GE RENEWABLE PLUS STORAGE FLEXIQ DISPATCHER EVALUATION

GE FLEXIQ Dispatcher Review Report

General Electric Company

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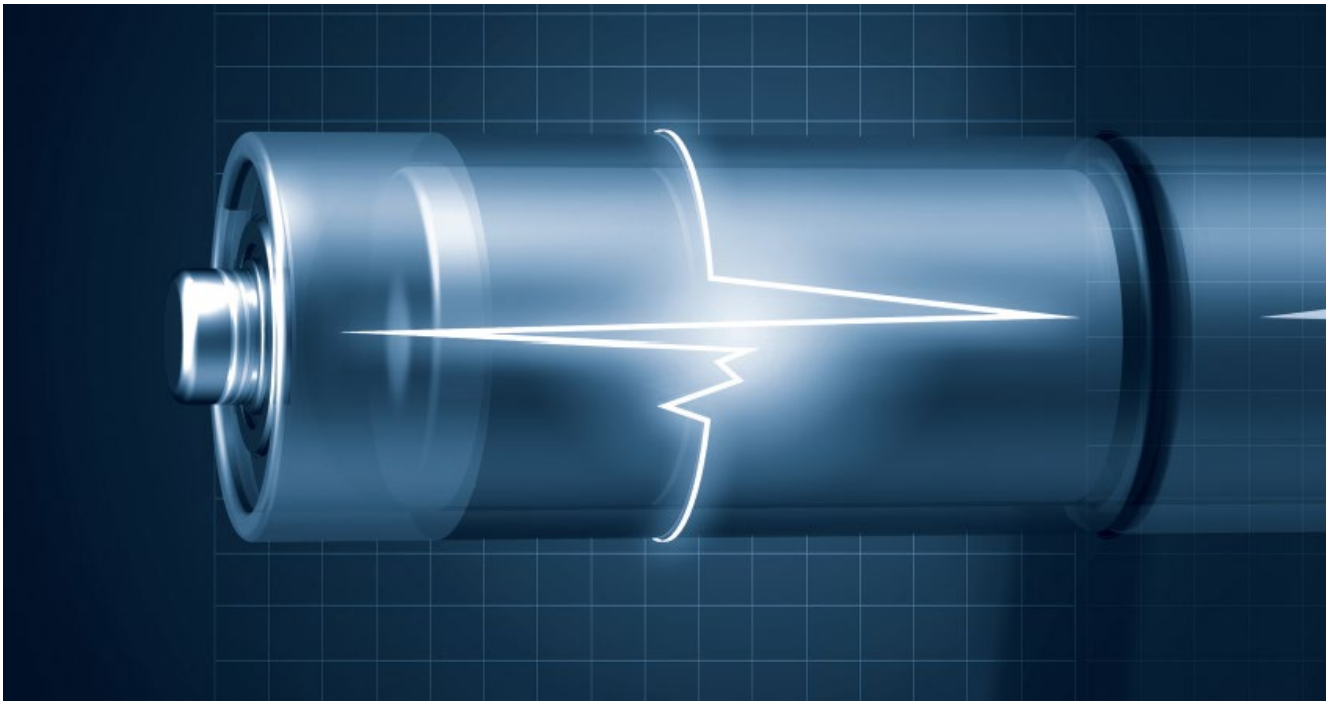

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The following table lists some of the abbreviations used in this Report.

Abbreviation	Meaning
AC	Alternating current
AEP	Annual energy production
BESS	Battery energy storage system
BoP	Balance of plant
CDR	Conceptual Design Review
DC	Direct current
ESS	Energy storage system
FLEXIQ Dispatcher	GE's FLEXIQ Dispatcher for Hybrid Renewables Plant(s)
GE	General Electric Company
IEC	International Electrotechnical Commission
ISO	International Standards Organization
LER	GE Large Energy Reservoir
MPC	Model predictive control
OTA	Over-the-air
PCC	Point of Common Coupling
POI	Point of interconnect(ion)
PV	Photovoltaic
ROC	Remote Operations Center
SCADA	Supervisory Controls and Data Acquisition
SOC	State of charge
UDH	Unit Data Highway
VA, kVA, MVA	Volt-amp (kilovolt-amp, megavolt-amp) – ac rating of (real and reactive) electrical power
VAR, kVAR, MVAR	Volt-amp reactive (kilovolt-amp reactive, megavolt-amp reactive) – ac rating of reactive electrical power
Wac, kWac, MWac	Watt ac (kilowatt ac, megawatt ac) – ac rating of real electrical power
Wp, kWp, MWp Wdc, kWdc, MWdc	Watt-peak (kilowatt peak, megawatt peak) – equivalent to dc electrical power rating of PV modules

EXECUTIVE SUMMARY

DNV reviewed General Electric Company's (GE) FLEXIQ Dispatcher for Hybrid Renewables Plants (GE's FLEXIQ Dispatcher). This is an optimization based supervisory controller for a hybrid renewable plant consisting of a renewable generator coupled with a battery energy storage system (BESS). DNV analyzed FLEXIQ Dispatch algorithms, compared the simulated performance of FLEXIQ dispatch with state-of-art modeling tools and reviewed software platform reliability, security, and scalability.

The FLEXIQ Dispatcher is based on model predictive control (MPC) moving horizon optimization. The algorithms are versatile, such that they can dispatch towards offtaker-based solar (or/and wind) plus storage use cases as well as merchant energy market revenue maximization. The FLEXIQ Dispatcher platform accepts SCADA parameters from plant engineering subsystems and electrical sub-systems, as well as time-series forecasts of renewable production, energy, and market prices. The methodology adjusts and corrects real-time plant outputs as the event horizon draws closer and predictions increase in certainty. The control methodology allows for configurability to different generation technologies, storage use cases and market products.

DNV compared FLEXIQ Dispatcher's optimization results against baseline results using offline simulation algorithms. GE's FLEXIQ Dispatcher employs a model predictive control (MPC) approach to calculate the hybrid plant control setpoints based on forecasted and actual photovoltaic (PV) generation, and nodal prices. To provide a software performance comparison, DNV has utilized a combination of rule-based dispatch and nodal price-based optimization. The rule-based methods establish the baseline operating capability and performance of a hybrid solar plus storage plant and are in line with the state-of-art implementation of rule-based approaches. The performance review was conducted for three applications, three plant configurations, and two different locations. The three individual applications include: 1) hybrid plant ramping control; 2) renewable production forecast (scheduled energy) firming; and 3) renewable energy arbitrage. In this review, DNV independently evaluated GE's FLEXIQ Dispatcher results for each application as a software only output; however, it noted that a hybrid plant controller would likely perform several functions at the same time. The use cases were selected based on DNV's opinion of most commonly contracted solar plus storage use cases. DNV concluded that GE's FLEXIQ Dispatcher software performance exceeded DNV's baseline results for most use case scenarios.

Ramp rate control application: GE's FLEXIQ Dispatcher outperformed an industry standard rule-based model in ramp rate control. The GE FLEXIQ Dispatcher ramp rate control results are summarized in Table ES-1. The results were quantified in three measures:

(1) **Ramp rate violation percentage**: The ramp rate violation percentage based on 10% threshold for GE scenarios were lower than the baseline results simulated by DNV: The baseline scenarios show 0.3% - 0.6% violation at Desert Rock and 0.6% - 1.5% violation at Penn State; GE scenarios have less than 0.1% violation. GE FLEXIQ Dispatcher improved on the rule-based approach via increased utilization of the battery.

(2) **Facility energy delivered**: For DC-coupled cases GE's FLEXIQ Dispatcher was able to provide additional facility energy over the rule-based approaches by increased utilization of the battery; as much as 20% improvement for one of the cases (a DC-coupled plant with a PV DC:AC ratio of 2.0:1). For the AC-coupled configurations, GE's FLEXIQ Dispatcher and DNV's simulated performance were similar, as there was no excess PV energy to charge the battery.

(3) **Battery throughput:** GE's FLEXIQ Dispatcher utilized the BESS more than the baseline rule-based approach implemented by DNV, higher throughput, for the DC-coupled cases; for Case 3, which represented a high solar resource with low intermittency. GE's FLEXIQ Dispatcher facilitated more than three times (3X) BESS throughput.

This allowed GE's FLEXIQ Dispatcher to increase energy delivery and reduce ramp rate violations compared to a solely rule-based approach.

Table ES- 1 GE FLEXIQ Dispatcher Ramp Rate Control Results

	Low intermittency /High Solar			High intermittency / Lower solar		
PV DC:AC ratio	**1.2 AC**	**1.6 DC**	**2.0 DC**	**1.2 AC**	**1.6 DC**	**2.0 DC**
±10% ramp rate violation (% of time)	0%	<0.1%	0%	<0.1%	0%	0%
Facility energy delivered (% of total PV available)	99%	93-94%	87-90%	99%	95%	92-94%
PV energy not utilized (% of total PV available)	0%	2-3%	5-8%	0%	<1%	1-3%

Scheduled energy firming: GE's FLEXIQ Dispatcher outperformed an industry standard rule-based model in several measures for scheduled energy firming. The GE FLEXIQ Dispatcher energy firming results are summarized in Table ES- 2. The overall results indicate that the model predictive control and optimization embedded into GE's FLEXIQ Dispatcher results in increased energy delivered for the solar plus storage facility. Additionally, GE's FLEXIQ Dispatcher is also able to simultaneously address multiple firming violation thresholds for energy firming by maintaining low violation numbers across 2.5%, 5%, and 7.5% thresholds. GE's results further demonstrate improved battery utilization (as quantified by throughput) and reduced PV energy unutilized, while maintaining lower annual average state of charge (SOC). GE's FLEXIQ Dispatcher utilized a Model Predictive Control optimization framework that was able to make battery charge and discharge decisions beyond PV generation versus firm schedule; and thereby increased battery utilization and lowered annual average SOC (e.g., preemptively discharge battery in preparation for future charging and discharge battery when the plant's firm schedule is set to zero), which can be broadly categorized as battery SOC management activities. These results determine that GE's FLEXIQ Dispatcher could provide operational improvements to a hybrid plant over a state-of-art rule-based control strategy. The comparison results are quantified in the following measures:

(1) **Firming violations**: The performance metric for firming violations was set to three (3) different thresholds of 2.5%, 5%, and 7.5%. GE's FLEXIQ Dispatcher was configured to reduce firming violations across all deviation thresholds, whereas the rule-based method only focused on violations greater than a 5% threshold. Comparison of GE's and baseline results show that GE's FLEXIQ Dispatcher provided a significant reduction in the number of violations for 2.5% threshold, while offering comparable performance at the 5% and 7.5% thresholds. GE communicated that FLEXIQ Dispatcher can be configured to minimize violations over multiple thresholds, and the results demonstrate this capability.

(2) **Facility energy delivered:** GE's FLEXIQ Dispatcher provided additional facility energy over the rule-based approach in all cases. Most improvements were observed for DC-coupled configurations; with 2.0 DC-coupled at Desert Rock, showing greater than 21.8% improvement over the rule-based approach that charges the battery with excess PV and allows hybrid facility output up to 95% of the firm schedule.

(3) **Battery throughput**: GE's FLEXIQ Dispatcher utilized the BESS more than the industry standard rule-based approach, with higher throughput in all cases. Most improvement was observed for the DC-coupled configurations with the highest PV DC capacity (2:1), including almost four-times (4x) more utilization than one of the DC-coupled

cases. The increased throughput in GE's results indicates more battery cycles compared to the baseline results; however, the number of cycles remained lower than 365 annual cycles, which is a typical industry expectation.

(4) **PV energy unutilized**: GE's FLEXIQ Dispatcher was able to reduce PV energy unutilized in comparison to the rule-based approaches in all cases. The most improvement was observed for the DC-coupled configurations with highest PV DC capacity.

(5) **Average battery SOC**: – GE's FLEXIQ Dispatcher was able to operate the BESS at lower annual average SOC compared to the rule-based model.

Table ES- 2 GE FLEXIQ Dispatcher scheduled energy firming results

	Low intermittency /High Solar			High intermittency / Lower solar		
PV DC:AC ratio	**1.2 AC**	**1.6 DC**	**2.0 DC**	**1.2 AC**	**1.6 DC**	**2.0 DC**
2.5% threshold violation (% of time)	5-6%	3-4%	1-2%	9%	8-9%	5-6%
5% threshold violation (% of time)	4-5%	3%	1-2%	8-9%	7-8%	5%
7.5% threshold violation (% of time)	4-5%	2-3%	1-2%	8%	7-8%	5%
Facility energy delivered (% of total PV available)	98%	91-92%	88-89%	96%	90-91%	90%
PV energy not utilized (% of total PV available)	0%	3-5%	6-7%	2%	4-5%	4-5%

Energy arbitrage: DNV implemented a baseline methodology that performed day ahead scheduling by solving a fixed-horizon mixed integer real time program problem. Thirty-seven-hour ahead PV-production and price forecasts were used as inputs. Plant loss tree parameters, engineering parameters, and interconnection limits are embedded into optimization constraints, which creates the plant bid and schedule. In a second stage, DNV used a heuristic methodology to firm the plant output to plant schedule. GE's FLEXIQ Dispatcher performs moving-horizon optimization with an objective to maximize plant revenue.

GE's FLEXIQ Dispatcher outperformed an industry standard baseline algorithm in arbitrage revenue. The GE FLEXIQ Dispatcher scheduled energy arbitrage results are summarized in Table ES- 3. At the modelled location—Desert Rock (with high solar resource and low intermittency)—GE's control system produced higher revenue than the control methodology by 1.5% to 7.5%. At the Penn Station location (with reduced solar resource and higher levels of intermittency) GE's control system estimated higher revenue by 0.5% to 3.1%. Overall, GE's real-time dispatcher with a multi-objective optimizer can achieve higher actual revenue compared to the industry standard approach of scheduled dispatch plus real-time rule-based firming.

This is due to two main reasons:

- GE's FLEXIQ Dispatcher performs moving horizon optimization by executing intra-day and intra-hour adjustments based on market clearing prices and renewable production forecast improvements. The baseline algorithm does not provide any correction after the clearing prices are published. The GE FLEXIQ Dispatcher can relax firming requirements to maximize revenue. Assume a situation where market clearing prices are presently low, but high after a few hours. GE's FLEXIQ Dispatcher may choose to hold back discharge now, even if under supplying with respect to its schedule, to make higher revenue in the future. Consider a situation where market clearing prices are

presently high but expected to be low after a few hours. GE's control system may choose to discharge now even if over supplying with respect to its schedule.

- GE's FLEXIQ Dispatcher chooses to curtail more PV than the industry standard model, especially for the modelled location that has a higher number of negative price hours. Since GE's FLEXIQ Dispatcher can perform intra-day and intra-hour corrections, when BESS SOC is at maximum, PV production during negative price hours is curtailed. The baseline algorithm implemented by DNV does not provide any correction after the clearing prices are published; therefore, excess solar production after storage charging is exported to the grid even when market clearing prices are negative. This occurs when forecasted prices at an hour were positive, but dispatch was not corrected post market clearing even when cleared price is negative. This implies that the project pays for exporting energy on those hours.

Table ES- 3 GE FLEXIQ Dispatcher scheduled energy arbitrage results

	Low intermittency /High Solar						High intermittency / Lower solar			
PV DC:AC ratio	**1.2 AC**		**1.6 DC**		**2.0 DC**		**1.6 DC**		**2.0 DC**	
High/Low Case	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**
Average Cycles	326	235	327	266	319	260	163	128	141	116
Average SOC	43%	42%	42%	42%	41%	41%	33%	52%	27%	27%
Max Achievable Revenue ($M)	$10.67	$10.67	$13.03	$13.01	$16.64	$16.33	$5.66	$5.60	$7.28	$6.97
Total Actual Revenue ($M)	$9.94	$9.54	$12.03	$11.74	$15.27	$14.85	$4.31	$4.26	$5.27	$5.21

Software Platform Reliability: DNV conducted a high-level review of FLEXIQ Dispatcher's reliability with a focus on its software development lifecycle, update strategies, and outage mitigation strategies. GE utilizes an Agile framework which is an established iterative method for software development, and appropriate third-party tools. A formal technical review process has been established by GE which seeks feedback from several key internal stakeholder teams. FLEXIQ Dispatcher software updates are performed via the Predix EdgeOS and Edge Manager interfaces. Updates are performed by uploading a release to the platform, and automatically updating all instances or manually choosing instances to update. Due to the containerization of the FLEXIQ Dispatcher application, multiple versions of the application can be present on the Edge device at a given time, which enables fast fail-back to the last working version.

All services provided by the FLEXIQ Dispatcher are containerized and hosted under Predix EdgeOS, which has built-in hardware health monitoring and service monitoring and is capable of restarting services automatically. In the event of an outage, the plant controller will continue to dispatch the plant based on commands preloaded by FLEXIQ Dispatcher for the next 24 hours. The plant controller also allows for up to one week of pre-programmed setpoints which can be utilized in the event of a complete communications failure without plant shutdown. GE's Mark Vie controllers can operate in a simplex, duplex or triple modular redundant configuration. High availability for FLEXIQ Dispatcher is accomplished by running FLEXIQ Dispatcher on one, two, or three Edge devices in parallel, each communicating with its respective controller. At a high-level, GE has appropriate alerts and diagnostics that are tracked via its Supervisory Control and Data Acquisition (SCADA) system. GE has stated that most issues with FLEXIQ Dispatcher can be solved remotely via its Remote

Operations Center (ROC) which is available 24/7/365 and that disaster recovery plans, service level agreements (SLAs), and response times are specific to their customers.

DNV considers GE's approach and processes to ensuring FLEXIQ Dispatcher's reliability to be in line with industry norms.

Software Platform Security

DNV conducted a review of the software security documentation relating to the FLEXIQ Dispatcher and received clarifications from GE. The system appears to be well-designed with security in mind from the outset which should prevent unforeseen security gaps. The use of a Docker container, provided the hardware is not overburdened by the requirements of the software, introduces the concept of immutability and simplifies the process of patching and updating the software components. This is viewed as a strength by DNV. The barrier devices deployed between the various segments of the network are in accordance with established practices and international standards. One noteworthy observation relates to the use of only passwords for authentication. Given the exponential increase in computing power available, the security of passwords has been substantially degraded despite any required complexity. It is recommended that consideration is given to deploying 'two factor authentication' on all human interactions with the system.

Given that a cloud solution is utilized, it is expected that the cloud platform conforms to an international standard of, for example, ISO 27017. The use of a major cloud provider, namely Amazon Web Services, is sensible given their reputation for security but the responsibility lays with GE to verify this.

GE stated that they implemented the CIS 7.1 controls to Implementation group three (IG3) which is the most comprehensive under this standard and suitable for a corporation the size of GE. If these controls are fully implemented and maintained in the production environment, then a good level of cybersecurity is attainable.

It is recommended that complete system is subject to a comprehensive penetration test and subject to regular audit as part of the compliance program.

Software Platform Scalability: DNV is not aware of any challenges with scaling the deployment of FLEXIQ Dispatcher. FLEXIQ Dispatcher is deployed on GE's cloud-managed Predix Edge platform. Therefore, upgrades to the software can be performed with relative ease allowing the system to stay up to date with changing market rules and operations. DNV considers this capability instrumental for scaling the deployment of FLEXIQ Dispatcher. GE has created a high-level roadmap for the development of its ROC with a focus on creating capacity, building capability, and achieving regulatory compliance. DNV considers GE's approach reasonable.