645 tons/MWh
Combined Cycle Baseload	60 MW	0.484 tons/MWh
Full-power	127.5 MW	0.569 tons/MWh

In contrast to these highly efficient emission factors, the fossil-fuel fired generation fleet emission factor in the Mid-Atlantic region (an area roughly corresponding to the service area of PJM) is estimated by U.S. EPA at 0.824 tons/MWh.¹² This reflects a blended factor composed of many different types of fossil fuel fired power plants using various fuel types and prime movers. A summary of the average emission factors for various fossil power plant types are provided in *Table 2-4*.¹³

Table 2-4: U.S. Fossil Fleet Generation CO₂ Emission Factors

Fuel Type	Prime Mover	CO ₂ Emission Factor
Bituminous Coal	Steam Generator	1.08 tons/MWh
Distillate Fuel Oil	Steam Generator	0.822 tons/MWh
Natural Gas	Gas Turbine	0.654 tons/MWh
Natural Gas	Combined Cycle	0.485 tons/MWh

Emissions Displacement

This section presents the evaluation of the GhG emissions displaced by NJ TRANSITGRID in the Regional Fossil Generation Fleet due to the use of NJ TRANSITGRID both for transit consumption and for export to the wholesale market.

The first step is to pair the hourly weekday and weekend dispatch blocks constructed in the model and then pair them back to the scheduled generation for the NJ TRANSIT load (including the M&E and NEC lines) to create annual 8760-hour generation schedule for the period of analysis. These generation schedules are then input into the AVERT model to estimate the reductions in GhG emissions from the Regional Fossil Generation Fleet due to NJ TRANSITGRID generation displacement.

AVERT uses over 800 generation units located across twelve states (including New Jersey) in the Mid-Atlantic area for its analysis. However, the AVERT tool does not use location-





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based analysis and spreads the reductions across the cohort of marginal units at the same time across all state boundaries. In practice, time and location-based congestion and transmission losses impacts the determination and dispatch of the marginal resources. Marginal generators closer to the node where NJ TRANSITGRID injects its power will more likely be displaced more often and for longer periods.

Some marginal generators situated close to the proposed location of the NJ TRANSITGRID Main Facility most often identified by the AVERT statistical analysis include units at Keystone and Conemaugh, two large conventional steam coal-fired generating plants in Pennsylvania, the Kearney Generating Station natural gas-fired combustion turbine peaker plant in Kearny, New Jersey, and the Bergen Generating Station natural gas-fired combined cycle plant in Ridgefield, Bergen County, New Jersey. These plants are each evaluated separately as the marginal resource using the unit and plant specific AMPD and Form EIA-860 data to examine the extremes of the regional emission displacement results provided by AVERT.

Regional Fossil Generation Fleet

The results of each AVERT analysis using the three different NJ TRANSITGRID dispatch schemes is provided in **Table 2-5**. Under each scenario, significant reductions in CO₂ emissions on an annual basis results from dispatch of electric energy produced by NJ TRANSITGRID for self-power and for delivery to the wholesale market.

NJ TRANSITGRID Generation Schedule	Annual Energy Delivery	System Gross Reduction	NJ TRANSITGRID Emissions	Net Reduction
No.	(MWh)		(Tons of CO ₂)	
1	644,848	544,335	358,884	185,452
2	847,668	710,667	462,572	248,096
3	1,119,853	933,549	637,376	296,172

Table	2-5:	Regional	Fossil	Generation	Fleet C	202	Emission	Reduction	s
I GINIO	- •.	regional		Contraction					-

Using Generation Schedule 1 (i.e. the NJ TRANSIT load + Dispatch 1) a total system gross reduction of 544,335 tons of CO₂ emissions is estimated. NJ TRANSITGRID emissions of CO₂ to generate this amount of energy by contrast is only 358,884 tons resulting in a net reduction of 185,452 tons of CO₂ emissions in one year. This is the equivalent of removing 35,720 passenger vehicles from the roads for a period of one year. Using Generation Schedule 2 (i.e. the NJ TRANSIT load + Dispatch 2) and Generation Schedule 3 (i.e. the NJ TRANSIT load + Dispatch 3) even greater net emission reductions are achieved of 248,096 tons of CO₂ (or the





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equivalent of 47,785 passenger vehicles) and 296,172 tons of CO₂ (57,045 passenger vehicles), respectively.¹⁴

Steam Coal Baseload Displacements

The Keystone Generating Station is a 1,711 MW capacity, coal power plant located on roughly 1,500 acres in Armstrong County, Pennsylvania. The plant was built and originally commissioned in 1967-68. The Conemaugh Generating Station is an 1,872 MW baseload coal-powered plant located on 1,750 acres in New Florence, Pennsylvania. The Conemaugh plant was built in 1970-71. The Keystone and Conemaugh plants are dispatched nearly continuously and baseload resources with generation capacity factors during the analysis period of 82.5% and 74.3%, respectively.

The Keystone and Conemaugh coal plants have two 936 MW coal-fired steam generating units each, and in 2018 generated 13,339 GWh and 12,274 GWh respectively with CO₂ emission factors of approximately 0.950 tons/MWh. Both plants are included by the AVERT model as part of the cohort of multi-state marginal resources that would be displaced by NJ TRANSITGRID generation. As these large energy producing plants are located relatively close to NJ TRANSITGRID it is instructive to repeat the emissions displacement analysis modelling these plants as the sole marginal resource.

To do this, the three NJ TRANSITGRID Generation Schedules are used to calculate the net reduced generation on an hour-to-hour basis during the period of analysis. In other words, the generation provided by NJ TRANSITGRID is assumed to reduce the generation provided by the coal plant by the same amount plus the gross-up factor of 6.41% used by the AVERT model to simulate average station load at the generating plant.

The gross reduction of emissions is then estimated by multiplying the hourly emission factor of the coal plant (using AMPD hourly data) to the amount of displaced generation. The actual recorded historical dispatch of the coal plants is matched by NJ TRANSITGRID in the model. By modelling the NJ TRANSITGRID generation in this way, it replicates the dispatch schedule of the baseload steam coal plant, as the NJ TRANSITGRID Generation Schedule is modified to match the actual dispatch of the coal plants using the EPA AMPD data. This method assures that actual capacity factors are taken into consideration.

Emission reductions at the Keystone facility during the period of analysis that accounts for the dispatch of NJ TRANSITGRID into the system under its three different Generation Schedules are presented in *Table 2-6*.





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NJ TRANSITGRID Generation Schedule	Annual Energy Delivery	System Gross Reduction	NJ TRANSITGRID Emissions	Net Reduction	
No.	(MWh)	(Tons of CO ₂)			
1	532,000	647,420	354,137	293,283	
2	699,326	851,600	456,264	395,336	
3	923,879	1,125,204	628,216	496,987	

Using Generation Schedule 1 a total gross reduction of 647,420 tons of CO_2 emissions is estimated for the Keystone steam coal power plant. NJ TRANSITGRID emissions of CO_2 to generate this amount of energy by contrast is only 354,137 tons resulting in a net reduction of 293,283 tons of CO_2 emissions in one year. This is the equivalent of removing 56,489 passenger vehicles from the roads for a period of one year. Using Generation Schedule 2 and Generation Schedule 3 even greater net emission reductions are achieved of 395,336 tons of CO_2 (or the equivalent of 76,145 passenger vehicles) and 496,987 tons of CO_2 (95,647 passenger vehicles), respectively.

Natural Gas Peaker Plant Displacements

The Bergen Generating Station is a natural gas fired combined cycle power plant owned and operated by Public Service Electric and Gas Company (PSE&G). It is located on the banks of Overpeck Creek in Ridgefield, Bergen County, New Jersey. The plant supplies electricity to New Jersey and to New York City via the Hudson Project. It was originally built in 1995 and expanded in 2002. The Bergen Generating Station has six combustion turbines (four 112.5 MW capacity and two 183.6 MW capacity) that can feed two combined power plants (one of 325.2 MW capacity and the other 258.4 MW capacity).

In 2018, the Bergen facility generated 2,575 GWh of electric energy with an overall plant CO_2 emission factor of 0.706 tons/MWh. In 2018, the Bergen plant was the 5th biggest emitter of CO_2 in the New Jersey power generation sector with total CO_2 emissions of 1,817,124 tons. The Bergen facility operated principally as a peaker plant during the period of analysis with an overall capacity factor of 31.2% dispatching its four 112.5 MW combustion turbine engines with an average capacity factor of 23.2%, and its two 183.6 MW combustion turbine engines with an average capacity factor of 47.4%.

The Kearny Generating Station is a peaking power plant located on the banks of the Hackensack River in the South Kearny area of Kearny, New Jersey. It is owned and operated by





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PSE&G. The Kearny Generating Station has ten 60.5 MW combustion turbine engines operating as peaker engines. In 2018, the Kearny facility operated sparingly with a capacity factor of only 6.12% generating 311,158 MW of electric energy, with an overall plant CO₂ emission factor of 0.616 tons/MWh.



Figure 2-9: Natural Gas Plant Hourly Dispatch and Displacement

The NJ TRANSITGRID Main Facility generation was modelled using the historical dispatch of the Bergen plant to evaluate the emissions displacement potential for NJ TRANSITGRID as a PJM capacity resource subject to the economic dispatch of the PJM operator. To do this, the average annual hourly generation for each hour of the day for weekdays and weekends was analyzed using AMPD generation data. The Bergen hourly generation was then reduced by available capacity from the NJ TRANSITGRID plant using the Generation 3 Schedule (Full-power).

The average hourly dispatch during weekdays during the period of analysis, along with potential displacement by the NJ TRANSITGRID peaker engines is presented in *Figure 2-9*. Given the reduced CO_2 emission factors of the NJ TRANSITGRID plant at full power over the Bergen facility, dispatch of the NJ TRANSITGRID peaker engines alone that match the dispatch and capacity factor of the Bergen Generating Station may reduce CO_2 emissions by a total of 106,761 tons (20,563 passenger vehicles) over the period of a year.

<u>Summary</u>

As may be seen in *Figure 2-10*, the CO_2 emission factors for NJ TRANSITGRID rank amongst the lowest of all fossil-fuel generation sources discussed. Due to these higher efficiencies that result in lower emissions of CO_2 per hour of generation, NJ TRANSITGRID is





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able to provide significant environmental benefits by displacing and eliminating hundreds of thousands of tons of GhG emissions each year through generation of power for its own loads and to dispatch into the regional electric system.



Figure 2-10: Summary of CO2 Emission Factor (Tons/MWh) by Generation Source





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Figure 2-11: Summary of Annual CO2 Displacement (Tons) by Generation Source

Enhanced Emission Benefits

With NJ TRANSIT in control of the design and operation of its own generation resources through the implementation of NJ TRANSITGRID, several options to enhance the emission benefits even more may become available once they become technically and economically feasible. These options include: 1) use of energy storage systems in coordination with the planned solar array, 2) cogeneration and thermal dispatch of the heat energy exhaust of the three peaking engines, and 3) the use of alternative fuels for the combustion turbine engines. Each are considered in detail below.

Energy Storage Systems and Solar Array

The current plan for NJ TRANSITGRID includes the use of an on-site 0.6 MW solar array and up to 10 MW of energy storage using a flywheel system. The flywheel energy storage system (ESS) selected for NJ TRANSITGRID is primarily to be used for rapid cycling for frequency regulation and to provide the instantaneous supply of the large bursts of power on the order of 10-20 MW per second to match the anticipated step loads in the traction power system. Other types of flywheel energy storage systems, however, are also capable of providing longer charge/discharge cycles that allow for the use of flywheels for peak-load shifting.¹⁵ By using the





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solar array to charge up the ESS during off-peak hours and then dispatching the stored energy into the system during the peak demand hours when the LMP is typically at its highest (thereby dispatching less efficient power plants to match load) NJ TRANSITGRID will enhance its ability to displace additional CO₂ emissions from other power plants in the Regional Fossil Generation Fleet.

To evaluate these enhanced environmental benefits, the model assumes a four-hour discharge cycle between 14:00 - 17:00 at a constant rate (i.e. 25% of the state of charge of the flywheels each hour for four hours). While there is sunshine, the solar system charges the flywheels to a maximum of 10 MW. All additional solar energy, including energy produced during the 4-hour flywheel discharge, is dispatched to system. The total dispatched energy is then added to the Generation Schedule 2 (Break-even) and modelled in AVERT to evaluate the increased emission offsets. The model assumes a round-trip efficiency of 87%. Flywheel systems are able to achieve deep discharges without harm to the system; therefore the 4-hour discharge will essentially drain the ESS of stored energy.

Although it would not be technically or economically feasible to build solar arrays larger than the currently planned array of 0.6 MW for NJ TRANSITGRID, to test the ability of the proposed system to provide enhanced environmental benefits under different potential scenarios, solar arrays of 2.5 MW and 3.5 MW capacity are modelled along with up to 10 MW of energy storage. (See Part 1 regarding the discussion of the current infeasibility of powering NJ TRANSITGRID with solar power). Estimates of available solar power for a 0.6 MWdc, 2.5 MW and 3.5 MW system were performed using the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM).¹⁶

The enhanced emission benefits that result from each of the three solar and ESS scenarios considered is provided in **Table 2-7**. For the scenario using the 0.6 MW solar plant with 10 MW of flywheel storage, there is an additional net energy delivery of 889 MW above the baseline energy delivery using the Generation 2 Schedule (847,668 MW) and an additional 2,923 tons of CO_2 displacements from the Regional Fossil Generation Fleet.

For the scenario using the 2.5 MW solar plant with 10 MW of flywheel storage, there is an additional net energy delivery of 3,705 MW above the baseline energy delivery using the Generation 2 Schedule (847,668 MW) and an additional 5,265 tons of CO_2 displacements from the Regional Fossil Generation Fleet. For the scenario using the 3.5 MW solar plant with 10 MW of flywheel storage, there is an additional net energy delivery of 5,187 MW above the baseline energy delivery using the Generation 2 Schedule (847,668 MW) and an additional 6,506 tons of CO_2 displacements from the Regional Fossil Generation Fleet.





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	Annual NJ TRANSITGRID Energy Delivery	Fleet Gross Reduction w/Solar	Fleet Gross Reduction w/o Solar	Enhanced Fleet Net Reduction	
Technology	ly (MWh)		(Tons of CO ₂)		
0.6 MW Solar w/Energy Storage	848,557	713,590	710,667	2,923	
2.5 MW Solar w/Energy Storage	851,373	715,933	710,667	5,265	
3.5 MW Solar w/Energy Storage	852,854	717,173	710,667	6,506	

Table 2-7: Regional Fossil Fleet CO2 Emission Reductions with Solar and ESS

The results of the model for the 3.5 MW solar plant with 10 MW ESS is presented in *Figure* **2-12**. The state-of-charge (SOC) of the flywheels is shown along with the solar energy production throughout the day, the discharge energy between 14:00 - 17:00, and the total energy export including the discharge from the ESS and from the solar plant once the SOC has reached 10 MW.



Figure 2-12: Solar Plant with Energy Storage System





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Cogeneration & Thermal Dispatch

Although the heat exhaust from two of the NJ TRANSITGRID combustion turbine engines will be used in the combined cycle power plant, there will be no waste heat recovery units attached to the three peaker engines. This provides a future opportunity for NJ TRANSITGRID to use cogeneration of electric and thermal energy at the peaker engines to increase its production efficiency resulting in additional CO_2 emission reductions. The three peaker engines have a combined capacity of 67.5 MW that produce waste heat energy that could provide thermal energy to a nearby off-taker (such as a commercial refrigerated warehouse facility or an institutional building that could use the energy for heat).

The total system efficiency of a CHP system is the sum of the net useful electric energy and net useful thermal energy per total fuel energy input. Using cogeneration raises total system efficiency. As indicated previously, the electric efficiency of the peaker engines is estimated at 32.92%. According to technical literature for the LM2500, the proposed equipment in CHP applications between 20 to 40 MW, can obtain greater than 85% efficiency.¹⁷ Therefore, it is assumed that a total system efficiency for the CHP plant will achieve 75.125%. For the 67.5 MW power plant operating at 32.92% efficiency, a total system efficiency will therefore yield useful thermal energy equivalent to 86.55 MW.

However, as the total CHP system efficiency provides a measure for capturing the energy content of electricity and steam produced it does not adequately reflect the fact that electricity and steam have different qualities. The quality and value of electrical output is higher relative to heat output and is evidenced by the fact that electricity can be transmitted over long distances and can be converted to other forms of energy. To account for these differences in quality, the Public Utilities Regulatory Policies Act of 1978 (PURPA) discounts half of the thermal energy in its calculation of the efficiency standard, which is represented as the ratio of net electric output plus half of the net thermal output to the total fuel used in the CHP system. ¹⁸ It should be noted that conventional electrical generation technology is not always used to produce the useful thermal energy output if the CHP system did not exist: However, for thermal systems such as absorption chillers, it is not unexpected for conventional electric generation technologies to be displaced by CHP systems.

To account for the lower energy quality in the thermal output, as well as the possibility that sum of the displaced energy may not be from conventional generation technologies, 50% of the thermal output (or 43.27 MW) is taken as the effective CHP energy displacement on the Regional Fossil Generation Fleet. The Btu content of 43.27 MWh is approximately 150 MMBtu. The total plant efficiency, which is the weighted average of the electric efficiency and total system efficiency, is estimated at approximately 60%.





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To estimate the enhanced emission benefits that will result from use of the CHP system and increased system efficiency, the assumed net generation displacement (43.27 MW) is added to each dispatch hour in the Generation 2 Schedule (Break-even) when the NJ TRANSITGRID peaker plant is fully dispatched and then input into the AVERT model. The enhanced benefits include an additional 177,117 tons of CO₂ emission displacements. The summary results of the evaluation of added cogeneration to NJ TRANSITGRID is provided in **Table 2-8**.

Technology	Annual NJ TRANSITGRID Energy Delivery	Fleet GrossFleet GrossReductionReduction w/ow/CogenCogen		Enhanced Fleet Net Reduction
	(MWh)		(Tons of CO ₂)	
Cogeneration	1,057,670	887,784	710,667	177,117

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Alternative Fuels

RNG is a class of carbon-neutral biofuels that ultimately decrease the net CO_2 emissions of electric power production. Biofuels are carbon-neutral because they use biomass as feedstock that sequester carbon through the carbon fixation process, such as those that occur in plants or microalgae through photosynthesis. CO_2 in the atmosphere is absorbed by photosynthesizing organism where the carbon is fixed to build the organism's biomass.

Upon harvesting of this biomass (as agricultural products or organic wastes), this material can subsequently be used in the production of biofuels. Up until the time the biofuel is combusted, the carbon remains sequestered. However, when the biofuel is combusted, GhG are released in much the same proportion as the fossil-derived fuel. The difference is that by using biofuels such as RNG, a power plant that combusts these products is participating in a natural renewable cycle that ultimately neutralizes the GhG released by new biomass growing and fixing atmospheric carbon that essentially takes the place of the biomass in the fuel. The annual planting and harvest of corn use as feedstock for biofuels is one example of this regenerative, carbon-neutral process. So is the use of methane gas derived from landfills.

Current estimates are that supplies of RNG produced from a range of existing sources has the potential to meet ten percent of current natural gas demand and that the existing natural gas distribution network can be used to deliver the renewable fuel.¹⁹ However, recent initiatives by utilities, such as SoCalGas, the nation's largest natural gas distribution utility to subsidize and promote the use of RNG, and large-scale research programs such as those being conducted at the University of California at Davis, are providing promise of increased stocks and availability of RNG at prices similar to those of the current supply of fossil natural gas.²⁰ Many states electric





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renewable portfolio standard (RPS) programs also allow RNG to generate renewable energy credits (RECs) when it is used to produce electricity. A study conducted by UC Davis estimates that more than 20 percent of California's current natural gas use could be provided by RNG and that the sources of the biogas used in making refined RNG exist all over the country.

In future years, if RNG is used in the NJ TRANSITGRID system to replace up to 20percent of the current fossil natural gas supply, the system could provide an additional annual net reduction of CO_2 emissions of 97,561 tons. This represents a 20% reduction in the projected CO_2 emissions from NJ TRANSITGRID under the Generation 2 Schedule (Break-even) scenario.

High-Volume H2 Turbines is another promising future technology that can support zerocarbon emitting electric energy production. Several of the major natural gas-fired turbine manufacturers, including Mitsubishi Hitachi Power Systems, GE Power, and Siemens Energy all have developed H2 turbines.²¹ When H2 burns and combines with oxygen, it can produce electricity that delivers zero CO₂ emissions - only water and heat are exhausted. If H2 is blended with the natural gas supply to these turbines, the result is reduced carbon and GhG emissions.

The life-cycle production of carbon in the manufacture of H2 is also being significantly reduced. H2 production from renewables through electrolysis—which uses renewable power to split a water molecule—allows for the renewable H2 to be produced. Gas turbine units with H2 content ranging between 30% and 90% have been manufactured and used in industrial settings since the 1970's. When fired at 30% H2, high-volume H2 turbines can reduce carbon emissions by about 10% compared to a conventional combined cycle power production. Current research expects to bring H2 mixtures up to 90% resulting in up to 50% less CO₂ emissions.²² A 10% and 50% reduction in CO₂ emissions could result in overall reductions of 51,934 tons and 234,4440 tons, respectively by NJ TRANSITGRID when using new high-volume H2 turbines. This represents 10% and 50% reductions in the projected CO₂ emissions from NJ TRANSITGRID under the Generation 2 Schedule (Break-even) scenario.

<u>Summary</u>

A summary of enhanced emission benefits that could result from the use of solar energy plus energy storage systems, cogeneration, and high-volume H2 turbines are presented in *Figure 2-13*.





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Figure 2-13: Enhanced Annual CO2 Reductions (Tons) by Technology

Renewable Energy Credits (RECs)

Depending on its status as an electric power supplier in New Jersey, NJ TRANSITGRID may be required by regulation to include a certain percentage of renewable energy production in its total kilowatt-hours sold through the purchase and retirement of RECs, which are mechanisms used to support the development of renewable energy projects, such as solar or wind, by monetizing the environmental benefits of these technologies. By participating in these programs NJ TRANSITGRID, through its generation and sale of electricity, will support the market for zero-carbon emitting energy production.

As opposed to other types of carbon offset programs, RECs have the benefit of being additional and verifiable. The benefits are *additional* in that the benefits that result from renewable energy projects (zero-carbon emissions) prevent new carbon emissions by replacing carbonemitting technology. They are *verifiable* because each REC is minted with the production of each MWh of renewable energy, and then is registered, tracked and eventually retired by a clearinghouse monitor.

New Jersey currently operates one of the first and most successful solar REC programs, and in 2018 initiated a new offshore wind REC program to support development of 1100 MW of new offshore wind power.





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Endnotes

¹ The U.S. EPA AMPD web tool for querying and downloading historical Clean Air Markets Programs data may be accessed at this link: <u>https://ampd.epa.gov/ampd/</u>. The available data set used for this report includes is current up through the second quarter of 2019.

² Form EIA-860 detailed data with previous form data (EIA-860A/860B):

<u>https://www.eia.gov/electricity/data/eia860/</u>. The data accessed for this report was released on June 3, 2019 and constitutes the early release 2018 data. The next release date for the final data is planned for September 2019.

³ The higher heating value (HHV) is defined as the amount of heat released by the combustion unit's fuel It includes the latent heat of vaporization of water. In North America the thermal efficiency of a system is usually expressed in terms of HHV.

⁴ Jacobs Engineering Group, Inc. (July 2017), pp. 22-25. Figure 23: Gas Turbine Heat Rate

⁵ U.S. Energy Information Agency (EIA). Henry Hub Natural Gas Spot Price: <u>https://www.eia.gov/dnav/ng/hist/rngwhhdD.htm</u>

⁶ See Levitan & Associates. (2017), p. 5 for a discussion of the various options open to TRANSITGRID for participation in the PJM markets as a capacity resource, a self-scheduled energy-only resource with block loading, or as an energy-only resource subject to PJM economic dispatch.

⁷ The historical hourly real-time LMPs for aggregate and zonal pricing nodes for the period of analysis were retrieved from the PJM Data Miner 2 web site: <u>https://dataminer2.pjm.com/feed/rt_da_monthly_lmps/definition</u>

⁸ Avoided Emissions and Generation Tool (AVERT). A tool that estimates the emissions benefits of energy efficiency and renewable energy policies and programs. <u>https://www.epa.gov/statelocalenergy/avoided-emissions-and-generation-tool-avert</u>

⁹ Microeconomic theory generally identifies the break-even point on average variable costs as the lower limit for operating before a plant will be shut down. Although breaking even on average variable costs does not cover all fixed costs and in the long run will cause the firm to lose money (i.e. make negative economic profit), in the short-run the economic decision will be to operate the plant marginally above break-even if possible to contribute to on-going fixed expenses.

¹⁰ The "Full-power" dispatch scenario is meant to test the environmental benefits to be gained by full use of all engines on a 24/7 basis. It should be noted that running the Main Facility at full-power at all times will result in sales of excess power to PJM at times when the generating units are running at a financial loss. The other two dispatch scenarios are designed to avoid or balance these times of financial loss to assure that the generating units are not operating at a loss.

¹¹ Manufacturer information for the proposed equipment is provided in BEM Systems (November 2018), Appendix A. See discussion on emission estimates on pp 6-10.

¹² The system average CO2 emission factor is calculated by the AVERT model based on statistical energy dispatch of the fleet of generating resources.

¹³ U.S. Energy Information Agency (EIA). Electric Power Annual. <u>https://www.eia.gov/electricity/annual/</u> With Data for 2017 (Release Date: October 22, 2018). The following tables were used in calculation of





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the fossil fuel source CO2 emission factors: Table 8.1. Average Operating Heat Rate for Selected Energy Sources., Table 8.2 Average Tested Heat Rates by Prime Mover and Energy Source., Table A.3. Carbon Dioxide Uncontrolled Emission Factors.

¹⁴ U.S. EPA online Greenhouse Gas Equivalencies Calculator: <u>https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator</u>

¹⁵ See: Flywheel Energy Storage Study published by the Emerging Technologies Program San Diego Gas & Electric (March 2017). <u>https://www.etcc-ca.com/reports/flywheel-energy-storage-study</u>

¹⁶ National Renewable Energy Laboratory (NREL) System Advisor Model (SAM), version 2018.11.11 Revision 4 SSC 209 <u>https://sam.nrel.gov/</u>

¹⁷ See: <u>https://www.ge.com/content/dam/gepower-</u>

pgdp/global/en_US/documents/product/gas%20turbines/Fact%20Sheet/2018-prod-specs/LM2500-powerplants.pdf

¹⁸ See: U.S. Environmental Protection Agency. Combined Heat and Power Partnership. (March 2015). Appendix A: Expressing CHP. Efficiency.

https://19january2017snapshot.epa.gov/sites/production/files/2015-07/documents/catalog of chp technologies appendix a expressing chp efficiency.pdf

¹⁹ M.J. Bradley & Associates, LLC (April 2017). Renewable Natural Gas: The RNG Opportunity for Natural Gas Utilities. <u>https://www.mjbradley.com/news-events/renewable-natural-gas-rng-opportunity-natural-gas-utilities</u> Estimates of the amount of RNG that could be produced in the U.S. vary, but show that meaningful amounts of customer demand for natural gas could be met with RNG. The high end of a range of potential RNG volumes from an American Gas Foundation study is equal to ten percent of the natural gas delivered to U.S. customers in 2015. (p. iii).

²⁰ Jaffe, A.M. et al. (June 2016). The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute. University of California at Davis. <u>https://steps.ucdavis.edu/the-feasibility-of-renewable-natural-gas-as-a-large-scale-low-carbon-substitute/</u>

²¹ Patel, S. (May 1, 2019). High-Volume Hydrogen Gas Turbines Take Shape. Power Magazine. <u>https://www.powermag.com/high-volume-hydrogen-gas-turbines-take-shape/</u>

²² Noon, C. (January 2019). The Hydrogen Generation: These Gas Turbines Can Run On The Most Abundant Element In the Universe. GE Reports. <u>https://www.ge.com/reports/hydrogen-generation-gas-turbines-can-run-abundant-element-universe/</u>





NJ TRANSITGRID Benefits Evaluation Part 3 – Reliability and Flexibility Benefits Analysis

Part 3: Reliability and Flexibility Benefits Analysis





NJ TRANSITGRID Benefits Evaluation Part 3 – Reliability and Flexibility Benefits Analysis

Abstract

An Internal Reliability Model and External Reliability Model have been developed for NJ TRANSITGRID to quantify and value the reliability and flexibility benefits discussed in Part 1 of this report. Additionally, a novel concept for the development of a market for reliability and flexibility benefits on local circuits is discussed. This market anticipates the use of NJ TRANSITGRID spare capacity by the utility in response to proper price signals to respond to contingencies. This market would allow the utility to reallocate distributed generation resources for utilization on local circuits under specified circumstances to respond to losses of power from the grid.

The Internal Reliability Model tests the ability of NJ TRANSITGRID to respond to contingencies at the three internal connections located at Substation 41 (for the Amtrak portion of the NEC line), the Mason Substation (for the M&E line and the NJ TRANSIT Meadows Maintenance Complex) and the proposed new NJ TRANSITGRID East Hoboken Substation (for the HBLR line). The *External Reliability Model* assumes that only the connection at the Mason Substation will be feasible as a connection via switches and the existing distribution network wires to reconnect blocks of external utility customers.

For both models, the reliability levels experienced by the impacted loads are found to be a function of (1) the reliability of the distribution network, (2) the probability of NJ TRANSITGRID to successfully transition, and (3) the available internal energy capacity. The methodology for quantifying the added reliability provided by NJ TRANSITGRID to internal loads proceeds as follows:

- 1. Assign a baseline reliability measure to the traction power substation connections to NJ TRANSITGRID.
- 2. Quantify the probability that NJ TRANSITGRID will be available to energize the connections at a time when the grid may fail.
- 3. Use the baseline reliability measure (Step 1) and the Capacity Outage Table (Step 2) to quantify the amount of energy that NJ TRANSITGRID will be able to provide in the event of grid outages.

The results of the analysis of the *Internal Reliability Model* Loss of Energy Expectation (LOEE) baseline for the NJ TRANSITGRID connections to PSE&G is approximately 144 MWh/yr of unserved energy. The combined SAIDI (System Average Interruption Duration Index) at the three NJ TRANSITGRID connections to PSE&G is approximately 3.9 hrs/yr. Simulations indicate that there is a vanishingly small probability that NJ TRANSITGRID would not be able to cover peak loads at any of the three connections individually in blue-sky conditions and that for a loss of supply at all three connection points due to a severe systemic breakdown, NJ TRANSITGRID





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would have a 96.3% probability of supplying the lost load, significantly improving SAIDI for its internal connections in blue-sky and black-sky conditions.

A key component of the *External Reliability Model* is an estimation of the fair market price for reliability and flexibility services that NJ TRANSITGRID could offer to the utility for its connected customers. To estimate this price, information provided by PSE&G regarding their reliability planning process is used. The first step is to examine a PSE&G tariff filing to the New Jersey BPU to calculate the value of proposed reliability investments including the present-value cost for serving the average customer. Then, using that value, the second step is an estimation of the compensation that should be paid to NJ TRANSITGRID to provide the same reliability improvements at the same cost to the average customer as the proposed investments in the filing. In other words, the proper fair market price is that price that would make PSE&G indifferent to procuring the proposed reliability improvements from NJ TRANSITGRID or from other means as included in their tariff filings.

The results of the analysis of the *External Reliability Model* finds NJ TRANSITGRID could successfully provide power to any of 6 substations located along the Athenia-Essex transmission line that passes through the Mason Substation serving up to 1,600 customers at each substation and 28,000 customers overall. As with the *Internal Reliability Model*, the probability of any one of the NJ TRANSITGRID engines being unavailable at a time of contingency is vanishingly small. Using a Differential Revenue Requirement avoided-cost methodology, a per MW price for reliability and flexibility services is derived using a recent filing by PSE&G for implementation of a series of non-wires solutions for network reinforcement. Based on perceived benefits and improvements to SAIDI, the price signal is estimated at \$105/MWh.

The price signal for reliability and flexibility services for *External Reliability Model* may also serve as a proxy price for calculating benefits of the *Internal Reliability Model* since NJ TRANSITGRID still relies on PSE&G to energize the three main internal connections as necessary and depending on market conditions. Although the reliability benefits for the internal connections of the traction power system are better understood (and valued economically) in terms of system minutes of train delays caused by power interruption or delay-minutes per passenger-mile, the proxy reliability and flexibility price signal still provides a rational baseline for evaluating each gained minute of Loss of Load Expectation (LOLE) in the *Internal Reliability Model*.





NJ TRANSITGRID Benefits Evaluation Part 3 – Reliability and Flexibility Benefits Analysis

Introduction

Part 3 of this report uses the detailed model of the NJ TRANSITGRID Main Facility developed in Part 2 to quantify the reliability and flexibility benefits provided by NJ TRANSITGRID discussed in Part 1. This section provides a discussion to relate the resiliency goals of NJ TRANSITGRID to its reliability and flexibility capabilities, quantifies and values the benefits that flow from these capabilities, and describes a novel market concept for these services on local circuits of the distribution grid. This market for energy, reliability and flexibility based on the locational and operational advantages of distributed resources like NJ TRANSITGRID will enhance the economic feasibility of the program and thereby make its economic and societal benefits available to all stakeholders.

Resiliency, Reliability & Flexibility

The resiliency goal of NJ TRANSITGRID relates directly to grid resilience, which may be thought of as an intrinsic characteristic of the electric transmission and distribution grids to withstand and recover rapidly from service disruptions. However, as no standardized measures of grid resiliency currently exist, this analysis provides a measure of grid resiliency through a framework of desired levels of reliability and flexibility for the targeted components of the NJ TRANSIT system. Reliability and flexibility are what come into play once the resilient characteristic of the grid has been breached and therefore offer a good proxy measure of system resiliency. Reliability and flexibility, which describe well-defined capabilities of the grid, both have widely used measures in the power industry, particularly by electric distribution utilities, to benchmark and track customer service objectives.

Distribution *reliability* primarily relates to equipment outages and the resulting interruptions to customer power service. Under normal operating conditions, equipment stays energized and customers have access to quality power service that meets standardized voltage and frequency requirements. Distribution *flexibility* refers to the ability of grid operators to closely align supply and demand in the system using energy resources that can start, stop and ramp quickly, and economically, and operate across a wide output range. Increased levels of penetration of variable renewable generation into the distribution system is now causing new reliability issues for utilities associated with rapid and difficult to forecast voltage fluctuations that increased flexibility can mitigate. Customers located on feeders receiving power from intermittent sources such as solar arrays or onshore/offshore wind are exposed to significant power quality issues as a result. Uncontrolled fluctuations due to a lack of flexibility on the local circuits can lead to damage and failure of utility and customer equipment.

High levels of reliability and flexibility keep the grid resilient. In times of stress on the grid due to equipment failures, faults, or unforeseen peaks in demand, the operators of the distribution system rely on their reliability capabilities to withstand and recover from these contingencies. High





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levels of reliability and flexibility result in minimizing the number of customers that lose power and maximizing the response rate to reconnect and reenergize the circuits.

Reliability and flexibility capabilities are measured by the frequency and duration of events that lead to the unavailability of power to customers (where availability in power system analysis refers to the probability of circuits and equipment being energized). The measure of event duration is typically divided into three categories including momentary events (less than a few minutes), sustained events (more than a few minutes) and severe events (several hours to several days or even weeks). Momentary interruption events are typically caused by temporary faults being cleared by automated switching and reclosing devices. The momentary loss of power is due to the time it takes for the automated device to actuate and reset in response to the contingency. Sustained interruptions typically result from short circuits and faults that cannot be automatically cleared in a few minutes (or at all) or from a failure of equipment that requires service.

The difference in definition between a momentary and sustained interruption can vary between utilities, but the range of duration of a momentary interruption is generally 1-5 minutes and sustained interruptions can last up to several hours. Given the infrequent occurrence of severe events (several hours to several days or even weeks), electric utilities will typically evaluate and report reliability levels in ways that separate out the impact of severe interruptions caused by storms and other major events by defining Major Event Days that can be included or excluded from their analysis. Major Event Days typically are those where outages of several hours are experienced by a significant portion of the customer base. In this way reliability levels can report on normal operations that include high probability, low impact events (on the order of minutes and hours of interruption) and operations under extreme circumstances that include low probability, high impact interruption events (on the order of days or partial days of interruptions).

In the U.S., transmission and distribution system reliability (i.e. the availability of electric power) is enforced by the Federal Energy Regulatory Commission (FERC) in all the interconnected jurisdictions of the RTO's and ISO's in North America. FERC implements the Reliability Standards developed by the North American Electric Reliability Corporation (NERC), which makes state utility commissions and the utilities themselves subject to monetary penalties for violations of these standards. The NERC Reliability Standards are measured using standardized frequency and duration performance indices such as the Institute of Electrical and Electronics Engineers (IEEE) 1366-2003 Electric Power Distribution Reliability Indices. These include the most often used indices of SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), and CAIDI (Customer Average Interruption Duration Index).

To comply with NERC requirements, distribution systems are planned, designed. and constructed using, at minimum, an N-1 reliability operations scheme such that the system can meet customer demands and stay within thermal and voltage limits in the event of the loss of any





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single component (such as a transformer, breaker, transmission line, etc.). In severe system disturbances that result in the loss of multiple components, distribution systems can rely on a controlled interruption (load shedding) to maintain system integrity. Severe interruptions caused by storms and other major events have not typically been included in reliability planning by utilities since doing so could require substantial rate increases to pay for hardening of infrastructure to withstand infrequent events. However, with the increased number of severe storms in the last few years, distribution system planning is now taking these types of events into account.

Reliability in the NJ TRANSITGRID Service Area

In the period 2009-2017 (the most recent year with available data) PSE&G has an average SAIDI of 49.023 minutes (i.e. the average time in minutes that the typical customer was without power during the year), an average SAIFI of 0.737 events (i.e., the average number of outages experienced by the typical customer during the year) and an average CAIDI of 66.156 minutes (i.e., the average outage duration experienced by the typical customer during the year). It should be noted that these metrics are only averages for the entire PSE&G customer base, which in 2017 included approximately 2 million residential, commercial, institutional and industrial users. There is no detailed breakdown of the indices available by customer type or by feeder or locality to develop a better understanding of how service and reliability may vary within the system.

It should be noted that PSE&G has been primarily responsible for New Jersey scoring amongst the most reliable distribution systems of the fifty states and the District of Colombia since these indices began being tracked by the U.S. EIA after 2012. Compared to PSE&G's SAIDI in 2017 of 45 minutes, electric power for all U.S. customers was interrupted for an average of 7.8 hours (470 minutes). In 2017, the average U.S. utility customer experienced 1.4 interruptions counting Major Event Days and 1.0 interruption excluding Major Event Days (compared to 0.73 and 0.75 for PSE&G, respectively). PSE&G's self-reported reliability indices in the period 2009-2017 are presented in *Figure 3-1*.





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Figure 3-1: PSE&G IEEE Reliability Indices (2009-2017)

Traction Power System Reliability

Given the intended use of NJ TRANSITGRID to provide power to portions of the NJ TRANSIT and Amtrak system, it is important to note differences between how reliability is experienced by traction power systems and the general utility customer. Reliability of traction power systems relates directly to operating within a normal scheme configuration and schedule without causing safety hazards, train delays or public nuisance. While utility reliability may be expressed in interruption duration and frequency for its customers, for a traction power system minutes of train delays caused by power interruption or delay-minutes per passenger-mile is a more relevant metric. Mass transit service interruptions may also have damaging economic effects in excess of other uses and in some cases power failure to the traction system may cause catastrophic or life-threatening situations. In this light, reliability for traction power systems must be considered differently and in general tends to have higher economic value to society.





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Estimating the actual impact of electrical reliability on train delays is difficult given the number of sources of delays and their interactions. Causes of train delays include power failures, as well as multiple types of adverse track conditions and signal problems. One recent study completed by the Northeast Corridor Commission for the Gateway Program Development Corporation looking at five years (2014-2018) of delays at the North River Tunnels estimated overhead wire failures were the primary cause of up to 35% of the delays of 30 minutes or more on Major Event Days with 5 or more hours of delay. The overhead wire failures were the result of traction power interruptions or failures of the catenary system. The traction power incidents were more frequent, but catenary wire incidents resulted in more lost minutes per delay.¹

NJ TRANSITGRID Enhanced Resiliency

The reliability and flexibility benefits of microgrids like NJ TRANSITGRID stem directly from their ability to ride through momentary and sustained network outages and to island and reconfigure (or shed) internal loads in response to more severe network contingencies.

However, these benefits do not have to stay limited to NJ TRANSITGRID internal customers only. When used in coordination with the local utility and the application of proper price signals to value the reliability and flexibility services, NJ TRANSITGRID could be available to serve the distribution system and its connected loads. In this way, the reliability and flexibility benefits of NJ TRANSITGRID can accrue to two different sets of electric power customers including those primarily connected to NJ TRANSITGRID and those primarily connected to the distribution grid. This external microgrid reliability service would allow the utility to reconnect customers faster and increase the reliability levels of their networks. This reliability service could also provide on-call flexibility services to make up for real-time energy shortfalls or voltage fluctuations due to injections of intermittent renewable generation, unexpected levels of demand, or other contingencies such as the failure of a transformer or substation, or the unavailability of one or more power resources.

In blue-sky conditions NJ TRANSITGRID plans to have the 60 MW combined cycle power output and up to an additional 15 MW from the simple cycle combustion turbines primarily dedicated to serving internal loads on the NEC and M&E lines through connections at Amtrak's Substation 41 and the NJ TRANSIT Mason Substation. Electric power from NJ TRANSITGRID for the NEC will be provided from two 30 MW static frequency converters supplied from the onsite generation and transmitted by direct feeders to the existing electrified rail system. NJ TRANSITGRID will be able to energize up to 33 miles of track between Penn Station New York, through Newark Penn Station terminating at Jersey Avenue/County Yard in New Brunswick, NJ. This section of track is currently energized through connections at 7 track-side substations (including Substation 41) powered by PSE&G through a connection at Substation 38 (Metuchen).





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To provide traction power to the M&E line, NJ TRANSITGRID will also include two new overhead 230 kV transmission lines to the Mason Substation from the Main Facility. The Mason Substation (also known as NJ TRANSIT Meadows Substation) currently consists of two parallel 230 kV feeds that provide power to critical NJ TRANSIT rail facilities in Northern New Jersey. The Mason Substation will additionally serve as the point of interconnection for NJ TRANSITGRID with the PSE&G / PJM's 230 kV Northern New Jersey Athenia - Essex transmission line, as well as supply power to portions of the NJ TRANSIT Meadows Maintenance Complex. NJ TRANSITGRID will be able to energize approximately 17 miles of track on the M&E line through its connection at the Mason Substation between Hoboken Terminal and Millburn Station. The total estimated peak load for this section of track is 30 MW. Note that in addition to the Mason Substation there is a second substation with a 230-kV service connection (the JCP&L Summit Substation) that powers the M&E line. Both substations are each capable of supplying 100% of the power required to serve the entire M&E line.

NJ TRANSITGRID will also be able to provide power to the HBLR line and the North River Tunnels using a connection to the proposed new NJ TRANSITGRID East Hoboken Substation with additional connections out to Hoboken Terminal through the NJ TRANSIT West End and Henderson Street Substations. The HBLR traction power system is currently energized via 15 kV medium voltage sources at 15 traction power substations served by PSE&G. Power for the North River Tunnel mechanical systems is supplied via the 230 kV Athenia-Essex transmission connection at the Mason Substation. The estimated peak load for the HBLR, the Henderson Substation, and critical mechanical systems for the North River Tunnels is 20 MW.

This basic configuration for distribution of the NJ TRANSITGRID generation leaves the spare capacity of the three 22.5 MW single cycle combustion turbine peaker engines to participate in the PJM capacity auctions and offer power and reserve services on the day-ahead and real-time markets through its PJM interconnection to the Athenia-Essex transmission line at the Mason Substation. Capacity that is not committed to PJM by the day-ahead market is available for sale on the real time market.

A New Market for Reliability and Flexibility

Alternatively, this spare capacity could be committed to use on local circuits by the utility in response to proper price signals to respond to contingencies. With some foresight and planning, there could be schemes in place to allow the utility to reallocate distributed generation resources committed to the wholesale operator for utilization on local circuits under specified circumstances to respond to losses of power from the grid. For example, NJ TRANSITGRID, through its connections at the Mason Substation could be used to reenergize blocks of customers connected to substations on the Athenia-Essex transmission line in response to sustained interruption events lasting from a few minutes to a few hours. In more extreme conditions with widespread interruptions to grid service, after islanding from the distribution network and reconfiguring supply





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to its own internal loads, NJ TRANSITGRID could be reconnected to the network via its interconnection at the Mason Substation in coordination with the utility's restoration scheme to restore power to blocks of external network customers using its surplus generation capacity. Any such restoration scheme will need to define a reconfiguration approach that includes which switches to manipulate and define the priority of critical and secondary loads to be served (secondary loads are non-critical loads that will be reenergized only by virtue of being on a restoration path to a critical load).

Due to the inherent limited capacity of distributed generation as compared to the normal power flow, analyzing and controlling the dynamic performance of these interim power sources during this black-sky event is important to the successful transition and operation of this restoration process. The stability of the temporary distributed generation power source, frequency deviation, and transient voltages and currents will be operational constraints that must be monitored and controlled during the restoration of critical load.

In order to fully achieve the potential benefits of a new market for reliability and flexibility services on local circuits, several important pre-conditions are essential. The first pre-condition is the recognition by regulators and utilities that this local energy market on the circuits of the distribution grid is the minimum requirement needed for making distributed generation financially feasible. Distributed generation is at a marked disadvantage in terms of scale when competing on the wholesale market with merchant generation. Allowing distributed generation to participate in a market that fully realizes the value of the locational benefits it provides is a reasonable first step in promoting its use.

A second pre-condition is the development of positive (market-based) price signals that properly values these locational benefits combined with the use of dynamic (real-time) pricing to provide robust trading opportunities to both the distributed resources and the distribution networks. Currently, the application of the avoided costs principals of the Public Utility Regulatory Policies Act (PURPA) has led generally to a restricted, below-market valuation of energy produced by qualified facilities (i.e., small power producers of less than 20 MW using renewable power sources or highly efficient co-generation on local circuits via a retail interconnection). This under-valuation is reflected in the PSE&G Purchased Electric Power (PEP) Tariff. Using the so-called market-based avoided cost methodology, the PEP tariff uses a static energy payment method based on the monthly load-weighted average Residual Metered Load Aggregate LMP for the transmission zone in which the resource is located.

This method results in lower economic profits for distributed resource owners due to the loss of opportunity costs that might have been avoided by participating in the dynamic day-ahead and real-time markets. It is therefore essential that distributed generation instead receive true market-based value equivalent to dynamic real-time pricing. In addition, price signals can be developed under an alternative differential revenue requirement avoided-costs methodology





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(defined in PURPA) calculated as the difference between system revenue without the distributed generation and with the distributed generation so that the ability of these resources to delay or eliminate the need for costly network reinforcements by utilities may be realized.

The Internal Reliability Model

The Internal Reliability Model tests the ability of NJ TRANSITGRID to respond to contingencies at the three internal connections located at Substation 41 (for the Amtrak portion of the NEC line), the Mason Substation (for the M&E line and the NJ TRANSIT Meadows Maintenance Complex) and the proposed new NJ TRANSITGRID East Hoboken Substation (for the HBLR line). The reliability levels experienced by these internal loads is a function of (1) the reliability of the distribution network, (2) the probability of NJ TRANSITGRID to successfully transition, and (3) the available internal energy capacity. The methodology for quantifying the added reliability provided by NJ TRANSITGRID to internal loads proceeds as follows:

- Assign a baseline reliability measure to the traction power substation connections to NJ TRANSITGRID. In this case the system wide SAIDI measure reported by PSE&G is used. As the reliability for individual feeders and substations are not publicly reported by PSE&G, a lognormal distribution to estimate SAIDI measures at individual substations and feeders is constructed.²
- 2. Quantify the probability that NJ TRANSITGRID will be available to energize the connections at a time when the grid may fail. This probability is captured in a Capacity Outage Table that presents the joint probabilities that one or more of the NJ TRANSITGRID engines will not be available at any particular moment due to planned or unplanned outages at the Main Facility.
- 3. Use the baseline reliability measure (Step 1) and the Capacity Outage Table (Step 2) to quantify the amount of energy that NJ TRANSITGRID will be able to provide in the event of grid outages. In other words, this step will quantify how much lost load NJ TRANSITGRID can avoid by providing energy to the traction power systems at times when the grid would not be available.

Baseline Reliability Measure

The reported PSE&G SAIDI provides a starting point for the development of an estimate of the reliability of the distribution system at the three delivery points for power from the bulk electricity system to the targeted traction power components. The PSE&G system wide SAIDI value in 2017 (the most recent available data) is 44.610 min/yr (0.744 hrs/yr) when excluding Major Event Days.

Given the way the information is reported by PSE&G, it is not possible to use this information to identify differences by customer type (i.e. residential, commercial or industrial) or





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for specific sections of the distribution system. The indices only provide a very broad average over the entire customer base and service area. The internal reliability model assumes the 2017 SAIDI value as the mean of a lognormal distribution of possible SAIDI measures at different parts of the system (i.e. individual feeders) or under different use conditions (i.e. residential vs. industrial). An example random lognormal distribution for SAIDI using a mean value of 0.744 hrs/yr (i.e. the PSE&G system wide SAIDI value in 2017) is presented in *Figure 3-2*. In this random selection using 10,000 samples, the maximum value is 7.864 hrs/yr (close to the U.S. average of 8 hrs/yr.).



Figure 3-2: Example SAIDI Lognormal Distribution for PSE&G Circuits

By way of comparison, the industry reliability standard for the probability of the loss of supply at a substation from the bulk electricity system LOLE is 0.1 days/year (2.4 hrs/yr), which is equivalent to a customer experiencing one day of disconnection from the power source every 10 years. SAIDI and LOLE are similar in that both are risk measurements of the expected loss of load duration. SAIDI measures the risk from the viewpoint of a single customer at a single





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connection. The customer's interruption could be for a large variety of reasons, including loss of supply from the bulk power system. LOLE measures the risk from the point of view of the bulk electric system considering both reliability of the generation and the transmission system. SAIDI has been designed to measure normal operations and interruptions on the order of hours, whereas LOLE is designed to measure severe interruptions on the order of days or partial days. In the example probability distribution shown in *Figure 3-2*, the 90th percentile of the randomly sampled lognormal values in this model is 2.204 hrs, indicating that for at least 90% of the samples, the expectation of an interruption (measured in hrs/yr) will be less than the LOLE standard of 2.4 hrs/yr.





Interruptions of service at the three substation connections are assumed to be independent of one another. Therefore, a nonsequential Monte Carlo process is used to develop a distribution of baseline LOEE – or the expected energy not supplied in a period of time due to the probability of the load exceeding the available generation due to a loss of power. The results





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of the analysis of the baseline LOEE and SAIDI for the NJ TRANSITGRID connections to PSE&G is presented in *Figure 3-3* and *Figure 3-4*. Using 10,000 samples drawn from the lognormal probability distribution of the LOLE at each of the connections, and assuming peak load at each connection at the time of interruption, the LOLE for the system (the mean of the resulting distribution) is approximately 144 MWh/yr of unserved energy. The combined SAIDI at the three NJ TRANSITGRID connections to PSE&G is approximately 3.9 hrs/yr (or an average of 1.3 hrs/yr at each connection). These events lead to a loss of power of varying duration to the traction power systems resulting in passenger delays, potently damaged equipment, and sometimes more dangerous circumstances such as stranded trains.



Figure 3-4: Estimated SAIDI at NJ TRANSITGRID Connections

Capacity Outage Table

The probability of a successful transition of NJ TRANSITGRID to cover loss of load contingencies is a function of the availability of the generating units during these events





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considering the number of planned, unplanned, and forced outages of the equipment and the time needed to provide service. The availability factor therefore represents the percent of time that the turbines are available for service, either operating or in a state of ready reserve.

The availability factor reported by the manufacturer for the family of GE LM2500 turbines is 98.7%. The available internal energy capacity is determined through the development of a Capacity Outage Table that shows the cumulative probability of a certain outage state assuming that each of the five units (the two 30 MW combined cycle units and the three 22.5 simple cycle units) can be treated independently. The Capacity Outage Table for NJ TRANSITGRID is presented in **Table 3-1**. There is a 93.67% probability that the full 127.5 MW capacity would be available at any one time. There is a 3.7% probability that capacity would ever fall below the 105 MW threshold to cover the simultaneous peaks at all three connections if necessary.

Capacity in Service (MW)	Probability	Cum. Prob.
0	0.0000	0.0000
22.5	0.0000	0.0000
30	0.0000	0.0000
45	0.0000	0.0000
52.5	0.0000	0.0000
60	0.0000	0.0000
67.5	0.0002	0.0002
75	0.0010	0.0012
82.5	0.0005	0.0016
97.5	0.0247	0.0263
105	0.0370	0.0633
127.5	0.9367	1.0000

Table 3-1: NJ TRANSITGRID Capacity Outage Table

Avoidance of Lost Load

To analyze the ability of NJ TRANSITGRID to provide power in the event of these contingencies, the Capacity Outage Table (*Table 3-1*) is used to determine the probability that NJ TRANSITGRID will have enough power to cover the loss of load. As indicated in *Table 3-1*, there is a vanishingly small probability that NJ TRANSITGRID will not have enough available power to cover contingencies at peak load at any one of the connections to the Amtrak NEC, the M&E or HBLR lines. Further, given the very small probability (~10⁻⁸ - 10⁻¹²) that an interruption





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event would happen independently at two or three connections simultaneously, the standard LOLE of 2.4 hrs/yr is used instead to evaluate the ability of NJ TRANSITGRID to serve a blacksky scenario of a loss of power at 2 or 3 connections from the bulk electricity system. **Table 3-2** shows all combinations of peak loads at 2 and 3 connections and the probability that there will be enough capacity to cover these outages. For a loss of supply at all three connection points due to a severe systemic breakdown, NJ TRANSITGRID would have a 96.3% probability of supplying the lost load.

Amtrak (MW)	M&E (MW)	HBLR (MW)	Total Cap Out (MW)	Probability
60	30	20	110	0.9630
60	30	0	90	0.9753
60	0	20	80	0.9995
0	30	20	50	1.0000

Table 3-2: NJ TRANSITGRID Black-Sky Reliability Table

The External Reliability Model

Similar to the *Internal Reliability Model*, the reliability levels experienced by external loads serviced by NJ TRANSITGRID in the *External Reliability Model* is also a function of (1) the reliability of the distribution network, (2) the probability of NJ TRANSITGRID to successfully transition, and (3) the available internal energy capacity. The *External Reliability Model* assumes that only the connection at the Mason Substation will be feasible as a connection via switches and the existing distribution network wires to reconnect blocks of the utility customers.

A key component of the *External Reliability Model* is an estimation of the fair market price for reliability and flexibility services that NJ TRANSITGRID could offer to the utility for its connected customers. To estimate this price, information provided by PSE&G regarding their reliability planning process is used. The first step is to examine a PSE&G tariff filing to the New Jersey BPU to calculate the value of proposed reliability investments including the present-value cost for serving the average customer. Then, using that value, the second step is an estimation of the compensation that should be paid to NJ TRANSITGRID to provide the same reliability improvements at the same cost to the average customer as the proposed investments in the filing. In other words, the proper fair market price is that price that would make PSE&G indifferent to procuring the proposed reliability improvements from NJ TRANSITGRID or from other means as included in their tariff filings.





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Estimation of Reliability and Flexibility Price Signal

Based on the threat of potential monetary penalties for violations of the Reliability Standards, the reliability indices (i.e., SAIDI, SAIFI, CAIDI, etc.) have an economic value that incentivizes distribution utilities to maintain acceptable reliability levels. In response to these economic incentives, distribution utilities will typically make reliability the centerpiece of their short and long-term planning processes. The utilities can upgrade their networks to improve or maintain reliability at acceptable levels and thereby minimize potential economic penalties.

For example, PSE&G uses a standard electric distribution planning process to estimate load growth on the distribution grid each year. This analysis is completed by gathering information from customer requests for additional loads and then preparing circuit improvement strategies to meet new load requirements. Circuit improvements to accommodate load growth typically range from simple solutions such as moving load to a nearby circuit, to more complex upgrades like constructing an entirely new circuit. According to PSE&G, the costs associated with these upgrades can range from \$300,000 to \$8 Million per circuit. In place of costly investments in permanent network reinforcements to address reliability and flexibility concerns, utilities may also procure distributed resources for so-called non-wire alternatives to address their reliability planning needs. This replacement of network reinforcement with non-wire solutions allows a direct comparison of costs and benefits and the use of the differential revenue requirements avoided-cost methodology to determine a fair market price for these services.

One such effort to use non-wire alternatives to address reliability issues is the PSE&G *Clean Energy Future* program that was proposed to the BPU in September 2018. This program includes up to \$4 Billion dollars in new fixed investments over a 6-year period in clean energy and advanced technology to address concerns regarding the future resiliency, reliability, flexibility and energy efficiency on the PSE&G circuits. The planned *Clean Energy Future* investments include \$3.25 Billion for energy efficiency, electric vehicles and energy storage, and \$750 Million for an Energy Cloud program to improve smart-grid capabilities.

In October 2018, PSE&G filed its petition with BPU for the energy storage components of the program. This filing detailed five proposed energy storage subprograms to install 35 MW of new energy storage systems across the PSE&G distribution area. The program is projected to require up to \$109.38 Million of fixed investment costs and \$70.47 Million in on-going O&M and administrative costs over the projected 25-year life of the program for a total combined program expenditure of \$179.85 Million. In general, the energy storage program is meant to provide emergency back-up power for essential services, offset peak loads, provide frequency regulation and stabilize the electric distribution system.³

The energy storage subprograms include a Solar Smoothing project to install up to 10 MW of energy storage at five different installation sites for a total investment of \$13.1 Million and a Distribution Deferral project to install 13 MW of energy storage at seven different locations for a





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total investment of \$38.6 Million. The Solar Smoothing project will install up to 2 MW/2 MWh energy storage systems at large solar arrays to smooth voltage fluctuations on the local circuits. The Distribution Deferral project will install 1 MW/4 MWh distributed energy storage systems intended to address forecasted overloads on constrained circuits. These projects are all non-wires alternatives meant to delay or avoid permanent upgrades to the system such as additions of new transformers and switches or reconductoring power lines at overloaded substations and feeders. The three other subprograms include Outage Management to deploy up to 6 MW of mobile energy storage systems for a total cost of \$20 Million, Microgrids for Critical Facilities that will deploy up to 2 MW of solar-connected storage for a total cost of \$25.7 Million, and Peak Reduction for Public Sector Utilities that will deploy up to 4 MW of energy storage for a total cost \$20.9 Million.

In its filing, PSE&G proposes to recover the revenue requirements (including a net return on investment) associated with the direct costs of the program including all costs related to capital expenditures, and O&M costs including the administrative costs of running the program. PSE&G proposes to recover the net revenue requirements (i.e., net of any possible generated income) associated with the Energy Storage Programs via two components of a new Technology Innovation Charge (TIC) to the PSE&G approved Tariff for Electric Service. The net revenue requirements for the energy storage program is \$190.04 Million over 25 years or an annualized equivalent payment of \$16.43 Million using the reported PSE&G monthly after-tax Weighted Average Cost of Capital (WACC) of 0.6139%. The Net Present Value of this investment is in 2019 dollars is \$94.28 Million.

This revenue requirement averages \$5.43 Million per MW of available power to be used in energy delivery ranging from 0.5 MW to 2 MW over periods ranging from 2 to 4 hours. By comparison, the (NREL in its most recent evaluation of the costs of utility-scale Li-ion battery systems estimates costs ranging from \$1.36 to \$1.48 Million per MW for 4-hour energy capacity batteries.⁴ The NREL estimated cost includes capital costs and the fixed costs of O&M but excludes the administrative and financing costs and return on equity included in the PSE&G revenue requirement calculations.

PSE&G intends to use the proposed energy storage systems to address reliability and flexibility needs using the characteristics of the distributed resources to discharge rapidly in response to signals from automatic control software or manual signals from system operators. Alternatively, as the 22.5 MW combustion turbine peaker engines of NJ TRANSITGRID may also be dispatched rapidly for periods of 30 minutes to 4 hours in response to contingencies or voltage fluctuations, NJ TRANSITGRID could be used by PSE&G as distributed resources similar to the capabilities of the proposed energy storage system. These reliability and flexibility services would be stacked along with the capability of NJ TRANSITGRID to provide energy and significant demand reduction to the local circuits.




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Valuation of NJ TRANSITGRID Reliability and Flexibility Services

To estimate the reliability benefits that may be gained with the *Clean Energy Future* energy storage investment, the Interruption Cost Estimate (ICE) Calculator planning tool developed by Lawrence Berkeley National Laboratory is used.⁵ This on-line tool is designed for electric reliability planners at utilities, government organizations, etc., to estimate interruption costs and benefits associated with reliability improvements that can be measured by anticipated changes in the IEEE reliability indices. The costs and benefits are state-specific and account for the mix of impacted residential, and commercial and industrial (C&I) customers. The model is based on the perceived financial losses experienced by each customer type as a result of an interruption in electric service.

To achieve the benefit, equal to the proposed \$94 Million present value cost of the *Clean Energy Future* energy storage program (i.e. a Benefit-to-Cost ratio of 1), the ICE Calculator, estimates that an improvement in SAIDI of 2.81 minutes (or a 6.3% reduction from 2017 levels) is required. Although PSE&G did not offer specific estimated benefits associated with the investment in *Clean Energy Future* energy storage program, by comparison with the PSE&G filing for the \$750 Million Energy Cloud portion of *Clean Energy Future*, PSE&G estimates a Benefit-to-Cost ratio of 1.25 and a reduction in SAIDI of 2 % or approximately 1 min/yr.⁶ The results of the ICE Calculator model are presented in *Table 3-3*.

Sector	No. of Customers	Total Benefit (2019 \$M)	Benefit per Customer (2019 \$)
Residential	1,709,514	\$1.53	\$0.90
Small C&I	225,928	\$60.38	\$267.25
Medium and Large C&I	10,468	\$32.26	\$3,081.69
Total:	1,945,910	\$94.17	\$48.39

Table 3-3: PSE&G Clean Energy Future Program Benefits

For purpose of this analysis it will be assumed that NJ TRANSITGRID through a series of switching manipulations can provide power to one of several substations located along the Athenia-Essex transmission line that passes through the Mason Substation. The model assumes a typical substation providing power to a mix of residential, commercial and industrial customers with a 12.47 kV service available to as many as 4 feeders per bus. A typical service feeder with a peak load of 7 MVA and average demand of 4.8 MVA may have as many as 400 customers connected. Each NJ TRANSITGRID simple cycle 22.5 MW combustion turbine could provide power for up to 3 feeders at peak load and 4 feeders at average load with some load curtailment. Therefore, each of the NJ TRANSITGRID 22.5 MW simple cycle combustion turbine engines would be capable of providing stand-by power to energize up to 1,600 customers connected to 4 feeders on a typical 12.47 kV substation bus. There are 6 substations connected to the Athenia-





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Essex transmission line between the Mason Substation and the Athenia Switching Station that could receive reliability services from NJ TRANSITGRID including (from north to south) Clifton, Nutley, Cook Road, Belleville, Kingsland, and Turnpike.

Assuming each of the substations will experience a SAIDI within the lognormal distribution illustrated in *Figure 3-1*, the probability is vanishingly small (~10⁻⁸) that any two substations would experience an interruption at the same time that is not caused by a system wide disturbance. Therefore, in blue-sky conditions there is a very high probability (as per the Capacity Outage Table in *Table 3-1*) that one, two or three of the 22.5 MW engines will be available to provide power in buckets of 22.5 MW as needed to any of the connected blocks of customers at each of the six substations. As standby services at each substation could serve up to 4,800 customers each (3 engines serving 4 feeders) a total of 28,000 customers connected at the 6 substations would see improvements in their SAIDI using this scheme. (It should be noted that alternatively the reliability services could be connected to larger commercial or industrial customers through other substations such as the USPS Daniels Processing Center or the NJ TRANSIT Meadows Maintenance Complex).

As in the Internal Reliability Model, a LOLE of 1.3 hours per year is assumed to be the expected SAIDI for any one of the substations. This results in the three 22.5 MW engines (total 67.5 MW) covering an LOEE of 87.5 MWh/yr. Assuming this value remains constant over the 25-year analysis period, a total of 2,193.75 MWh will be served. The ICE Calculator model indicates total benefits per customer over the 25-year analysis period at approximately \$48 per customer (accounting for the variation in the number of customer types as presented in **Table 3-3**) or \$230,400 per substation in avoided capital costs. In other words, \$230,400 is the investment avoided by the utility to provide these network reinforcements when using NJ TRANSITGRID instead of the other non-wires solutions at the unit cost of the proposed *Clean Energy Future* energy storage program.

The cost of delivering the power is therefore \$105/MWh (\$230,400 divided by the 2,193.75 MWh LOEE served by NJ TRANSITGRID). This is the estimated fair market price to be paid for NJ TRANSITGRID power committed to serving the identified customer blocks with restoration services to increase customer SAIDI in the PSE&G service area.





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Figure 3-5: Reliability and Flexibility Price Signal

As may be seen in the demand curve presented in *Figure 3-5*, the price depends on the amount of LOEE being covered by the reliability resource. When only a single 22.5 MW engine is committed, the total LOEE is limited to 731.25 MWh and the price signal rises to \$315/MWh. Similarly, when only 2 units are committed (45 MW), the LOEE is limited to 1,462.5 MWh and the price signal is \$158/MWh. As may be expected, as the LOEE increases, the scale benefits of the resource start to outweigh the locational benefits until the price signal reaches parity with the average real-time LMP (\$32/MWh) at the Kearny pricing node (see Figure 3-6 and Figure 3-7). The utility would use the demand curve to select the amount of reliability it desires for the given investment. In this presentation of the model, the inelastic vertical supply curve at \$105/MWh matches the planned investment by PSE&G for its implied reliability goals.





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Figure 3-6: Real-time LMP Time Series (2017-2018) Kearny Pricing Node (PJM)

The price signal for reliability and flexibility services for external customers may also serve as a proxy price for calculating benefits of the *Internal Reliability Model* since NJ TRANSITGRID still relies on PSE&G to energize the three main internal connections as necessary and depending on market conditions. As discussed in the section on Traction Power System Reliability (see the *Introduction*), the reliability benefits for the internal connections are better understood (and valued economically) in terms of system minutes of train delays caused by power interruption or delayminutes per passenger-mile. However, the proxy reliability and flexibility price signal still provides a rational baseline for evaluating each gained minute of LOLE in the *Internal Reliability Model*.

This reliability and flexibility price signal is higher than the typical day ahead and real-time LMP paid at the Kearny pricing node. As may be seen in *Figure 3-6* and *Figure 3-7* although LMP may be as high as \$600 for short periods of time due to extreme scarcity pricing, LMP exceeds \$105/MWh more than 2.4% of the time due to moderate scarcity conditions. This estimated price for reliability services is therefore in-line with market-based pricing for expected levels of blue-sky scarcity. This pricing scheme provides a fair return for the owner of the distributed generation and allows the market on the local circuits to attract this generation to cover utility demand.





NJ TRANSITGRID Benefits Evaluation Part 3 – Reliability and Flexibility Benefits Analysis



Figure 3-7: Real-time LMP Histogram (2017-2018) Kearny Pricing Node (PJM)

Conclusion

A key to the valuation of the reliability and flexibility benefits of NJ TRANSITGRID presented here is the understanding that SAIDI is improved when reliability reinforcements are installed to handle contingencies. The improvement in SAIDI is not necessarily linked to the actual use of the reinforcements – just their availability for use. In other words, NJ TRANSITGRID improves SAIDI for the utility and its customers by being available for use and the value of the benefits stems from the availability. It is this ability to improve SAIDI that is the basis for the valuation of its energy and reserve services using the differential revenue requirements avoided costs methodology.

The reliability and flexibility benefits evaluated in this analysis are part of a family of economic benefits that distributed generation offers to the grid that currently have no conventional market value. These economic benefits could play an important role in the formation of a potential





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value stack of energy services that will make distributed resources a viable business model. These economic benefits include environmental, commercial and technical benefits. The environmental benefits, discussed and quantified in Part 2, derive from total emission reductions. The commercial benefits include potential reductions in the retail price of energy to local consumers, profit to owners of distributed resources who stand to gain if their energy can be sold at rates higher than wholesale, and network hedging benefits available to all stakeholders that protect against wholesale price fluctuations when distributed resources are used for peak shaving or load shifting. The technical benefits include potentially significant reductions in peak loading needed from conventional resources, flattening of voltage fluctuations, curtailment of system loss, as well as the reliability and flexibility benefits being discussed here.

These economic values ultimately stem from two competitive advantages of distributed generation over conventional generation. The first are the locational advantages that derive from the physical location of the distributed resource within the distribution network. The second are the operational advantages associated with the selective ability these resources leverage to participate in global technical and environmental grid optimizations while simultaneously maximizing their opportunity for profit (or to avoid loss of opportunity costs). These advantages combine to create the prospect for a local market on the circuits of the distribution network where distributed generation can sell at prices somewhat higher than the wholesale level (due to their increased locational value) and customers could buy at prices somewhat lower than the retail level (due to the selective optimization of the resource).

Another important factor in this market are the trade-offs between locational value and economies of unit scale. In a market where small and large resources will compete there will always be a question of efficiency and how best to meet efficiency goals that can be answered with the application of clear price signals. In this way distribution utilities can make solid decisions to use distributed generation to delay or eliminate the need for more expensive permanent network upgrades. As will be seen, there may be other ways to maintain required levels of network reliability such as adding more large-scale generation, demand response, large-scale battery storage, or network reinforcement. However, these alternatives may be at a technical and economic disadvantage when the economies of scale are fairly evaluated against the locational and operational advantages of distributed resources.

Ultimately, the value of these benefits on this new local market will depend strongly on the degree of coordination with all stakeholders including the operators of the distribution system and the wholesale energy market. With increasing penetration of distributed resources, regulators and electricity distribution utilities face greater uncertainty regarding short- and long-term planning for network requirements and the ultimate evolution of system costs. Distribution system operators must continue to be guaranteed adequate revenue and rate of return on investments to incentivize performance under such uncertainties. These new local markets for energy must serve all stakeholders and methods must be provided to regulators to overcome information asymmetries





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that will develop and to manage uncertainty. This will enable regulators to align incentives for utilities to cost-effectively integrate distributed energy resources while taking advantage of opportunities to reduce system costs and improve performance.

End Notes

¹ Gateway Program Update. July 22, 2019.

http://www.gatewayprogram.org/wp-content/uploads/2019/07/19-07-22 GDC-BoardUpdate FINAL.pdf

² It is well-documented in power system reliability literature that SAID, as well as the other common IEEE reliability measures are lognormally distributed. For example, see the IEEE Standard 1366 (<u>https://standards.ieee.org/project/1366.html</u>) or J. H. Eto, K. H. LaCommare, M. D. Sohn and H. C. Caswell, Evaluating the Performance of the IEEE Standard 1366 Method for Identifying Major Event Days, in IEEE Transactions on Power Systems, vol. 32, no. 2, pp. 1327-1333, March 2017.

³ In the Matter of the Petition of Public Service Electric and Gas Company for Approval of its Clean Energy Future- Electric Vehicle and Energy Storage (CEF-EVES) Program on a regulated basis. BPU Docket No. EO18101111. Filed October 11, 2018.

https://nj.pseg.com/aboutpseg/regulatorypage/regulatoryfilings

⁴ NREL. (June 2019). Cost Projections for Utility-Scale Battery Storage Technical Report NREL/TP-6A20-73222. <u>https://www.nrel.gov/docs/fy19osti/73222.pdf</u>

⁵ Interruption Cost Estimate (ICE) Calculator Planning Tool: <u>https://icecalculator.com/home</u>

⁶ In the Matter of the Petition of Public Service Electric and Gas Company for Approval of its Clean Energy Future-Energy Cloud (CEF-EC) Program on a regulated basis. BPU Docket No. EO18101115. Filed October 11, 2018. <u>https://nj.pseg.com/aboutpseg/regulatorypage/regulatoryfilings</u>





Technical Appendix (Matlab program code)

Appendix A: Environmental Benefits Model Appendix B: Reliability & Flexibility Benefits Model





Appendix A: Environmental Benefits Model



NJ TRANSITGRID Environmental Benefits Model

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- Steam Coal Baseload Plant Emissions Displacement
- Enhanced Emission Benefits Solar power and energy storage system
- Cogeneration & Thermal Dispatch Enhanced Emission Benefits
- Alternative Fuels Enhanced Emission Benefits
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Load Data and Set Model Parameters

```
close all; clc; clear;
cd 'C:\Users\matth\Desktop\LILITH\BRS Temp\GbD\NJT\NJTransitGrid\Deliverables\Benefits Evaluation\Matlab'
load('njt_emissions_data');
% load('model_date.mat'); % array of dates for period of analyais (03 Mar 18 to 28 Feb 19)
% load('nec_load.mat'); % NEC load data for the period of analysis
% load('me_load.mat'); % M&E load data for the period of analysis
% load('gas_price.mat'); % Henry Hub natural gas spot price for the period of analysis
% load('heat_rate.mat'); % incremental heat rate values for TRANSITGRID (Btu/kWh)
% load('pjm_lmp.mat'); % PJM LMP for the Kearny Pricing Node for the period of analysis
% load('vom.mat'); % variable O&M costs for the period of analysis
% load('dispatch.mat'); % optimum dispatch
load('avert');
                               % AVERT results: generation fleet ghg emission offsets
load('ampd');
                                % EPA AMPD emissions data (hourly by unit) & EIA facility data
% set transitgrid nameplate capacity
gt_mw = 22.5; % Peaker engine name-plate capacity (MW)
ccp_mw = 60; % Baseload power (MW) -- (combined cycle power)
fullpower_mw = 127.5; % Full-power (MW) -- (combined cycle and peaker engines)
% set heat rate values
hr gt=heatrate{heatrate.mw==gt mw,2};
hr ccp=heatrate{heatrate.mw==ccp mw,2};
hr_fullpower=heatrate{heatrate.mw==fullpower_mw,2};
% Set emission rates and emission factors. Emission rates are provided in
% pounds (tons) per hour of CO2. The emission factor is the rate of CO2
% emissions (tons) per MW of generation. Note: "m" will generally refer to
% "greenhouse gas (GhG) emissions" (short tons of carbon dioxide)
% GhG emission rate for the LM2500 22.5 MW engine (tons/hr)
m rate = 14.5085;
% TRANSITGRID emmission factors
m factor ccp=2*m rate/ccp mw;
m_factor_gt=m_rate/gt_mw;
```

```
m_factor_full=...
    (ccp_mw*m_factor_ccp+3*gt_mw*m_factor_gt)/fullpower_mw;
```

Figure: Incremental Heat Rate

```
figure;
plot(heatrate.(1), heatrate.(2),'-o','MarkerFaceColor','blue',...
    'MarkerSize',4);
ytickformat('%.2f')
title('Incremental Heat Rate');
ax = gca;
ax.FontSize = 8;
xlabel('MW','FontSize',10);
ylabel('Heat Rate (Btu/kWh)', 'FontSize',10);
xlimit=[22.5;45;60;82.5;105;127.5];
ystart = 7000.* ones(length(xlimit),1);
ystop = 17000.* ones(length(xlimit),1);
tx = [xlimit.';xlimit.';nan(1,length(xlimit))];
ty = [ystart.';ystop.';nan(1,length(xlimit))];
line(tx(:),ty(:))
str = {'GT 1', 'GT 2', 'ST', 'GT 3', 'GT 4', 'GT 5'};
text(xlimit+1.5,ystart+200,str,'Rotation',90);
ax.YTickLabel=cellstr(num2str(ax.YTick'));
set(gca, 'YGrid', 'on', 'XGrid', 'off');
% Figure: Henry Hub Natural Gas Spot Prices
figure;
plot(model_date, gas_price, 'b');
title('Henry Hub Natural Gas Spot Prices');
xlabel('Date','FontSize',10);
ytickformat('usd');
set(gca, 'YGrid', 'on', 'XGrid', 'off');
% Figure: Average Hourly LMP at the Kearney Pricing Node
lmp_year = table(model_date, pjm_lmp);
nrow_lmp_year = size(lmp_year,1);
lmp_year.day_number = weekday(lmp_year.model_date);
lmp_year.disp_hour = hour(lmp_year.model_date);
lmp_year = movevars(lmp_year, 'disp_hour', 'After', 'model_date');
lmp_year = movevars(lmp_year,'day_number','After','model_date');
% dispatch hours (weekday hours = 0-23/weekend hours = 24-47).
for i = 1:nrow_lmp_year
    if lmp year.day number(i)==1 || lmp year.day number(i)== 7
            lmp_year.disp_hour(i) = lmp_year.disp_hour(i) + 24;
    else
             lmp year.disp hour(i);
    end
end
hours = (0:47)';
lmp_avg = table(hours);
nrow_lmp_avg = size(lmp_avg,1);
lmp_avg.total_hours = zeros(nrow_lmp_avg, 1);
lmp_avg.total_lmp = zeros(nrow_lmp_avg, 1);
for i = 1:nrow_lmp_year
    for j = 1:nrow_lmp_avg
        if lmp_year.disp_hour(i)==j-1
           lmp avg.total hours(j) =...
               lmp_avg.total_hours(j)+1;
```

```
lmp_avg.total_lmp(j) =...
              lmp_avg.total_lmp(j)+ lmp_year.pjm_lmp(i);
        end
    end
end
for j = 1:nrow_lmp_avg
    % lmp annual hourly averages
    lmp_avg.lmp_avg(j) =...
        lmp_avg.total_lmp(j)/lmp_avg.total_hours(j);
end
d=lmp_avg(1:24,1);
d.weekday=lmp_avg{1:24,4};
d.weekend=1mp_avg{25:48,4};
d.value(1:24,1:2) = [d.(2) d.(3)];
b=d{:,{'hours'}};
c=d{:,{'value'}};
b = categorical(b,b);
figure;
width = 1;
ba = bar(b,c,'barwidth',width,'facecolor','flat','edgecolor','none');
title('Average Hourly LMP at the Kearney Pricing Node');
ax = gca;
ax.FontSize = 8;
ytickformat('usd');
set(gca, 'YGrid', 'on', 'XGrid', 'off');
legend('Weekday','Weekend','location','southoutside',...
    'orientation', 'horizontal');
legend('boxoff');
ba(1).CData = [0, 0.4470, 0.7410];
                                      % dk blue
ba(2).CData = [0.9290, 0.6940, 0.1250]; % orange
```





Average Hourly LMP at the Kearney Pricing Node

Bid Curve

An incremental cost curve or offer curve that consists of hourly MW-Price pair segments for the entire period of analysis. The model uses the hourly/daily/seasonal variation in historic LMP, natural gas spot prices, variable O&M costs, and the NJT load to set hourly bids into the wholesale/retail markets. The bid prices are meant to reflect average variable costs only and does not take into consideration owner sunk costs or fixed operating costs. The purpose is to construct a dispatch model that might reflect actual operating conditions to measure emissions. It is not meant to provide a financial model of the central power plant that incorporates economic profit considerations.

```
% bid curve table
bid_curve = table(model_date,me_load,nec_load); % add njt load (M&E, NEC)
nrow_bid_curve = size(bid_curve,1);
                                                 % 8760 rows
DayForm = 'long';
[bid_curve.day_number,bid_curve.day_name] = weekday(bid_curve.model_date,DayForm);
bid_curve.disp_hour = hour(bid_curve.model_date);
bid curve = movevars(bid curve, 'disp hour', 'After', 'model date');
bid_curve = movevars(bid_curve, 'day_number', 'After', 'model_date');
bid_curve = movevars(bid_curve, 'day_name', 'After', 'model_date');
% dispatch hours (weekday hours = 0-23/weekend hours = 24-47).
for i = 1:nrow bid curve
    if bid_curve.day_number(i)==1 || bid_curve.day_number(i)== 7
            bid_curve.disp_hour(i) = bid_curve.disp_hour(i) + 24;
    else
             bid_curve.disp_hour(i);
    end
end
%
  NJT load is always served.
bid_curve.njt_load_mw = me_load + nec_load;
% available baseload capacity after NJT load
bid_curve.ccp_mw = zeros(nrow_bid_curve, 1);
% available peaker capacity after NJT load
```

```
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```

```
bid_curve.peak_mw = zeros(nrow_bid_curve, 1);
% evaluate available baseload and peak capacity for each hour
for i = 1:nrow bid curve
    if bid_curve.njt_load_mw(i)>=ccp_mw
        bid_curve.ccp_mw(i) = 0;
        bid_curve.peak_mw(i) = fullpower_mw - bid_curve.njt_load_mw(i);
    else
         bid_curve.ccp_mw(i) = ccp_mw - bid_curve.njt_load_mw(i);
         bid_curve.peak_mw(i) = fullpower_mw - bid_curve.ccp_mw(i)- bid_curve.njt_load_mw(i);
    end
end
% evaluate bid prices
for i = 1:nrow bid curve
    % cost of baseload (CCP) per MWh
    bid curve.baseload bid(i) = (hr ccp/1000*gas price(i))+vom(i);
    % cost of full-power (CCP + peak) per MWh
    bid curve.fullpower bid(i) = (hr fullpower/1000*gas price(i))+vom(i);
    % total CCP net revenue per hour (dollars)
    bid_curve.baseload_net_rev(i) =...
        (pjm_lmp(i)-bid_curve.baseload_bid(i))*bid_curve.ccp_mw(i);
    % total full-power (CCP + peak) net revenue per hour (dollars)
    bid_curve.fullpower_net_rev(i) =...
        (pjm_lmp(i)-bid_curve.fullpower_bid(i))*(bid_curve.ccp_mw(i)+bid_curve.peak_mw(i));
end
% Figure: TRANSIT Grid Bid Prices vs. LMP
bid = bid curve(:,[1 10 11]);
bid.lmp = pjm_lmp(:,1);
bid = bid(bid.(1)>=datetime(2018,06,01) & bid.(1)< datetime(2018,06,14) ,:);
figure;
plot(bid.(1), bid.(2),'r', bid.(1), bid.(3),'g', bid.(1), bid.(4),'b');
title('TRANSIT Grid Bid Prices vs. LMP');
xlabel('Date','FontSize',10);
ytickformat('usd');
set(gca, 'YGrid', 'on', 'XGrid', 'off');
tstart = datetime(2018,06,1);
tend = datetime(2018,06,14);
xlim([tstart tend]);
```



TRANSITGRID Hourly Dispatch & Generation Schedule

The 8760 hourly results of the bid curve incorporating the hourly/daily /seasonal variation evaluated in the bid curve table are summarized into 24 average hourly blocks for weekdays and weekends. These averages are then used to compute average net revenue for each hour of the day as a basis for optimization of dispatch to export sales. The dispatch blocks are then paired back with the must-serve NJT load to form the 8760-hour generation schedule to use in the emissions analysis.

```
% njt_disp table
njt_disp = table(hours); % summarize 8760 to 48 (24 weekdays/24 weekends)
nrow_njt_disp = size(njt_disp,1); % 48 rows
% create table columns for summarizing totals
njt disp.total hours = zeros(nrow njt disp, 1);
njt_disp.me_mw = zeros(nrow_njt_disp, 1);
njt_disp.nec_mw = zeros(nrow_njt_disp, 1);
njt_disp.baseload_mw = zeros(nrow_njt_disp, 1);
njt disp.fullpower mw = zeros(nrow njt disp, 1);
njt_disp.baseload_net_rev = zeros(nrow_njt_disp,1);
njt_disp.fullpower_net_rev = zeros(nrow_njt_disp,1);
% construct annual totals by hour from bid curve table for
% njt load, available baseload/full power capacity, and net revenue
% for PJM dispatch of excess energy.
for i = 1:nrow_bid_curve
    for j = 1:nrow_njt_disp
        if bid_curve.disp_hour(i)==j-1
           % total number of each hour (1-47) in the year.
           njt disp.total hours(j) =...
               njt_disp.total_hours(j)+1;
           % total annual M&E MW by hour
           njt_disp.me_mw(j) =...
               njt_disp.me_mw(j)+ bid_curve.me_load(i);
           % total annual NEC by hour
           njt disp.nec mw(j) =...
```

file:///C:/Users/matth/Desktop/LILITH/BRS Temp/GbD/NJT/NJTransitGrid/Deliverables/Benefits Evaluation/Matlab/html/NJT_Emissions_072719.html 7/28

```
njt_disp.nec_mw(j)+ bid_curve.nec_load(i);
           % total available baseload power by hour after njt load
           njt_disp.baseload_mw(j) =...
               njt disp.baseload mw(j)+ bid curve.ccp mw(i);
           % total available peaker power by hour after njt load
           njt_disp.fullpower_mw(j) =...
               njt_disp.fullpower_mw(j)+ bid_curve.peak_mw(i);
           % total net revenue by hour for the baseload dispatch
           njt_disp.baseload_net_rev(j) =...
               njt_disp.baseload_net_rev(j)+bid_curve.baseload_net_rev(i);
           % total net revenue by hour for the fullpower dispatch
           njt disp.fullpower_net_rev(j) =...
               njt_disp.fullpower_net_rev(j)+bid_curve.fullpower_net_rev(i);
         end
    end
end
% construct hourly averages for njt load, available baseload/full power
% capacity and net revenue for PJM dispatch of excess energy.
for j = 1:nrow njt disp
    % average available baseload dispatch by hour
    njt_disp.baseload_mw_avg(j) =...
        njt_disp.baseload_mw(j)/njt_disp.total_hours(j);
    % average available full power dispatch by hour
    njt_disp.fullpower_mw_avg(j) =...
        njt_disp.fullpower_mw(j)/njt_disp.total_hours(j);
    % average baseload net revenue by hour
    njt_disp.baseload_net_rev_avg(j) =...
        njt_disp.baseload_net_rev(j)/njt_disp.total_hours(j);
    % average full power net revenue by hour
    njt disp.fullpower net rev avg(j) = ...
        njt_disp.fullpower_net_rev(j)/njt_disp.total_hours(j);
end
```

Figure: TRANSITGRID Baseload Average Hourly Capacity

```
d=njt_disp(1:24,1);
d.weekday=njt_disp{1:24,9}; % average hourly capacity
d.weekend=njt_disp{25:48,9};
d.value(1:24,1:2) = [d.(2) d.(3)];
b=d{:,{'hours'}};
c=d{:,{'value'}};
b = categorical(b,b);
figure;
width = 1;
ba = bar(b,c,'barwidth',width,'facecolor','flat','edgecolor','none');
title('Baseload Average Hourly Capacity');
ax = gca;
ax.FontSize = 8;
ytickformat('%0.2f');
set(gca, 'YGrid', 'on', 'XGrid', 'off');
legend('Weekday','Weekend','location','southoutside',...
    'orientation', 'horizontal');
legend('boxoff');
ba(1).CData = [0, 0.4470, 0.7410];
                                       % dk blue
ba(2).CData = [0.9290, 0.6940, 0.1250]; % orange
ylabel('MW','FontSize',10);
xlabel('Hour','FontSize',10);
```

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Figure: TRANSITGRID Full Power Average Hourly Capacity

```
d=njt_disp(1:24,1);
d.weekday=njt_disp{1:24,10}; % average hourly capacity
d.weekend=njt_disp{25:48,10};
d.value(1:24,1:2) = [d.(2) d.(3)];
b=d{:,{'hours'}};
c=d{:,{'value'}};
b = categorical(b,b);
figure;
width = 1;
ba = bar(b,c,'barwidth',width,'facecolor','flat','edgecolor','none');
title('Full Power Average Hourly Capacity');
ax = gca;
ax.FontSize = 8;
ytickformat('%0.2f');
set(gca, 'YGrid', 'on', 'XGrid', 'off');
legend('Weekday', 'Weekend', 'location', 'southoutside',...
    'orientation', 'horizontal');
legend('boxoff');
ba(1).CData = [0, 0.4470, 0.7410];
                                       % dk blue
ba(2).CData = [0.9290, 0.6940, 0.1250]; % orange
ylabel('MW','FontSize',10);
xlabel('Hour','FontSize',10);
```

Figure: TRANSITGRID Baseload Average Hourly Net Revenue

```
d=njt_disp(1:24,1);
d.weekday=njt disp{1:24,11}; % average hourly net revenue
d.weekend=njt_disp{25:48,11};
d.value(1:24,1:2) = [d.(2) d.(3)];
b=d{:,{'hours'}};
c=d{:,{'value'}};
b = categorical(b,b);
figure;
width = 1;
ba = bar(b,c,'barwidth',width,'facecolor','flat','edgecolor','none');
title('Baseload Average Hourly Net Revenue');
ax = gca;
ax.FontSize = 8;
ytickformat('usd');
set(gca, 'YGrid', 'on', 'XGrid', 'off');
legend('Weekday','Weekend','location','southoutside',...
    'orientation', 'horizontal');
legend('boxoff');
ba(1).CData = [0, 0.4470, 0.7410];
                                       % dk blue
ba(2).CData = [0.9290, 0.6940, 0.1250]; % orange
```

Figure: TRANSITGRID Full-power Average Hourly Net Revenue

```
d=njt_disp(1:24,1);
d.weekday=njt_disp{1:24,12}; % average hourly net revenue
d.weekend=njt_disp{25:48,12};
d.value(1:24,1:2) = [d.(2) d.(3)];
b=d{:,{'hours'}};
c=d{:,{'value'}};
```

```
b = categorical(b,b);
figure;
width = 1;
ba = bar(b,c,'barwidth',width,'facecolor','flat','edgecolor','none');
title('Full-power Average Hourly Net Revenue');
ax = gca;
ax.FontSize = 8;
ytickformat('usd');
set(gca, 'YGrid', 'on', 'XGrid', 'off');
legend('Weekday','Weekend','location','southoutside',...
'orientation','horizontal');
legend('boxoff');
ba(1).CData = [0, 0.4470, 0.7410]; % dk blue
ba(2).CData = [0.9290, 0.6940, 0.1250]; % orange
```

The hourly average net revenue data is used to calculate optimized dispatch schedules in three scenarios:*Dispatch 1 ("maximize revenue"); *Dispatch 2 ("break even"); and *Dispatch 3 ("full power"). The calculation of the dispatch blocks uses the optimized dispatch schedule in *dispatch* which has three settings: *off; *baseload; and *full-power.

```
% dispatch 1 ("maximize revenue")
for j = 1:nrow_njt_disp
    if dispatch.disp1(j) == "off"
        njt_disp.disp1(j)=0; % hourly load
        njt_disp.disp1_rev(j)=0; % total annual net revenue by hour
    elseif dispatch.disp1(j) == "baseload"
        njt_disp.disp1(j)=njt_disp.baseload_mw_avg(j); % hourly load
        njt_disp.disp1_rev(j)=njt_disp.baseload_net_rev(j); % total annual net revenue by hour
    else
        njt disp.disp1(j)=njt disp.baseload mw avg(j)+...
            njt disp.fullpower mw avg(j); % hourly load
        njt_disp.disp1_rev(j)=njt_disp.fullpower_net_rev(j); % total annual net revenue by hour
    end
end
% dispatch 2 ("break even")
for j = 1:nrow_njt_disp
    if dispatch.disp2(j) == "off"
        njt_disp.disp2(j)=0; % hourly load
        njt_disp.disp2_rev(j)=0; % total annual net revenue by hour
    elseif dispatch.disp2(j) == "baseload"
        njt disp.disp2(j)=njt disp.baseload mw avg(j); % hourly load
        njt_disp.disp2_rev(j)=njt_disp.baseload_net_rev(j); % total annual net revenue by hour
    else
        njt_disp.disp2(j)=njt_disp.baseload_mw_avg(j)+...
            njt_disp.fullpower_mw_avg(j); % hourly load
        njt disp.disp2 rev(j)=njt disp.fullpower net rev(j); % total annual net revenue by hour
    end
end
% dispatch 3 ("full power")
for j = 1:nrow_njt_disp
    if dispatch.disp3(j) == "off"
        njt_disp.disp3(j)=0; % hourly load
        njt_disp.disp3_rev(j)=0; % total annual net revenue by hour
    elseif dispatch.disp3(j) == "baseload"
        njt_disp.disp3(j)=njt_disp.baseload_mw_avg(j); % hourly load
        njt_disp.disp3_rev(j)=njt_disp.baseload_net_rev(j); % total annual net revenue by hour
    else
        njt_disp.disp3(j)=njt_disp.baseload_mw_avg(j)+...
```

```
njt_disp.fullpower_mw_avg(j); % hourly load
        njt disp.disp3 rev(j)=njt disp.fullpower net rev(j); % total annual net revenue by hour
    end
end
% hourly dispatch blocks
for j = 1:nrow_njt_disp
    njt_disp.me_mw_avg(j)= njt_disp.me_mw(j)/njt_disp.total_hours(j);
    njt_disp.nec_mw_avg(j)= njt_disp.nec_mw(j)/njt_disp.total_hours(j);
    njt_disp.me_mw_avg(j)=round(njt_disp.me_mw_avg(j));
    njt_disp.nec_mw_avg(j)=round(njt_disp.nec_mw_avg(j));
    njt_disp.disp1(j)=round(njt_disp.disp1(j)/5)*5;
    njt_disp.disp2(j)=round(njt_disp.disp2(j)/5)*5;
    njt_disp.disp3(j)=round(njt_disp.disp3(j)/5)*5;
    njt_disp.njt_block1(j) =...
        njt_disp.disp1(j)+ njt_disp.me_mw_avg(j)+ njt_disp.nec_mw_avg(j);
    njt disp.njt block2(j) =...
        njt_disp.disp2(j)+ njt_disp.me_mw_avg(j)+ njt_disp.nec_mw_avg(j);
    njt disp.njt block3(j) =...
        njt_disp.disp3(j)+ njt_disp.me_mw_avg(j)+ njt_disp.nec_mw_avg(j);
end
njt_disp = movevars(njt_disp,'disp3_rev','After','njt_block3');
njt_disp = movevars(njt_disp,'disp2_rev','After','njt_block3');
njt_disp = movevars(njt_disp,'disp1_rev','After','njt_block3');
```

Figure: TRANSITGRID Weekday Hourly Dispatch Blocks

```
d=njt disp(1:24,[1 17 16 13 14 15]); %nec, me, disp1, disp2, disp3
d.disp2 = d.disp2(:,:) - d.disp1(:,:);
d.disp3 = d.disp3(:,:) - d.disp2(:,:) - d.disp1(:,:);
d.value(1:24,1:5) = [d.(2) d.(3) d.(4) d.(5) d.(6)];
b=d{:,{'hours'}};
c=d{:,{'value'}};
b = categorical(b,b);
figure;
width = 0.6;
ba = bar(b,c,'stacked','barwidth',width,'facecolor','flat',...
    'edgecolor', 'none');
title('Weekday Hourly Dispatch Blocks');
ax = gca;
ax.FontSize = 8;
ylabel('MW','FontSize',10);
ax.YTickLabel=cellstr(num2str(ax.YTick','%.0f'));
set(gca, 'YGrid', 'on', 'XGrid', 'off');
legend('NEC','M&E','Disp.1','Disp.2','Disp.3','location','southoutside',...
    'orientation', 'horizontal');
legend('boxoff');
ba(1).CData = [1 1 1]*0.8;
                                        % grey
ba(2).CData = [1 \ 1 \ 0.4];
                                        % yellow
ba(3).CData = [0.9290, 0.6940, 0.1250]; % orange
ba(4).CData = [0, 0.4470, 0.7410];
                                       % dk blue
ba(5).CData = [0.3010, 0.7450, 0.9330]; % lt blue
```

```
Figure: TRANSITGRID Weekend Hourly Dispatch Blocks
```

```
d=njt_disp(25:48,[1 17 16 13 14 15]);
d.disp2 = d.disp2(:,:) - d.disp1(:,:);
d.disp3 = d.disp3(:,:) - d.disp2(:,:) - d.disp1(:,:);
d.value(1:24,1:5) = [d.(2) d.(3) d.(4) d.(5) d.(6)];
b=d{:,{'hours'}};
c=d{:,{'value'}};
b = categorical(b,b);
figure;
width = 0.6;
ba = bar(b,c,'stacked','barwidth',width,'facecolor','flat',...
    'edgecolor', 'none');
title('Weekend Hourly Dispatch Blocks');
ax = gca;
ax.FontSize = 8;
ylabel('MW','FontSize',10);
ax.YTickLabel=cellstr(num2str(ax.YTick','%.0f'));
set(gca, 'YGrid', 'on', 'XGrid', 'off');
legend('NEC','M&E','Disp.1','Disp.2','Disp.3','location','southoutside',...
    'orientation', 'horizontal');
legend('boxoff');
ba(1).CData = [1 \ 1 \ 1]^*0.8;
                                        % grey
ba(2).CData = [1 \ 1 \ 0.4];
                                        % yellow
ba(3).CData = [0.9290, 0.6940, 0.1250]; % orange
ba(4).CData = [0, 0.4470, 0.7410];
                                     % dk blue
ba(5).CData = [0.3010, 0.7450, 0.9330]; % lt blue
```

TRANSITGRID Generation Schedule

The generation schedule is the total generation of the TRANSITGRID engines including energy for the NJT must-serve load and for sale on wholesale/retail markets as per the forecasted dispatch schedules (i.e. *generation = njt load + dispatch*).

```
% add njt load to the three dispatch scenarios to get total annual generation
generation = bid_curve(:,1:4);
nrow_generation=size(generation,1);
for i = 1:nrow_generation
    for j = 1:nrow_njt_disp
        if generation.disp_hour(i)==j-1
            generation.gen1(i) = me_load(i)+nec_load(i)+ njt_disp.disp1(j);
            generation.gen2(i) = me_load(i)+nec_load(i)+ njt_disp.disp2(j);
            generation.gen3(i) = me_load(i)+nec_load(i)+ njt_disp.disp3(j);
            end
        end
        end
    end
```













TRANSITGRID Emissions

Calculation of TRANSITGRID greenhouse gas (GhG) emissions under each of the 8760 dispatch/generation schemes.

```
% generation 1: njt baseload plus dispatch 1 (maximize profit)
for i = 1:nrow generation
    if generation.gen1(i)<=ccp mw</pre>
        generation.ghg gen1(i) = generation.gen1(i)*m factor ccp;
    else
        generation.ghg_gen1(i) = ccp_mw*m_factor_ccp +...
            (generation.gen1(i)-ccp_mw)*m_factor_gt;
    end
end
% generation 2: njt baseload plus dispatch 2 (break-even)
for i = 1:nrow_generation
    if generation.gen2(i)<=ccp_mw</pre>
        generation.ghg_gen2(i) = generation.gen2(i)*m_factor_ccp;
    else
        generation.ghg_gen2(i) = ccp_mw*m_factor_ccp +...
            (generation.gen2(i)-ccp_mw)*m_factor_gt;
    end
end
% generation 3: njt baseload plus dispatch 3 (full power)
for i = 1:nrow_generation
    if generation.gen3(i)<=ccp_mw</pre>
        generation.ghg_gen3(i) = generation.gen3(i)*m_factor_ccp;
    else
        generation.ghg_gen3(i) = ccp_mw*m_factor_ccp +...
            (generation.gen3(i)-ccp_mw)*m_factor_gt;
    end
end
% total transitgrid ghg emissions (tons)
m njt = [ sum(generation{:,8}) sum(generation{:,9}) sum(generation{:,10})]';
% total generation (mw)
mw njt = [sum(generation{:,5}) sum(generation{:,6}) sum(generation{:,7})]';
% transitgrid emission factors
m_factor_njt = (m_njt./mw_njt)';
```

Regional Fossil Generation Fleet Emissions Displacement

Calculation of reduced emissions in the regional fossil generation fleet due to the use of TRANSITGRID both for internal energy and for export to the wholesale market. The three TRANSITGRID 8760 hourly generation schemes are input into the *AVERT* model. The results of each simulation is % then imported into the model in the "avert" variable.

```
% gross regional fossil emission displacement by transitgrid
m_avert = [ sum(avert{:,2}) sum(avert{:,3}) sum(avert{:,4})]';
% net regional fossil emission displacement by transitgrid
m_avert_net = (m_avert-m_njt);
```

Natural Gas Peaker Plant Emissions Displacement

Evaluation of emission displacements assuming a natural gas peaker plant is the marginal resource. As the peaker plant operates at low capacity factors the evaluation is made over averaged annual hourly dispatch as provided in U.S. EPA and U.S. EIA plant operations data for the analysis period. An average emissions factor is calculated for the peaker plant based on the government hourly emissions and operating data. The displacement is then calculated by applying the difference between the emission factors for the natural gas plant and TRANSITGRID to the peaker plants output. Only weekday dispatch is considered.

```
% natgas_unitXhour: table of hourly unit emissions for bergen & kearny
[natgas unitXhour.day number,natgas unitXhour.day name] =...
    weekday(natgas unitXhour.model date,DayForm);
natgas unitXhour.disp hour = hour(natgas unitXhour.model date);
natgas_unitXhour = movevars(natgas_unitXhour,'disp_hour','After','model_date');
natgas_unitXhour = movevars(natgas_unitXhour,'day_number','After','model_date');
natgas_unitXhour = movevars(natgas_unitXhour,'day_name','After','model_date');
nrow_natgas = size(natgas_unitXhour,1);
% set dispatch hours (weekday 0-23/weekend 24-47)
for i = 1:nrow_natgas
    if natgas_unitXhour.day_number(i)==1 || natgas_unitXhour.day_number(i)== 7
            natgas_unitXhour.disp_hour(i) = natgas_unitXhour.disp_hour(i) + 24;
    else
             natgas_unitXhour.disp_hour(i);
    end
end
% natgas_unit_disp: analyze hourly dispatch
natgas_unit_disp=varfun(@sum,natgas_unitXhour,'InputVariables',{'op_time' 'mw' 'ghg'},...
       'GroupingVariables',{'facility' 'unit'});
natgas unit disp.Properties.VariableNames{'GroupCount'} = 'hour count';
natgas_unit_disp = join(natgas_unit_disp,natgas_unit);
% emissions factor (tons ghg/mw)
natgas_unit_disp.m_factor=natgas_unit_disp.sum_ghg./natgas_unit_disp.sum_mw;
% capacity factor
natgas_unit_disp.cap_factor=natgas_unit_disp.sum_mw./...
    (natgas_unit_disp.hour_count.*natgas_unit_disp.name_capacity);
% natgas_plant: summary of plant characteristics
natgas_plant=varfun(@mean,natgas_unit_disp,'InputVariables',...
    {'m_factor' 'cap_factor'},'GroupingVariables',{'facility'});
natgas plant.Properties.VariableNames{'GroupCount'} = 'unit count';
% number of units (engines) per plant
bergen unit=natgas plant{1,2};
kearny_unit=natgas_plant{2,2};
% natgas_plant_disp: plant dispatch for each hour of the day
natgas plant disp=varfun(@sum,natgas_unitXhour, 'InputVariables', {'mw' 'ghg'},...
       'GroupingVariables',{'facility' 'disp_hour'});
natgas_plant_disp.Properties.VariableNames{'GroupCount'} = 'unit_hours';
% mw_avg: average hourly dispacth for each hour of the day
nrow_natgas_disp = size(natgas_plant_disp,1);
   for i= 1:nrow natgas disp
       if natgas_plant_disp.facility(i) == 'bergen'
           natgas_plant_disp.mw_avg(i)=...
                (natgas_plant_disp.sum_mw(i)/natgas_plant_disp.unit_hours(i))*bergen_unit;
       elseif natgas_plant_disp.facility(i) == 'kearny'
           natgas_plant_disp.mw_avg(i)=...
                (natgas plant disp.sum mw(i)/natgas plant disp.unit hours(i))*kearny unit;
       end
   end
```

Figure: Natural Gas Plant Weekday Hourly Dispatch with TRANSITGRID Generation Displacement

```
d = natgas_plant_disp(natgas_plant_disp.facility == 'bergen', [2 6]);
d.disp3=njt_disp.(15);
d.ng_disp=d.(2)-d.(3);
```

```
d=d(1:24,:);
d.value(1:24,1:2) = [d.(4) d.(3)];
b=d{:,{'disp_hour'}};
c=d{:,{'value'}};
b = categorical(b,b);
figure;
width = 0.6;
ba = bar(b,c,'stacked','barwidth',width,'facecolor','flat',...
    'edgecolor','none');
title('Natural Gas Plant Weekday Hourly Dispatch');
ax = gca;
ax.FontSize = 8;
ylabel('MW','FontSize',10);
ax.YTickLabel=cellstr(num2str(ax.YTick','%.0f'));
set(gca, 'YGrid', 'on', 'XGrid', 'off');
legend('Natural Gas Plant','TRANSITGRID','location','southoutside',...
    'orientation', 'horizontal');
legend('boxoff');
ba(1).CData = [0, 0.4470, 0.7410];
                                        % dk blue
ba(2).CData = [0.9290, 0.6940, 0.1250]; % orange
% m_factor: emissions factor (tons ghg/mw)
natgas_plant_disp.m_factor=...
       natgas_plant_disp.sum_ghg./natgas_plant_disp.sum_mw;
% m_factor_delta: difference between the emissions factors at natural gas
% plant and transitgrid
natgas_plant_disp.m_factor_delta=...
      natgas plant disp.m factor-m factor full;
% natural gas plant net emissions
f = natgas_plant_disp(natgas_plant_disp.facility == 'bergen', :);
% insert transitgrid dispatch schedules for evaluation
f.disp1=njt_disp.disp1;f.disp2=njt_disp.disp2;f.disp3=njt_disp.disp3;
% evaluate weekdays only
f=f(1:24,:);
% net bergen emission displacement by transitgrid
m_bergen_net = [365*(sum((f{:,8}).*(f{:,9}))) 365*(sum((f{:,8}).*(f{:,10})))...
```

365*(sum((f{:,8}).*(f{:,11})))]';



Steam Coal Baseload Plant Emissions Displacement

Evaluation of displacements assuming a baseload steam coal plant is the marginal resource. As the baseload steam coal plants operate at high capacity factors the evaluation is made on an 8760 hourly dispatch as provided in U.S. EPA and U.S. EIA plant operations data fo the analysis period. An hourly emissions factor is calculated for the coal plant for each hour of the day during the period of analysis based on the government hourly emissions and operating data. The displacement is then calculated by applying the difference between the emission factors for the coal plant and TRANSITGRID to the coal plant output. The analysis evaluates every operating hour of the coal plant on an hur-by-hour basis thrughout the period of analysis so that the hourly/daily/seasonal variation is represented.

```
% coal_unitXhour: table of hourly unit emissions for keystone & conemaugh
[coal unitXhour.day number,coal unitXhour.day name] =...
    weekday(coal_unitXhour.model_date,DayForm);
coal_unitXhour.disp_hour = hour(coal_unitXhour.model_date);
coal_unitXhour = movevars(coal_unitXhour,'disp_hour','After','model_date');
coal unitXhour = movevars(coal unitXhour,'day number','After','model date');
coal_unitXhour = movevars(coal_unitXhour,'day_name','After','model_date');
nrow_coal = size(coal_unitXhour,1);
% set dispatch hours (weekday 0-23/weekend 24-47)
for i = 1:nrow coal
                        %add dispatch hours
    if coal_unitXhour.day_number(i)==1 || coal_unitXhour.day_number(i)== 7
            coal_unitXhour.disp_hour(i) = coal_unitXhour.disp_hour(i) + 24;
    else
             coal_unitXhour.disp_hour(i);
    end
end
% coal_unit_disp: analyze houry duspatch of the coal steam engines
coal_unit_disp=varfun(@sum,coal_unitXhour,'InputVariables',{'op_time' 'mw' 'ghg'},...
       'GroupingVariables',{'facility' 'unit'});
coal unit disp.Properties.VariableNames{'GroupCount'} = 'hour count';
```

```
coal_unit_disp = join(coal_unit_disp,coal_unit);
% emissions factor (tons ghg/mw)
coal_unit_disp.m_factor=coal_unit_disp.sum_ghg./coal_unit_disp.sum_mw;
% capacity factor
coal_unit_disp.cap_factor=coal_unit_disp.sum_mw./...
    (coal_unit_disp.hour_count.*coal_unit_disp.name_capacity);
% coal plant: summary of plant characteristics
coal_plant=varfun(@mean,coal_unit_disp,'InputVariables',...
    {'m_factor' 'cap_factor'},'GroupingVariables',{'facility'});
coal plant.Properties.VariableNames{'GroupCount'} = 'unit_count';
% number of units (engines) per plant
conemaugh unit=coal plant{1,2};
keystone_unit=coal_plant{2,2};
% coal_plant_disp: plant dispatch for each hour of the year
coal_plant_disp=varfun(@sum,coal_unitXhour,'InputVariables',{'mw' 'ghg'},...
       'GroupingVariables',{'facility' 'model_date'});
coal plant disp.Properties.VariableNames{'GroupCount'} = 'unit hours';
coal_plant_disp = join(coal_plant_disp,generation(:,[1 5 6 7]));
nrow_coal_disp=size(coal_plant_disp,1);
\% _gross-up factor_: the AVERT model provides a grossup factor to account for the
% average system losses and station power from the fleet gerating plants
grossup_factor = 0.0641;
% generation 1 - coal plant emission displacements
  for i=1:nrow coal disp
     if coal plant disp.sum mw(i) ~=0
        coal plant disp.offset1(i)=...
            ((coal_plant_disp.gen1(i)*(1+grossup_factor))./...
            coal_plant_disp.sum_mw(i))*...
            coal_plant_disp.sum_ghg(i);
        coal plant_disp.njt_ghg1(i)=...
            m_factor_njt(1)*coal_plant_disp.gen1(i);
     else
         coal_plant_disp.offset1(i)=0;
         coal_plant_disp.njt_ghg1(i)=0;
     end
  end
% generation 2 - coal plant emission displacements
for i=1:nrow_coal_disp
     if coal plant disp.sum mw(i) ~=0
        coal_plant_disp.offset2(i)=...
            ((coal_plant_disp.gen2(i)*(1+grossup_factor))./...
            coal plant disp.sum mw(i))*...
            coal plant disp.sum ghg(i);
     coal_plant_disp.njt_ghg2(i)=...
            m_factor_njt(2)*coal_plant_disp.gen2(i);
     else
         coal_plant_disp.offset2(i)=0;
         coal_plant_disp.njt_ghg2(i)=0;
     end
end
% generation 3 - coal plant emission displacements
for i=1:nrow_coal_disp
     if coal_plant_disp.sum_mw(i) ~=0
        coal plant disp.offset3(i)=...
            ((coal_plant_disp.gen3(i)*(1+grossup_factor))./...
            coal_plant_disp.sum_mw(i))*...
```

```
coal_plant_disp.sum_ghg(i);
coal_plant_disp.njt_ghg3(i)=...
m_factor_njt(3)*coal_plant_disp.gen3(i);
else
coal_plant_disp.offset3(i)=0;
coal_plant_disp.njt_ghg3(i)=0;
end
end
g = coal_plant_disp(coal_plant_disp.facility == 'keystone', :);
% gross keystone emission displacements by transitgrid
m_keystone=[sum(g.offset1) sum(g.offset2) sum(g.offset3)]';
% transitgrid emissions following keystone dispatch
m_njt_c=[sum(g.njt_ghg1) sum(g.njt_ghg2) sum(g.njt_ghg3)]';
% net keystone emission displacement by transitgrid
m_keystone_net=(m_keystone-m_njt_c);
```

Enhanced Emission Benefits - Solar power and energy storage system

Evaluation of additional emission displacemnts that result from use of solar power with 10 MW flywheel energy storage system. The current plan for TRANSITGRID includes the use of an on-site 0.6 MW solar array and up to 10 MW of energy storage using a flywheel system. By using the solar array to charge up the energy storage system during off-peak hours and then dispatching the stored energy into the system during the peak demand hours when the LMP is typically at its highest (thereby dispatching less efficient power plants to match load) TRANSITGRID may enhance its ability to displace additional CO2 emissions from other power plants.

The model assumes a four-hour discharge between 14:00 - 17:00 at a constat rate. The solar system charges the flywheels to maximum of 10 MW, all additional solar energy including energy produced during flywheel discharge is dispatched to system. The dispatched energy is added to the dispatch 2 ("break-even") generation scheme and modelled in *AVERT* to evaluate the increased emission offsets.

```
% load data
load('solar'); % solar generation data for Newark from NREL System Advisor Model
s=solar{:,2}./1000;solar{:,2}=s;s=solar{:,3}./1000;solar{:,3}=s;
s=solar{:,4}./1000;solar{:,4}=s;
% three system sizes are tested: 600kW, 2500kW and 3500 kW
s0600=solar(:,[1 2]); s2500=solar(:,[1 3]); s3500=solar(:,[1 4]);
nrow_solar = size(solar,1);
% set discharge cycle
discharge_hour = (14:17)';
% round-trip efficiency
rnd trp = 0.87;
% discharge rate (25% of the state of charge (SOC) each hour for 4 hours
discharge_rate = 0.25;
% maximum charge is 10 MW. Flywheels can sustain 100% depth of discharge
max_charge = 10;
s0600.charge=zeros(nrow solar, 1);s0600.discharge=zeros(nrow solar, 1);
s0600.solar_disp=zeros(nrow_solar, 1);s0600.total_disp=zeros(nrow_solar, 1);
s2500.charge=zeros(nrow_solar, 1);s2500.discharge=zeros(nrow_solar, 1);
s2500.solar_disp=zeros(nrow_solar, 1);s2500.total_disp=zeros(nrow_solar, 1);
s3500.charge=zeros(nrow solar, 1);s3500.discharge=zeros(nrow solar, 1);
s3500.solar_disp=zeros(nrow_solar, 1);s3500.total_disp=zeros(nrow_solar, 1);
```

```
% 600kW solar system and 10 MW flywheel
for i=2:nrow solar
        s0600.charge(i)=min(max charge,s0600.charge(i-1)+(rnd trp*s0600.solar 0600(i)));
        s0600.solar_disp(i)=(-1)*max((s0600.charge(i-1)+rnd_trp*s0600.solar_0600(i))-10,0);
        if hour(s0600.model_date(i))==13
            soc=s0600.charge(i);
        end
        if ismember(hour(s0600.model_date(i)),discharge_hour)
             s0600.charge(i)=soc*...
                (max(discharge_hour)- hour(s0600.model_date(i)))*discharge_rate;
            s0600.discharge(i)=(-1)*discharge_rate*soc;
            s0600.solar_disp(i)=(-1)*s0600.solar_0600(i);
        end
end
s0600.total disp=s0600.discharge+s0600.solar disp;
s0600.gen2 = generation.gen2;
                                % add dispatch2 for evaluation
s0600.gen2 = s0600.gen2-s0600.total_disp;
% 2500kW solar system and 10 MW flywheel
for i=2:nrow_solar
        s2500.charge(i)=min(max_charge,s2500.charge(i-1)+(rnd_trp*s2500.solar_2500(i)));
        s2500.solar_disp(i)=(-1)*max((s2500.charge(i-1)+rnd_trp*s2500.solar_2500(i))-10,0);
        if hour(s2500.model date(i))==13
            soc=s2500.charge(i);
        end
        if ismember(hour(s2500.model_date(i)),discharge_hour)
             s2500.charge(i)=soc*...
                (max(discharge_hour) - hour(s2500.model_date(i)))*discharge_rate;
            s2500.discharge(i)=(-1)*discharge_rate*soc;
            s2500.solar_disp(i)=(-1)*s2500.solar_2500(i);
        end
end
s2500.total_disp=s2500.discharge+s2500.solar_disp;
s2500.gen2 = generation.gen2; % add dispatch2 for evaluation
s2500.gen2 = s2500.gen2-s2500.total_disp;
% 3500kW solar system and 10 MW flywheel
for i=2:nrow solar
        s3500.charge(i)=min(max charge,s3500.charge(i-1)+(rnd trp*s3500.solar 3500(i)));
        s3500.solar_disp(i)=(-1)*max((s3500.charge(i-1)+rnd_trp*s3500.solar_3500(i))-10,0);
        if hour(s3500.model date(i))==13
            soc=s3500.charge(i);
        end
        if ismember(hour(s3500.model_date(i)),discharge_hour)
          s3500.charge(i)=soc*...
                (max(discharge_hour)- hour(s3500.model_date(i)))*discharge_rate;
            s3500.discharge(i)=(-1)*discharge_rate*soc;
            s3500.solar_disp(i)=(-1)*s3500.solar_3500(i);
        end
end
s3500.total_disp=s3500.discharge+s3500.solar_disp;
s3500.gen2 = generation.gen2; % add dispatch2 for evaluation
s3500.gen2 = s3500.gen2-s3500.total_disp;
```

```
% gross avert emission displacements by transitgrid with solar/ess
% evaluated against the generation 2 scheme (break-even)
% three values for 600kW, 2500 kW, and 3500 kW solar plants
m_avert_s=[sum(avert{:,5}) sum(avert{:,6}) sum(avert{:,7})]';
% net avert emission displacements by transitgrid with solar/ess
m_avert_net_s=(m_avert_s-m_avert(2));
```

Cogeneration & Thermal Dispatch Enhanced Emission Benefits

Evaluation of additional emission displacements that result from the use of waste heat energy of the three peaker combustion turbine engines to provide thermal energy to a nearby off-taker. (i.e. chillers for a commercial refrigerated warehouse, heat for space heating or domestic hot water).

```
% CHP nameplate electric power of the peaker engines
CHPmw=3*gt mw;
% electric efficiency = equivalent Btu content of a kWh of electricity
% (3412 Btu) divided by the heat rate
CHPe eff = 3412/hr gt;
CPPe_eff = 3412/hr_ccp;
% the total system efficiency of CHP system is sum of the net useful electric
% energy and net useful thermal energy per total fuel energy input. using
% cogeneration raises total system efficiency. A value of 75.125%
% efficiency is selected
CHPsys_eff = 0.75125;
% estimate useful thermal energy recovered from the three peaker engines
CHPq=CHPsys_eff*(CHPmw/CHPe_eff)-CHPmw;
% effective electric generation using the FERC efficiency standard (50%)
ferc = 0.5;
CHPq_ferc = ferc*CHPq;
% covert to megawatt thermal to Btu
CHPq btu=CHPq ferc *3412*1000;
%total plant efficiency (cpp and chp plants)
plant_eff = (ccp_mw*CPPe_eff+CHPmw*CHPsys_eff)/fullpower_mw;
% evaluate avert emission displacement assuming additional generation
% displacement is equal to the effective electric geration (i.e. the conventional
% fossil fleet generation that would be used to produce the useful thermal
% energy output if the CHP system did not exist).
% use generation 2 dispatch scheme (break-even). Add effective electric energy
% generation for those hours when peaker plant is fully dispatched (i.e.
% greter than 105 MW)
cogen_disp = generation{:,6};
nrow_cogen = size(cogen_disp,1);
for i=1:nrow_cogen
    if cogen_disp(i)>105
        cogen_disp(i)=cogen_disp(i)+CHPq_ferc;
    end
end
% gross avert emission displacements by transitgrid with cogeneration
```

```
% evaluated against the generation 2 scheme (break-even)
m_avert_c=(sum(avert{:,8}))';
% net avert emission displacements by transitgrid with cogeneration
m_avert_net_c=(m_avert_c-m_avert(2));
```

Alternative Fuels Enhanced Emission Benefits

Renewable Natural Gas (RNG)

```
% evaluation of the use of RNG in the TRANSITGRID system to replace up to
% 20-percent of the current fossil natural gas supply.
rng = 0.20;
% additional emissions reductions is equal to removing 20% of the current
% estimate of ghg emissions. in this case, the generation 2 ("break-even")
% scenario is assumed.
m_rng = rng*m_njt(2);
```

High-Volume Hydrogen Gas Turbines

```
% evaluation of 10% and 50% reduction in ghg emissions
h1 = 0.10;
h2 = 0.50;
m_h1 = h1*m_njt(2);
m_h2 = h2*m_njt(2);
```

Summary Results

Emission Factor (tons/MWh) by Generation Source

```
m_fctr_str=categorical({'Nat Gas CC (NJT)',
                                             'Hybrid (NJT)',...
'Nat Gas GT (NJT)', 'Nat Gas GT (Avg.)', 'Nat Gas CC (Bergen)',...
'Steam Petrol.',
                       'Fossil Gen. Fleet (Avg.)',
                                                   'Steam Coal (Key.)',...
'Steam Coal (Cone.)', 'Steam Coal (Avg.)'})';
sum_ef = table(m_fctr_str,...
   'VariableNames',{'desc'});
sum_ef.value(1) = m_factor_ccp;
sum_ef.value(2) = m_factor_njt(3);
sum_ef.value(3) = m_factor_gt;
sum_ef.value(4) = 0.654;
                          % source: U.S. Energy Information Agency (EIA)
sum_ef.value(5) = natgas_plant{1, 'mean_m_factor'};
sum_ef.value(6) = 0.822; % source: U.S. Energy Information Agency (EIA)
sum_ef.value(7) = 0.824;
                             % source: U.S. EPA AVERT model
sum ef.value(8) = coal_plant{2, 'mean m factor'};
sum_ef.value(9) = coal_plant{1, 'mean_m_factor'};
sum_ef.value(10) = 1.076;
                              % source: U.S. Energy Information Agency (EIA)
sum_ef = sortrows(sum_ef,2);
```

Figure: Emission Factor (tons/MWh) by Generation Source

```
b=sum_ef{:,{'desc'}};
c=sum_ef{:,{'value'}};
b = categorical(b,b);
figure;
```

file:///C:/Users/matth/Desktop/LILITH/BRS Temp/GbD/NJT/NJTransitGrid/Deliverables/Benefits Evaluation/Matlab/html/NJT_Emissions_072719.... 24/28

```
width = 0.4;
barh(b, c, width);
title('Emission Factor');
ax = gca;
ax.FontSize = 8;
xlabel('Emission Factor (tons/MWh)','FontSize',10);
%ax.YTickLabel=cellstr(num2str(ax.YTick','%.0f'));
set(gca, 'YGrid', 'on', 'XGrid', 'off');
```

Annual CO2 Displacement (Tons) by Generation Source

```
m_disp_str = categorical({'Disp.1','Disp.2','Disp.3'})';
sum_m = table(m_disp_str,...
        'VariableNames',{'desc'});
sum_m.value(1:3,1) = m_bergen_net';
sum_m.value(1:3,2) = m_avert_net';
sum_m.value(1:3,3) = m_keystone_net';
```

Figure: Annual CO2 Displacement (Tons) by Generation Source

```
b=sum_m{:,{'desc'}};
c=sum_m{:,{'value'}};
b = categorical(b,b);
figure;
width = 0.8;
ba = bar(b, c, width, 'FaceColor', 'flat');
title('Annual CO2 Displacement');
ax = gca;
ax.FontSize = 8;
ylabel('Annual CO2 Displacement (tons)', 'FontSize', 10);
ax.YTickLabel=cellstr(num2str(ax.YTick','%.0f'));
set(gca, 'YGrid', 'on', 'XGrid', 'off');
% text(1:length(c(:,1)),c(:,1),num2str(c(:,1)'),'vert','bottom','horiz','center',...
      'FontSize',8,'Rotation',90);
%
ba(1).CData = [1 1 1]*0.8;
ba(2).CData = [1 1 0.4];
ba(3).CData = [0.9290, 0.6940, 0.1250];
legend('Nat Gas','Fleet','Coal','location','southoutside','orientation',...
    'horizontal');
legend ('boxoff');
```

Enhanced Benefits

```
enhanced_str=categorical({'0.6 MW Sol.','2.5 MW Sol.','3.5 MW Sol.',...
'H2 (10%)', 'RNG (20%)', 'Cogen', 'H2 (50%)'})';
sum_enh = table(enhanced_str,...
'VariableNames',{'desc'});
sum_enh.value(1) = m_avert_net_s(1);
sum_enh.value(2) = m_avert_net_s(2);
sum_enh.value(3) = m_avert_net_s(3);
sum_enh.value(4) = m_h1;
sum_enh.value(5) = m_rng;
sum_enh.value(6) = m_avert_net_c;
sum_enh.value(7) = m_h2;
sum_enh = sortrows(sum_enh,2);
```

Figure: Enhanced Benefits

```
b=sum_enh{:,{'desc'}};
c=sum_enh{:,{'value'}};
b = categorical(b,b);
figure;
plot(b, c,'-o','MarkerFaceColor','blue',...
    'MarkerSize',4);
title('Enhanced Benefits');
ax = gca;
ax.FontSize = 8;
%xlabel('MW','FontSize',10);
ylabel('Displaced Emissions (tons)','FontSize',10);
ax.YTickLabel=cellstr(num2str(ax.YTick','%.0f'));
set(gca, 'YGrid', 'on', 'XGrid', 'off');
```





Emission Factor


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NJ TRANSITGRID Benefits Evaluation

Appendix B: Reliability & Flexibility Benefits Model



Contents

- Warnings
- Load Data and Set Model Parameters
- SAIDI Distrubition
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- Table 01: Capacity Outage Table
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- Figure 03: LOLE
- Figure 04: LMP Time Series
- Figure 05: LMP Histogram
- Price Signal Model
- Figure 06: Price Signal

Warnings

```
warning('off','all')
warning
```

All warnings have the state 'off'.

Load Data and Set Model Parameters

```
close all; clc; clear;
cd 'C:\Users\matth\Desktop\LILITH\BRS Temp\GbD\NJT\NJTransitGrid\Deliverables\Benefits Evaluation\Part 3\Matlab'
load('lmp2018'); % kearny lmp 2018
load('lmp2017'); % kearny lmp 2017
```

SAIDI Distrubition

```
log_sampsize = 10000;
% set baseline SAIDI in hours per year
    saidi = .744;
% set mean equal to baseline SAIDI. take complement for data < 1
    ln_mu = -log10(saidi);
    std = .30;
    ln_sigma = -log10(std); % take complement for data < 1
    r = lognrnd(ln_mu,ln_sigma,log_sampsize,1);
```

Figure 01: SAIDI Lognormal Random Sample

```
% plot figure
figure;
h = histogram(r,'Normalization','pdf');
h.NumBins = 40;
% lognormal pdf
hold on;
% make distribution
pd = makedist('Lognormal','mu',ln_mu,'sigma',ln_sigma);
z = max(h.Data);
x = 0:.01:z;
y = pdf(pd,x);
% plot left axis
```

```
yyaxis left;
   plot(x,y,'-r');
   ylabel ('Probability Density');
% lognormal cdf
   hold on;
% make distribution
   p = logncdf(x,ln mu,ln sigma);
% plot right axis
   yyaxis right;
   plot(x,p,'-b');
   ylabel ('CDF');
   ax = gca;
   ax.YColor = 'b';
% plot text
   p90 = prctile(h.Data,90);
   y1 = max(r);
   y2 = min(r);
   txt = strcat(num2str(log_sampsize,'%04d'),' Samples');
   txt = txt + "\n" + "SAIDI = " + num2str(saidi,'%.3f');
   txt = txt + "\n" + "Max = " + num2str(y1, '%.3f');
   txt = txt + "\n" + "Minimum = " + num2str(y2,'%.3f');
   txt = txt + "\n" + "90th Percentile = " + num2str(p90, '%.3f');
   txt = compose(txt);
   txt = splitlines(txt);
   ylimtxt = get(gca,'ylim'); ylimtxt = ylimtxt*.95;
   xlimtxt = get(gca,'xlim');
   text((xlimtxt(1)+xlimtxt(2)/2),(ylimtxt(1)+ylimtxt(2)/2),txt,'FontSize', 8);
% legend
   lgd = legend('data', 'Normal PDF', 'Normal CDF', 'Location', 'northeast');
   lgd.FontSize = 8;
   set(get(h(1), 'Annotation'), 'LegendInformation'), 'IconDisplayStyle', 'off');
% labels
   xlabel('SAIDI (hours/yr)');
   ax = gca;
   ax.FontSize = 8;
% grid
   grid on;
% export and close figure
   saveas(gcf,'(01) SAIDI.png');
   %close;
```



Table 01: Capacity Outage Table

```
% availability/unavaiability of units
   av = 0.987;
   u = 1-av;
% unit capacity
   cap = [30;30;22.5;22.5;22.5];
% count of units
   n = size(cap,1);
% state matrix
   a = zeros(2^n, n);
      for k = 0:2^n-1
        a(k+1,:) = (dec2bin(k,n)-'0');
      end
% capaciy outage matrix
   capt = a*cap;
   b=a;
   b(b == 1) = av;
   b(b == 0) = u;
   capt(:,2)=prod(b,2);
   capt = sort(capt,1);
   [G,ID] = findgroups(capt(:,1));
   COT = [ID splitapply(@sum,capt(:,2),G)]
```

COT =

0	0.0000
22.5000	0.0000
30.0000	0.0000
45.0000	0.0000
52.5000	0.0000
60.0000	0.0000
67.5000	0.0002
75.0000	0.0010
82.5000	0.0005
97.5000	0.0247
105.0000	0.0370
127.5000	0.9367

SAIDI Distribution

```
% load at transitgrid internal connections
% [Amtrak, M&E, HBLR]
   load_mw = [60 30 20]';
% random sample and scenario count
   samp_size = 10000;
   scen = 10000;
   nrow r = size(r,1);
   samp i = zeros(samp size,3);
\% table of scenarios (LOLE at the 3 connections and total)
   samp_j = zeros(scen,4);
   for j = 1:scen
       for i = 1:samp_size
       % select from the uniform distribution
           k = randperm(nrow_r,3)';
       % select from the lognormal distribution
           s = r(k,:);
        % fill sample table
           samp i(i,:) = s;
        end
        % fill scenario table and calculate statistics
            samp_load = samp_i*load_mw;
            samp_j(j,1:3) = mean(samp_i,1);
            samp_j(j,4) = sum(samp_j(j,1:3));
            samp_j(j,5) = mean(samp_load,1);
    end
```

Figure 02: LOEE

```
% plot figure
   figure;
   s_load = samp_j(:,5);
   hs = histogram(s_load(:,1), 'Normalization', 'pdf');
   hs.NumBins = 40;
% normal pdf
   hold on
   pds = fitdist(s load, 'Normal');
   z1 = min(hs.Data);
   z2 = max(hs.Data);
   x = z1:.1:z2;
   y = pdf(pds, x);
% plot left axis
   yyaxis left;
   plot(x,y,'-r');
   ylabel ('Probability Density');
   ax = gca;
   ax.FontSize = 8;
% normal cdf
   hold on;
   p = cdf(pds, x);
% plot right axis
   yyaxis right
   plot(x,p,'-b');
   ylabel ('CDF');
   ax = gca;
   ax.YColor = 'b';
   ax.FontSize = 8;
   p90 = prctile(hs.Data,90);
   p50 = prctile(hs.Data,50);
% plot text
   txt = strcat(num2str(log_sampsize,'%04d'),' Samples');
   txt = txt + "\n" + "LOEE = " + num2str(p50,'%.3f');
   txt = txt + "\n" + "90th Percentile = " + num2str(p90,'%.3f');
   txt = compose(txt);
   txt = splitlines(txt);
```

```
ylimtxt = get(gca,'ylim'); ylimtxt = ylimtxt*.95;
xlimtxt = get(gca,'xlim');
text(xlimtxt(1)+.15,ylimtxt(2)/2,txt,'FontSize',8);
% legend
lgd = legend('data','Normal PDF','Normal CDF','Location','northwest');
lgd.FontSize = 8;
set(get(get(hs(1),'Annotation'),'LegendInformation'),'IconDisplayStyle','off');
% labels
xlabel('Loss of Energy Expectation (MWh/yr)');
% grid
grid on;
% export figure and close
saveas(gcf,'(02) LOEE.png');
%close;
```



Figure 03: LOLE

```
% plot figure
   figure;
   s_hrs = samp_j(:,4);
   hs = histogram(s_hrs(:,1),'Normalization','pdf');
   hs.NumBins = 40;
% normal pdf
   hold on
   pds = fitdist(s_hrs, 'Normal');
   z1 = min(hs.Data);
   z2 = max(hs.Data);
   z lim = z2*1.1;
   x = z1:.001:z2;
   y = pdf(pds, x);
% left axis
   yyaxis left;
   plot(x,y,'-r');
   ylabel ('Probability Density');
   ax = gca;
   ax.FontSize = 8;
% normal cdf
   hold on;
   p = cdf(pds, x);
% right axis
   yyaxis right
```

```
plot(x,p,'-b');
   ylabel ('CDF');
   ax = gca;
   ax.YColor = 'b';
   ax.FontSize = 8;
% plot text
   p90 = prctile(hs.Data,90);
   p50 = prctile(hs.Data,50);
   y1 = max(samp load);
   y^2 = min(samp load);
   txt = strcat(num2str(log_sampsize,'%04d'),' Samples');
   txt = txt + "\n" + "LOLE = " + num2str(p50, '%.3f');
   % txt = txt + "\n" + "Max = " + num2str(y1,'%.3f');
   % txt = txt + "\n" + "Minimum = " + num2str(y2,'%.3f');
   txt = txt + "\n" + "90th Percentile = " + num2str(p90,'%.3f');
   txt = compose(txt);
   txt = splitlines(txt);
   ylimtxt = get(gca,'ylim'); ylimtxt = ylimtxt*.95;
   xlimtxt = get(gca,'xlim');
   text(xlimtxt(1)+.002,ylimtxt(2)/2,txt,'FontSize',8);
% legend
   lgd = legend('data', 'Normal PDF', 'Normal CDF', 'Location', 'northwest');
   lgd.FontSize = 8;
   set(get(hs(1), 'Annotation'), 'LegendInformation'), 'IconDisplayStyle', 'off');
% labels
   xlabel('Loss of Load Expectation (hrs/yr)');
% grid
   grid on;
% export figure and close
   saveas(gcf,'(03) LOLE.png');
    %close;
```



Figure 04: LMP Time Series

```
% plot figure
    figure;
    lx = [lmp2017.(1); lmp2018.(1)];
    ly = [lmp2017.(8); lmp2018.(8)];
    plot(lx, ly, 'b');
% labels
    xlabel('Date', 'FontSize', 8);
```

```
ylabel('$/MWh','FontSize',8);
ytickformat('usd');
set(gca, 'YGrid', 'on', 'XGrid', 'on');
ax = gca;
ax.FontSize = 8;
% export figure and close
saveas(gcf,'(04) LMP Time Series.png');
%close;
```



Figure 05: LMP Histogram

```
% data
   lim = 105;
                               % target price signal
   X = (ly >= 105);
                              % count of values above target value in full sample
   sz_ly = numel(ly);
                              % count of target value in full sample
   mn_ly = mean(ly);
                              % mean value of lmp in full sample
   p_lim = nnz(X)/sz_ly;
                             % percentage of 1mp above target value in full sample
   z1 = 0; z2 = 125;
                              % distribution limits
   ly(ly(:,1)<=z1,:)=[];
                             % drop negative values
   ly(ly(:,1) >= z2,:) = [];
                              % drop large values
% plot figure
   figure;
   h = histogram(ly, 'Normalization', 'pdf');
   h.NumBins = 40;
% lognormal pdf
   hold on
   pds = fitdist(ly, 'Lognormal');
   x = z1:.1:z2;
   y = pdf(pds, x);
% left axis
   yyaxis left;
   plot(x,y,'-r');
   ylabel ('Probability Density');
   ax = gca;
   ax.FontSize = 8;
% lognormal cdf
   hold on;
   p = logncdf(x,pds.mu,pds.sigma);
% right axis
   yyaxis right
   plot(x,p,'-b');
```

```
ylabel ('CDF');
   ax = gca;
   ax.YColor = 'b';
   ax.FontSize = 8;
% plot text
   p90 = prctile(h.Data,90);
   p50 = prctile(h.Data, 50);
   txt = strcat(num2str(sz_ly,'%04d'),' Samples');
   txt = txt + "\n" + "LMP Avg. = " + num2str(mn ly,'%.3f');
   txt = txt + "\n" + "90th Percentile = " + num2str(p90,'%.3f');
    txt = txt + "\n" + "Percent over $" + num2str(lim, '%.0f')+...
        " = " + num2str(p lim, '%.3f');
   txt = compose(txt);
   txt = splitlines(txt);
   ylimtxt = get(gca,'ylim'); ylimtxt = ylimtxt*.95;
   xlimtxt = get(gca,'xlim');
   text(xlimtxt(1)+70,ylimtxt(2)/2,txt,'FontSize',8);
% legend
   lgd = legend('data','Logormal PDF','Logormal CDF','Location','Best');
   lgd.FontSize = 8;
    set(get(h(1), 'Annotation'), 'LegendInformation'), 'IconDisplayStyle', 'off');
% grid
    grid on;
% labels
   xlabel('$/MWh', 'FontSize',8);
   xtickformat('usd');
   set(gca, 'YGrid', 'on', 'XGrid', 'on');
   ax = gca;
   ax.FontSize = 8;
% export figure and close
    saveas(gcf,'(05) LMP Histogram.png');
    %close;
```



Price Signal Model

```
% Determine demand curve based on long-term reliability improvement goals.
% Set total number of customers/connections to be served
% substations
    sbs = 6;
% feeders per substation bus
    sbs_fd = 4;
```

```
% connections per feeder per engine
  fd_con = 400;
\ensuremath{\$} connections per substation per engine
  sbs_con = fd_con*sbs_fd;
% engines (total)
   unt tot = 3;
% total connections per subs for all engines
   sbs con tot = sbs con*unt tot;
% total connections for all sbs
   sbs con all = sbs con tot*sbs;
% benefits per customer from increasing the reliability
% estimated by ICE Calculator for a desired improvement of SAIDI of 6%
   ben con = 48;
\ensuremath{\$} avoided capital costs per substation
   avoided_cost = sbs_con_tot*ben_con;
\ calculate loss of energy expectation (LOEE) (mwh/yr)
% estimated baseline loss of load expectation (LOLE) (hrs/yr)
   lole = 1.3;
% engine power available (mw)
   ut_mw = 22.5;
% engines availabled
   unt = 3;
% LOEE for one year (mwh/yr)
   loee = lole*ut mw*unt;
% analysis period (yrs)
   yrs = 25;
% LOEE for whole analysis period
   loee tot = loee*yrs;
% determine inelastic supply curve
% price signal ($/MWh)
   pr = avoided_cost/loee_tot;
% inelastic supply curve
   pntx = zeros(1,unt_tot);
   pnty = zeros(1,unt_tot);
   for i = 1:unt tot
       pntx(:,i) = lole*ut mw*yrs*i;
        pnty(:,i) = avoided cost/(lole*ut mw*yrs*i);
   end
% add average LMP price
  pntx(:,4) = avoided_cost/mn_ly;
  pnty(:, 4) = mn ly;
```

Figure 06: Price Signal

```
% demand curve
   xt = (100:100:7500);
   yt = avoided cost./xt;
% plot figure
   figure;
   plot(xt,yt);
% set limits
   ylim([0 600]);
   xlim([0 7500]);
% grid
   grid on;
% plot price points
   hold on;
   scatter (pntx,pnty,'filled');
% plot inelastic supply curves
   hold on;
   for i = 1:size(pntx,2)
       pl = line([pntx(:,i) pntx(:,i)], ylim);
       pl.LineStyle = '--';
   end
```

```
% legend
   lgd = legend('Demand Curve','Price Point','Supply Curve','Location','northeast');
   lgd.FontSize = 8;
   set(get(pl(1),'Annotation'),'LegendInformation'),'IconDisplayStyle','off');
% grid
   grid on;
% labels
   xlabel('LOEE (MWh)','FontSize',8);
   ylabel('$/MWh', 'FontSize',8);
   ytickformat('usd');
   set(gca, 'YGrid', 'on', 'XGrid', 'on');
   ax = gca;
   ax.FontSize = 8;
% export figure and close
   saveas(gcf,'(06) Price Signal.png');
   %close;
```



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