Energy Storage and Battery Test Facilities: *National Benchmarking Report*

Prepared for:

Special Legislative Committee

(Established pursuant to Section 134 in Chapter 47 in the Acts of 2017)

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Prepared by

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Executive Summary

This report outlines a preliminary benchmarking study conducted for the special legislative commission as established in Section 134 in Chapter 47 in the Acts of 2017 (herein referred to as the Commission) with the intent of identifying and describing test facilities for potential grid-integrated energy storage technologies. The scope of the study includes test facilities designed to advance the design of new battery cell technologies, as well as facilities designed to advance new battery systems towards commercially viable products. We found thirteen (13) test facilities, of which five (5) operate in association with a university, six (6) operate as national laboratories within the U.S. Department of Energy, and two (2) operate otherwise within the federal government or as a private entity. The benchmarking of these facilities is provided in Table 1.

The university-based facilities generally focus on testing pilot-scale cell prototypes and/or prototype systems closer to commercialization. These labs were generally served industry, entrepreneurs or researchers using a membership and/or fee-for-service model.

The DOE-supported National Laboratories focus on early-stage research of novel technologies, rarely venturing beyond pilot-scale proofs-of-concept. They assist small private businesses, but these collaborations are more likely to require applications to programs and grants as opposed to an open fee-for-service model.

Between these university and national lab based facilities, a potential gap was identified in transitioning energy-storage technology from pilot-scale prototypes to pre-commercialized systems. The identified test facilities are scattered geographically around the U.S., as shown in Figure 1.

This benchmarking scope was limited in time and resources, but provides a platform for further investigation by the Commission to more fully assess energy storage test facilities in the U.S. and opportunities for Massachusetts to advance a new test facility to support and attract technology innovation and business development in the Commonwealth.

Table 1: A summary of the benchmarked test facilities

Facility	Industry Focus	Technical Capability	TRL (1-9)	Funding Source	Location
NY-BEST TCC & RIT BPC	EV and grid energy storage	Fabrication, testing, commercial certification	4-8 (estimated)	Consortium, state support, private partners, member fees	New York State/ Rochester, NY
UMich Battery Lab	EV and grid energy storage (Li-ion)	Fabrication and testing of pilot-scale batteries	6-7 (estimated)	University, private partner, user fees	Ann Arbor, MI
UWash Clean Energy Testbeds	Clean energy	Fabrication and characterization	6-8 (estimated)	University, user fees	Seattle, WA
UMD CALCE Battery Group	Li-ion reliability	Battery failure analysis	6-9 (estimated)	University, user fees	Maryland
Penn State BATTERY	EV battery integration	Integration simulation and testing	6-7 (estimated)	Unknown	Pennsylvania

Sandia National Lab BATLab and ESAL	Abuse Testing	MW-scale electrical testing	4-5 (estimated)	Federal	New Mexico
Argonne National Lab	Chemistry Research	Pilot-scale testing, failure analysis of existing batteries	1-3, 8-9 (estimated)	Federal	Illinois
National Renewable Energy Lab	Electric vehicles and grid integration	Simulation for design, characterization, and integration	3-7 (estimated)	Federal	Colorado
Lawrence Berkeley Battery Group	Novel battery design and chemistry	Fabrication of advanced designs, simple characterization	2-3 (given)	Federal	California
Idaho National Lab Battery Test Center	EV batteries	Testing of pilot and commercial-scale batteries	<4; 7-8 (given)	$6-8 million/year	Idaho
Pacific Northwest National Lab	Clean energy	Pilot-scale fabrication and characterization	1-3 (given)	Federal, some private	Washington State
Johnson Space Center ESTA	Energy systems in space	Unknown	1-9 (estimated)	NASA	Texas
Fraunhofer CSE ESI Lab	Clean energy system integration	Lab and field testing of large systems	>6 (given)	Private contracting	South Boston, MA

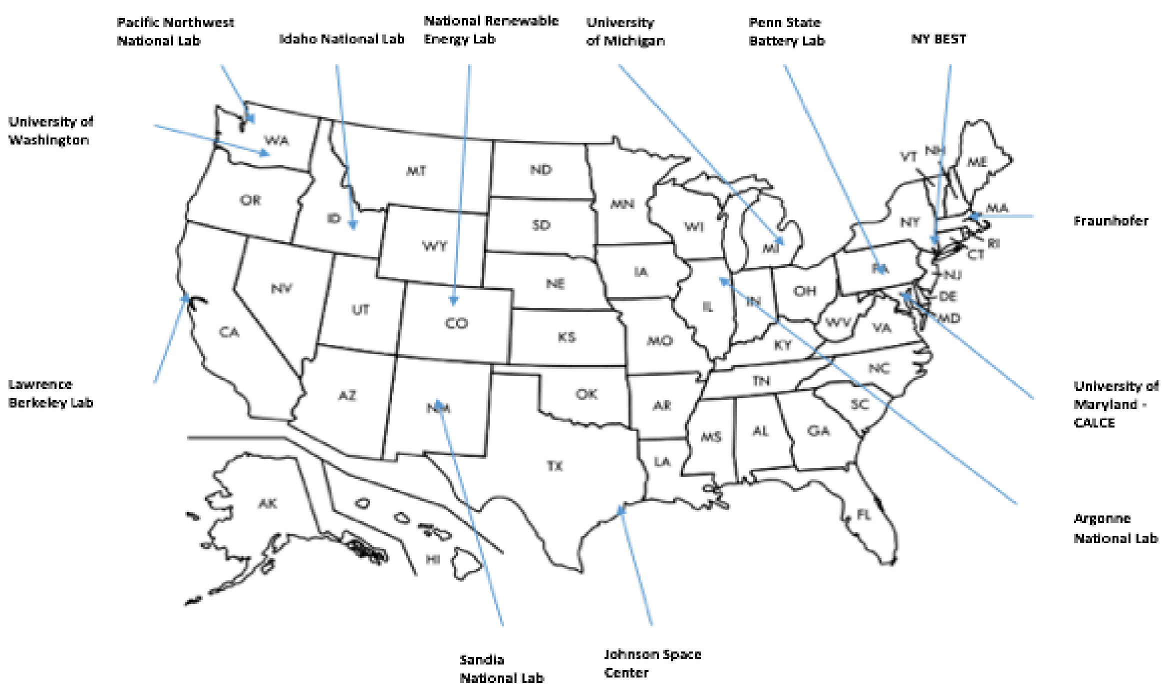

Figure 1: Geographic location of benchmarked labs

1. Introduction

This report provides a benchmarking study for test facilities working on cell and system scale energy storage technologies applicable for grid-integration. The report was prepared for the special legislative commission as established in Section 134 in Chapter 47 in the Acts of 2017 (the Commission), in coordination with Representative Solomon Goldstein-Rose. The research and report was completed by the UMass Clean Energy Extension. The team identified U.S. located test facilities, researched key attributes concerning the technical capabilities and financial establishment and operations of the facilities, and identify questions for further investigation. Research was conducted through internet resources and, as available, direct communications with staff at the test facilities.

1.1 Motivation

The goal of this benchmarking study is to provide a foundation for the Commission to better understand the range of existing test facilities, who they serve, and how the operate, and to help the Commission consider the form and role of a test facility in Massachusetts. To the extent the Commission solicits a consultant to explore the design and business plan and viability for a Massachusetts test facility, this benchmarking report is meant to be helpful in preparing a scope of work and to provide a starting point for a consultant's review of existing facilities.

1.2 Scope

In this report, we aim to benchmark facilities that may offer either competition, or collaboration opportunities, to a possible Massachusetts test facility supporting energy storage development.

Specifically, we concentrated on facilities that:

- Focus on energy storage technologies with primary applications for grid-integrated, inclusive of testing facilities at both cell-level and system-level. Technologies were not limited to lithium ion batteries.
- Are open to private and academic entrepreneurs, startups interested in additional R&D, and/or government research. Test facilities within storage companies that only work on internal R&D were not considered in the benchmarking scope.
- Operate between basic research and finished product. A technology readiness level (TRL) scale is used to consider this aspect of the scope.

Within this scope, we identified 13 facilities, of which 5 were affiliated with universities, 6 were within U.S. DOE National Laboratories, and 2 operated in another manner. We specifically researched whether any facilities pro-actively sought out emerging research to offer testing services or collaboration, and found no such facility.

1.3 Technology Readiness Level (TRL)

For the purposes of this benchmarking, we assessed all facilities in terms of a Technology Readiness Level (TRL) scale. We use the scale adopted by the Massachusetts Clean Energy Center (MassCEC), which is shown the Table 2.

Table 2: Technology Readiness Levels

TECHNOLOGY READINESS LEVELS (TRL)	
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant experiment
TRL 6	System/Subsystem model or prototype demonstration in relevant environment
TRL 7	System prototype demonstration in an operational environment
TRL 8	Actual system completed and qualified in an operation environment
TRL 9	Actual system proven through successful mission operations
The TRL descriptions are defined by ARPA-E	

The language for this TRL scale has not been updated for some time, so TRL values applicable to battery benchmarking were adopted. We marked TRL 1-3 as the stage in which research publications are typically offered, TRL 4 as the point at which a technology prototype is able to be describe conceptually, TRL 5 as the point at which a pilot-scale prototype is manufactured, TRL 7 as the point at which a technology becomes an integrated prototype under final testing, and TRL 8 as the point at which a technology becomes a version 1.0 product. Under this scale, the testing facilities we identified generally operate between TRL 4 and 7, noting that grid-integrated technology requires far more reliability testing and certification than comparable consumer technology. The range is often referred to as the "Valley of Death", due to the difficult nature of moving a technology from research to a well-tested, pre-commercialized prototype.

We were able to ask representatives, usually high-level researchers or managers, of some facilities to offer a TRL range for their facilities. We estimated TRL ranges for the rest. Note that the TRL scale is *not* standardized, especially with regards to its exact language. At times, we found a facility's position relative to the "Valley of Death" a more useful framing device.

1.4 Disclaimer

This report is a preliminary effort conducted under a condensed timeframe with limited resources. Our aim is to outline the existing energy storage test facilities, provide useful technical and contact information, and offer some remaining questions and key observations. The report recognizes that there may be some additional test facilities that we did not uncover, and that all information reported is not fully verified and only as accurate as our time and resources allowed.

1.5 Research Team and Acknowledgements

This research and report results primarily from the work of Ajey Panday and Reno Sarge who served as engineering interns to the Clean Energy Extension. The project was overseen by Chris Beebe, CEE Research Engineer, and by Dwayne Breger, CEE Director. The team thanks Representative Solomon Goldstein-Rose for his motivation and input.

1.6 Key Terms and Acronyms

DOD: United States Department of Defense.

DOE: United States Department of Energy. Provide funding to National Labs that work at various levels on clean energy.

EV: Electric vehicle.

IP: Intellectual property, including patents and trademarks.

Li-ion battery: lithium-ion battery. Currently leading standard technology for rechargeable batteries in electric cars and consumer electronics.

TRL: Technology Readiness Level. Also referred to as Technology Readiness Coefficient (TRC). An informal measure of how close to deployment a technology is, from theoretical understanding to product proven in the field.

"Valley of Death": Phase of development between proofs-of-concept for basic research and production-ready technology. Relatively few technologies make this gap, which requires a significant level of design, testing, and risk.

2. University Based Test Facilities

We identified five battery test facilities tied to research universities. These facilities are particularly appropriate models for Massachusetts to consider. Each of these facilities have varying relationships to their partner universities, home state, and industry. Some are more academic research labs than open test facilities, and some seem to only rely on universities to provide space and initial funding.

2.1 NY-BEST Test and Commercialization Center & RIT Battery Prototyping Center

Industry Focus	Technical Capability	TRL	Funding Source	Location
EV and grid energy storage	Fabrication, testing, commercial certification	4-8 (estimated)	Consortium, state support, private partners, member fees	New York State/ Rochester, NY

The NY-BEST Technology Commercialization Center (TCC) is an energy storage testing facility opened in 2014 in collaboration between the New York Battery and Energy Storage Technology (NY-BEST) Consortium, and testing and certification corporation DNV-GL. The Rochester Institute of Technology (RIT) Battery Prototyping Center (BPC) is an associated fabrication center open to members of NY-BEST. The consortium itself comprises a long list of private companies, universities, and public nonprofits.

Technical Capacity

The facility is now a primary testing site for DNV-GL and is open to members of NY-BEST. A list of the equipment for the RIT Battery Prototyping Center including a full set of equipment for fabricating and characterizing pilot-scale Li-ion cells, as well as a 1000 ft^2 dry room. Equipment for the BPC is given in Appendix I.

Business and Operation

Pricing for access the TCC of BPC is not given—only the price of general membership, which is $500 per year for startups of less than 25 employees. The consortium has a large board of directors comprising executives from member organizations, as well as a small internal administration staff. It is unclear who manages operation of the TCC, but the contact person for the facility is an employee of DNV-GL.

Key Issues and Questions

It would be quite useful to know the detailed equipment list for the TCC, as well as how these facilities are funded. It unclear how much startups are expected to pay for using the facility. This information is especially pertinent because NY-BEST has quite similar goals to the Massachusetts in terms of fostering innovation in energy storage and is a geographically close facility.

2.2 University of Michigan Battery Lab

Industry Focus	Technical Capability	TRL	Funding Source	Location
EV and grid energy storage (Li-ion)	Fabrication and testing of pilot-scale batteries	6-7 (estimated)	University, private partner, user fees	Ann Arbor, MI

The University of Michigan (UMich) Battery Lab is an 8,000 ft^2 small facility spread across two floors in the North Campus of the University of Michigan. It opened in 2016 with backing from Ford Motor Company and the Michigan Economic Development Corporation, and it offers fee-for-service fabrication and characterization of pilot-scale coin cells, cylindrical cells, and pouch cells for EV and grid applications.

Technical Capacity

The lab itself has a full equipment set for fabricating, characterizing, and testing Li-ion coin and pouch cells of up to 5 Ah. The test capabilities are aligned with pilot-scale operations – the lab tests cells, not systems, and the battery technologies here are intended for EV- or grid-scale applications. See Appendix I for a list of equipment at the facility.

Business and Operation

The UMich Battery Lab was started at the request of Ford Motor Company, which wanted a lab for individually testing batteries offered by suppliers. However, Ford did not need the facility full-time, so it let the lab conduct outside contract work as well. This legacy can be seen in the hardware the lab uses, which in some cases are made by companies with experience in mass production. The facility is a university lab, but it freely works with outside companies, offering "IP-protected" assistance. To that end, the facility website has a page clearly marking rates by hour, day, batch, or test for fabrication, assembly, and use of equipment. The IP considerations were quite important to the lab – it has deliberately tried to make the process for collaboration as simple as possible especially in comparison to the process for working with National Laboratories.

The facility started with a $10 million initial budget over five years and it has a staff of four, including one laboratory manager, one operation and maintenance staffer, one post-doctoral research fellow, and one part-time business manager. Clients are also asked to supply a staffer of their own to ensure that tests are being done in the desired manner.

The lab currently runs at 70-80% capacity, and it is currently self-sufficient based on its user fees. Clients are primarily from the Michigan/Detroit area, but some clients travel further for this lab's services.

Key Issues and Questions

This lab's business model should be further investigated. I appears to operate on a relatively low-budget, at high capacity, and reports that it is financially self-sufficient operating on user fees.

2.3 University of Washington Clean Energy Testbeds

Industry Focus	Technical Capability	TRL	Funding Source	Location
Clean energy	Fabrication and characterization	6-8 (estimated)	University, user fees	Seattle, WA

The University of Washington Clean Energy Testbeds (WCET) was opened in 2017 as a 15,000 ft^2 facility run by the University of Washington Clean Energy Institute (CEI).

Technical Capacity

The WCET is open to entrepreneurs working on all aspects of clean energy – including grid-integrated energy storage. The facility is split into three testbeds: Scale-Up and Characterization, Systems Integration, and Research Training. The Scale-Up and Characterization Testbed has a wide array of fabrication and testing instruments (not limited to energy storage), and the Systems Integration Testbed in particular has a 40kWh/30W energy storage system for testing battery management systems for grid applications. See Appendix I for a list of key equipment in the Clean Energy Testbed (Note: we only noted equipment we were certain were for battery fabrication and testing.)

Budget and Operation

The entire WCET has a staff of eight, consisting of two directors (one technical and one managing), three staff scientists, one business development specialist, one entrepreneur-in-residence, and one investor-in-residence. The staffing implies a focus on commercialization, as opposed to a focus on research and early stage development.

Effectively, a startup could use the WCET for most of their fabrication and testing work, paying for procedures in an "a la carte" manner, with discounts on some procedures given for members, who pay a yearly or monthly fee. Currently, the list of users and programs at the WCET are rather sparse, although this may be a result of the lab being still in its first year.

The University of Washington CEI has a diversity program called Diversity in Clean Energy (DICE), which is a student-led group.

Key Issues and Questions

We were not able to clarify the sources or amounts of initial funding and annual budget for the facility. However, an initial press release noted that the Washington State legislature appropriated $8 million for initial construction of the facility.

The business design of having two directors – one managing and one technical – is noteworthy and further outreach to WCET on this structure may be helpful.

2.4 University of Maryland CALCE Battery Group

Industry Focus	Technical Capability	TRL	Funding Source	Location
Li-ion reliability	Battery failure analysis	6-9 (estimated)	University, user fees	Maryland

The University of Maryland (UMD) Center for Advanced Life Cycle Engineering (CALCE) is a large lab that was founded in 1986, focusing on long-term reliability testing on a large set of technologies, including batteries.

Technical Capacity

The UMD CALCE Battery Group offers destructive and non-destructive testing of batteries, including (but not limited to) electrochemical impedance spectroscopy, standard cycling tests, neutron imaging, and X-ray microscopy. The group focus on how Li-ion batteries fail in a wide range of applications – not just grid-integrated. There lab's website has broken links to pages explaining their tests in more detail. A list of the battery group's electrical testing equipment is supplied in Appendix I.

Business and Operation

The facility has a long list of academic researchers and a similarly long list of publications. The Battery Group has nine staff researchers and lists almost fifty publications. We found no information relating to their funding.

CALCE offers a program called Test Services and Failure Analysis (TSFA), which appears to be a consulting resource for private companies to access. There is no pricing information on the website, only a person to contact for a quote.

Key Issues and Questions

It is unknown how much the CALCE Battery Lab specifically addresses batteries in grid-integrated applications, and is focused particularly on Li-ion batteries. We also do not know the exact sources for CALCE funding or the lab offers a fee for services structure for private companies.

2.5 Penn State BATTERY Lab

Industry Focus	Technical Capability	TRL	Funding Source	Location
EV battery integration	Integration simulation and testing	6-7 (estimated)	Unknown	Pennsylvania

The Penn State Battery Application Technology Testing and Energy Research laboratorY (BATTERY) is a battery integration and testing facility affiliated with the Penn State Larson Transportation Institute. To that end, it focuses primarily on EV applications, using an AeroVironment ABC150 and AV900, a walk-in temperature-controlled test chamber, and hardware-in-loop (HIL) simulations. There is very little information on its website regarding collaboration or pricing, beyond very basic contact information for the director of the lab.

3. DOE National Laboratory Based Test Facilities

The United States Department of Energy (DOE) supports and funds multiple National Labs, which all focus in some capacity on renewable energy, including energy storage. These labs primarily focus on early-stage research, which is often cost-prohibitive and too risky for private companies. From what we could find, the research in DOE National Labs exists prior to the "Valley of Death."

Much of the work in National Labs is initiated through proposals in response to Broad Agency Announcements (BAAs) and working on awards given by government agencies, especially the DOE and Department of Defense (DOD). These labs also collaborate with private companies, but those companies tend to be large. Our research suggests that the general expectation is that users are expected to find their own funding for such collaborations.

However, there are programs for small businesses to collaborate with National Labs through the DOE, including Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) grants, both granted through the United States Small Business Administration (SBA).

The DOE has its own program as well, called Small Business Vouchers (SBV). The SBV program had a three-round pilot program, with applications closing on Earth Day (22 April) of 2015, 2016, and 2017. Each company selected through the application process received between $50k and $300k to work with a National Lab. To be eligible, these companies must have fewer than 500 employees, require services "not reasonably available in the private sector," and contribute 20% of the total budget for the collaboration. These companies could be in any sector related to clean energy – not just energy storage – and they had to sign IP agreements (either TAPA or Short CRADA) that in some cases made their work subject to export controls. There is no application for a fourth round as of January 2018.

3.1 Sandia National Lab BATLab and ESAL

Industry Focus	Technical Capability	TRL	Funding Source	Location
Abuse Testing	MW-scale electrical testing	4-5 (estimated)	Federal	New Mexico

Sandia's primary battery testing facility, the Battery Abuse Testing Lab (BATLab), focuses less on designing novel battery technology than on stress-testing existing technologies. Sandia also has a very large battery calorimetry lab, a Li-ion prototyping facility, and a test lab and testbed for energy storage, called the Energy Storage Analysis Lab (ESAL).

Technical Capacity

ESAL can test a wide-array of storage technologies, from mA to 1000A scale. They can even characterize MW scale systems, important for utility scale grid-integrated storage. The facility can account for factors like energy time shift, load following, power quality, and other considerations relevant to operators in the grid.

Business and Operation

The BATLab primarily works for the DOE Office of Vehicle Technologies, testing technology for EV applications. However, the lab also conducts research for other offices in the DOE, DOD, NASA, and private contractors. ESAL, meanwhile, works with organizations working on the grid, including independent system operators (ISOs) and regional transmission operators (RTOs), power producers, utilities, and R&D labs in academia and government.

Key Issues and Questions

Further details of these labs' toolsets and their benchmarks for testing should be explored.

3.2 Argonne National Lab

Industry Focus	Technical Capability	TRL	Funding Source	Location
Chemistry Research	Pilot-scale testing, failure analysis of existing batteries	1-3, 8-9 (estimated)	Federal	Illinois

Argonne's battery research focuses on cell-level development of novel technologies and post-testing support for batteries already in the field. This lab also spearheads the Joint Center for Energy Storage Research (JCESR), a partnership of several labs and universities aiming to advance beyond Li-ion technologies with regards to affordability and power capacity. Argonne's Chemical Science and Engineering department hosts three separate labs that are a part of the battery development life cycle. This includes a Cell Analysis, Modelling, and Prototyping Lab (CAMP), Electrochemical Analysis and Diagnostics Laboratory (EADL), and a Post Test Facility.

Technical Capacity

CAMP focuses on pouch and 18630 (cylindrical) cells in dry rooms that can accommodate up to six workers. The lab has equipment for semi-automated battery production for these small cells. EADL tests battery technologies, from pilot-scale cells to EV battery systems, using custom hardware and software tools. The lab has an environmental chamber, and mostly works with prototype storage technologies.

The Post-Test Facility, by contrast, works on failure and degradation analysis of existing batteries, using physical, spectroscopic, metallographic, electrochemical tests.

Business and Operation

Argonne works with DOE as well as academic researchers and other laboratories. The EADL facility also works on contracts for the United States Advanced Battery Consortium (USABC).

This lab also spearheads the Joint Center for Energy Storage Research (JCESR).

Key Issues and Questions

It would be interesting to ask JCESR about energy storage test facilities to compare with those we have identified. We also are unsure of what equipment exists in the Post-Test Facility in particular – and whether any of that equipment might be useful for technologies lower in the TRL scale.

3.3 National Renewable Energy Lab (NREL)

Industry Focus	Technical Capability	TRL	Funding Source	Location
Electric vehicles and grid integration	Simulation for design, characterization, and integration	3-5*(Transport)/ 6-7*(ESIF)	Federal	Colorado

The National Renewable Energy Lab (NREL) has two hubs for battery research: one in its Transportation department and one in its Energy Storage Integration Facility. The former is focusing on novel battery chemistry, including improved Li-ion, solid-state, lithium-air, and even liquid batteries. The latter, meanwhile, focuses on MW scale integration to power grids, including operation of buildings, vehicle charging systems, and energy storage.

Technical Capacity

NREL's Transportation department uses two simulation systems: they model fabrication with the Computer-Aided Engineering for Electric Drive Vehicle Batteries (CAEBAT) tool, and they model operation with the Battery Lifetime Analysis and Simulation Tool (BLAST). CAEBAT is effectively a CAD suite for battery technology, whereas BLAST considers temperature, state-of-charge history, current levels, and cycle depth and frequency to forecast the longevity and performance of battery systems in complex environments.

The ESIF, meanwhile is developing a hardware-in-the-loop (HIL) test platform for ~10 kW grid-connected energy storage systems – roughly the scale of Tesla Powerwall units. The platform can model how these energy storage systems behave within the grid, both with and without solar integration.

We found no information regarding hardware measures for fabricating and testing batteries.

Business and Operation

NREL is a DOE-supported lab, but it also frequently partners with large corporations, government programs, utilities, and other labs. They do sponsor incubators such as the Wells Fargo IN^2 incubator, which focuses on clean energy.

Key Issues and Questions

We were not able to establish what sort of hardware NREL uses regarding battery fabrication and testing, and how much of their CAEBAT and BLAST toolset is applicable to grid applications.

3.4 Lawrence Berkeley National Laboratory Battery Group

Industry Focus	Technical Capability	TRL	Funding Source	Location
Novel battery design and chemistry	Fabrication of advanced designs, simple characterization	2-3	Federal	California

The Lawrence Berkeley Lab (LBL) focuses on basic research. Batteries tested in the Battery Group are generally small scale proofs-of-concept for novel technologies.

Technical Capacity

The LBL Battery Group focuses less on in-depth battery testing and more on electrode design for Li-ion batteries (they mostly fabricate 1-10 mAh coin cells). To that end, they have relatively simple fabrication tools – they use “gloveboxes” as opposed to full dry rooms, and they use a standard-issue Maccor cycler. The entire operation is relatively small, with only “one of everything” in the fabrication and testing process.

The equipment for the lab is spread out between 3 rooms that are all relatively close to each other: one room for the coating and mixing, one room for assembly, and one room for the cycler. These rooms are close enough that transport between them is not cumbersome, though a re-designed facility might do well to place all the equipment in one room. The LBL Battery Group does not have a dry room and, although it would improve throughput, a dry room is difficult to conduct extended work. A key lesson from the group is to consider thermoelectric environmental chambers. Their old environmental chamber was water-based, which sometimes had problems with ice buildup. Switching to a thermoelectric chamber was a significant improvement to their process – not only was the new unit smaller, but it also did not suffer from ice buildup.

Business and Operation

The DOE provides most of the funding for LBL, and the Battery Group primarily does fabrication and cycling for projects within LBL, with the occasional contract for companies under the SBIR program.

The most significant way for a small company to work with LBL outside of the SBIR program is through the Cyclotron Road program, which is an incubator affiliated with LBL for “hard science innovators.” Companies brought into the incubator receive funding and full access to lab space within LBL for a two-year fellowship. The program has run through four cohorts, with applications for a fifth cohort opening in fall 2018.

Key Issues and Questions

The head of the Battery Group indicated that a significant amount of work could be done with simple equipment.

3.5 Idaho National Lab Battery Test Center

Industry Focus	Technical Capability	TRL	Funding Source	Location
EV batteries	Testing of pilot and commercial-scale batteries	<4; 7-8 (given)	$6-8 million/year	Idaho

The Battery Test Center at Idaho National Laboratory (INL) is the primary center for battery technology testing for the DOE Office of Energy Efficiency and Renewable Energy (EERE). The test facility provides 17,500 ft^2 of laboratory space equipped with tools that allow testing of several hundred batteries at the same time, ranging from small cells to complete EV-scale battery packs.

Technical Capacity

The INL Battery Test Center offers a wide set of testing equipment holding over 800 channels, with some units supplying DC voltages up to 1000 V and power as high as 350 kW. Some of these units can be operated independently of each other, and tests can be conducted in walk-in chambers that can be set to between -65°C and 190°C. The facility can also test battery vibration and operate with CAN buses, allowing for better simulation of EV battery systems.

Business and Operation

INL is primarily DOE-funded: only 2% of its work is from private contracts. However, the Battery Test Center sources 10-15% of its work from private contracts, which are often with small companies (although these contracts only rarely involve SBIR grants).

The Battery Test Center has an annual budget between $6-8 million, 15 permanent staff, and a small cycling cohort of interns and postdoc researchers. The facility is led by principal investigators (PIs), with test engineers who report to the PIs.

Key Issues and Questions

The group lead did not offer a detailed list of equipment.

3.6 Pacific Northwest National Lab

Industry Focus	Technical Capability	TRL	Funding Source	Location
Clean energy	Pilot-scale fabrication and characterization	1-3	Federal, some private	Washington State

Pacific Northwest National Lab (PNNL) is a 4500-employee laboratory with a nearly $1 billion annual budget run by the private nonprofit Battelle. The lab's focus is primarily early-stage research (the person we spoke to at PNNL placed it at TRL 1-3).

Technical Capacity

Its Advanced Battery Facility (ABF), which was started in 2015, is a ~1,200 ft^2 facility that focuses specifically on fabrication. Half of the facility is a dry room, and the other half is kept at an ambient environment. The facility generally fabricates batteries in the 0.1-2 Ah range, which is on par for consumer electronics, but barely pilot-scale for grid applications. The battery testing lab includes 1000-channel testing arrays and a high-precision tester that can run up to 100 A at 36 V.

The lab does not design its own products, and the technology it works mostly exists prior to the "Valley of Death." With regards to batteries, PNNL works at maximum with 1 kW units (either Li-ion or liquid flow) – that is, large enough to convince clients that it works.

Budget and Operation

Like most National Labs, PNNL is primarily funded by the DOE, although it also takes a significant amount of funding from the DOD and private contractors.

PNNL is a leader with regards to helping small businesses interface with the National Labs. Beyond running its own Economic Development Office and offering support for private companies applying for grants, they spearheaded a consortium called LIGHTMAT which, despite focusing on materials science and not energy storage, provides insight into how private companies can interface better with complex institutions like the DOE. Each of the approximately ten National Labs within this consortium has a small team that intimately know the capabilities of their respective labs. Private companies can directly contact these teams, who will guide the companies through the requisite processes so that the private companies don't get lost. This system helps address the criticism that working with the DOE and with National Labs is a confusing processes.

Key Issues and Questions

We were not able to get in contact with the head of the ABF or other PNNL battery testing facilities. It may be helpful to obtain an equipment list for the ABF, and evaluate the differences and overlaps between equipment for basic research and equipment for testing prototype systems.

4. Additional Test Facilities

Most labs we found either are affiliated with universities or are large DOE-supported endeavors. There are a few exceptions, however, including a new facility opened by the Fraunhofer Center for Sustainable Energy Systems in Boston.

4.1 Johnson Space Center Energy Systems Test Area

Industry Focus	Technical Capability	TRL	Funding Source	Location
Energy systems in space	Unknown	1-9 (estimated)	NASA	Texas

The Johnson Space Center is not a U.S. DOE National Lab – but a lab affiliated with NASA and its Energy Systems Test Area (ESTA). The ESTA is used to test power systems (including energy storage) in conditions simulating space. The information packet for the lab does not specifically mention the equipment used, but the lab offers tests regarding heat, short-circuiting, hazardous vibration, drop/crush testing, and heat/vent testing, among others. The ESTA website notes that anyone who wishes to work with the facility could contact them.

4.2 Fraunhofer Center for Sustainability Energy Systems (CSE) Energy Storage Integration Lab

Industry Focus	Technical Capability	TRL	Funding Source	Location
Clean energy system integration	Lab and field testing of large systems	>6 (given)	Private contracting	South Boston, MA

The Fraunhofer Center for Sustainability Energy Systems (CSE) Energy Storage Integration (ESI) Lab is a very new testing facility (opened December 2017) located in South Boston and run by research nonprofit Fraunhofer. It focuses on testing systems for integration within clean energy systems, especially on designing standards for safety and security within house-scale clean energy systems.

Technical Capacity

The ESI Lab tests late-stage prototypes for clean energy storage systems using a model "smart-home," and a combination of simulated and hardware components. This model accounts for rooftop solar arrays, load banks, and energy storage systems. The lab also conducts field tests for larger systems. All tests are performed by Fraunhofer staff.

At the systems level that the ESI Lab operates, Li-ion and liquid-flow batteries are both testing under similar equipment and integration – they are simply energy storage systems. The primary difference is that liquid-flow batteries tend to be built and tested at larger scales, necessitating field testing more often than lab testing.

Despite their work in testing energy systems, the ESI lab does not award certifications in the manner of UL or DNV.

Business and Operation

Fraunhofer CSE pulls from a wide array of funding, including MassCEC support and private R&D contracts. The most common structure for private R&D contracts is that the client approaches Fraunhofer with a prototype and a series of questions about the operation of their own system. From there, Fraunhofer and the client collaborate to determine what needs to be tested and how one should test those parameters. Once the tests are established, Fraunhofer runs the tests themselves.

A key issue in the energy storage industry is that there is no agreed upon standard for safety, efficiency, and security within grid-integrated energy storage systems. Thus, part of the ESI Lab's work is to help establish those standards.

At this point, the Fraunhofer ESI Lab is trying to promote itself, which is perhaps the closest any of the benchmarked labs approach to actively seeking out promising research to test.

Key Issues and Questions

The individuals at Fraunhofer CSE did not give exact specifications regarding the equipment in their lab, and they were unclear as to which elements were hardware emulations and which were simulated. It may be interesting to explore how early in the TRL scale one can operate before the testing requirements for liquid-flow and Li-ion batteries diverge significantly.

5. Key Observations

This report outlines a preliminary benchmarking study prepared for the Commission with the intent of identifying and describing test facilities supporting energy storage, applicable for grid-integration, that advance early-stage research and later-stage product development into commercially viable products. We found thirteen (13) such facilities, of which five (5) operate in association with a university, six (6) operate as part of the United States Department of Energy, and two (2) operate under other arrangements.

The university-supported facilities we found generally focused on testing pilot-scale prototypes and/or prototype systems that were nearer to commercial readiness. These facilities were typically established with state and/or corporate support, and open to external users through a membership and/or fee-for-service model.

The DOE-supported National Laboratories we found focused more on early-stage research of novel technology, rarely venturing beyond pilot-scale proofs-of-concept. They offer assistance to private businesses, but these collaborations are more likely to require competitive applications to programs and grants as opposed to an open simple fee-for-service model.

Findings and questions relating to our research and interviews with the test facilities, include the following.

- Many of these labs do their own fabrication, especially if they occupy earlier stages in the TRL scale. For later stages in the TRL scale, the need for fabrication capabilities may be less, though access to specialty manufacturers to support prototype development may be helpful.
- When speaking with a researchers at PNNL, the employee noted that to test technologies within the "Valley of Death," the prototypes and equipment would need to be quite large. In PNNL, batteries are fabricated and tested at most up to 1 kW – enough to prove that the concept works. However, pushing the technology further within grid applications would require systems starting at ~10 kW scale and moving up to MW scale.
- PNNL also informed us that the DOE has an Office of Electricity Delivery and Energy Reliability (OE), which is working on standards for grid-integrated energy storage. Dr. Imre Gyuk, who is the Director of Energy Storage Research at the DOE OE is the appropriate point person for that office.
- The group lead for the INL Battery Test Center stressed the importance of proper layout in a test facility to improve efficiency and flexibility of operations. This was especially true for power lines and testers.
- The business manager for the UMich Battery Lab stressed the importance of considering overseas vendors – although they may be more difficult to work with at times, they may offer superior products and services than local vendors.
- Fraunhofer CSE noted that the landscape in energy storage was fragmented and that there were few test facilities in the space. This tracks with our benchmarking study, in that there are a handful of laboratories that offer open testbeds, of which most are focused either on clean energy as a whole or on Li-ion batteries in EVs and grid applications. The availability of test facilities for liquid-flow energy storage technologies open to independent entrepreneurs or small businesses is especially limited. This may be due to less research on liquid-flow battery technology, but this need and opportunity remains unclear.
- The test facilities identified did not appear to employ outreach efforts to pro-actively seek emerging new research progress from institution and companies to recruit into the test facility. This opportunity should be explored further as to its impact on the business viability of the facility, and ability to expand technology options and business creation in Massachusetts.

As provided in Figure 2 and discussed above, the identified test facilities tend to cluster in the low TRL range in the national labs and in the higher TRL range for the university facilities. NY BEST, NREL, and Sandia do extend into the mid TRL scale. The extent to which these available test facilities sufficiently address the technology development needs and can adequately serve and encourage a Massachusetts energy storage cluster, or whether gaps in scope or geographical convenience create opportunities for a test facility in Massachusetts, will require further investigation. Coordinating a test facility with research institutions, clean energy incubators, and advanced manufacturing in Massachusetts should be further explored.

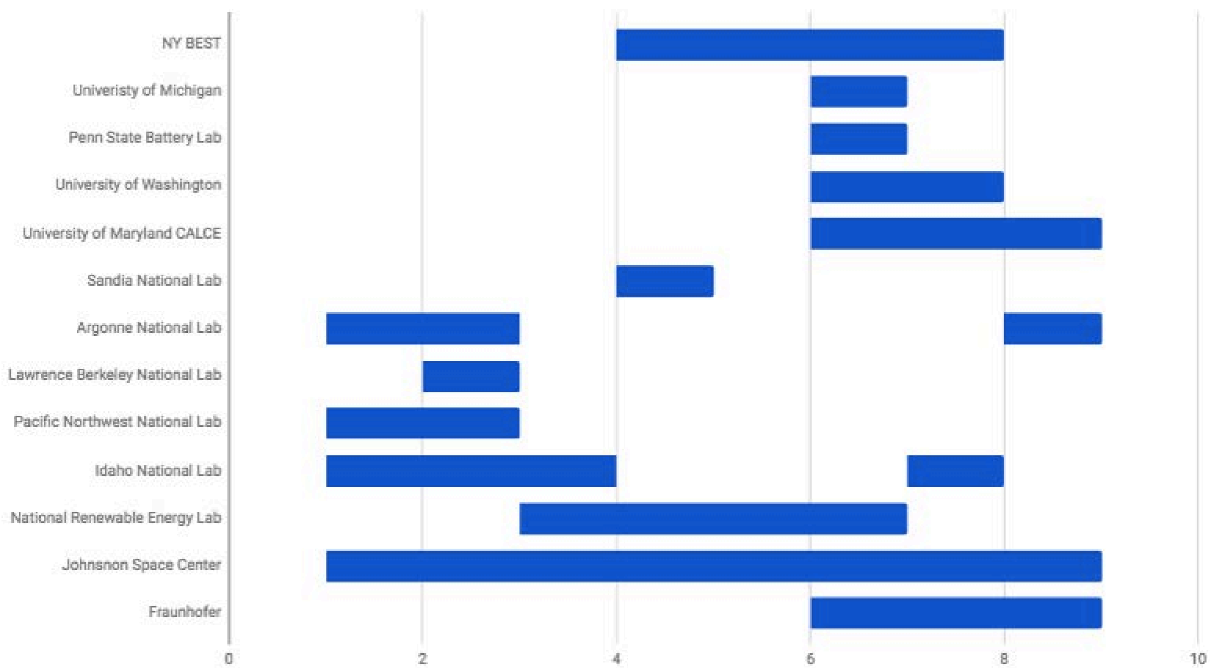

Figure 2: TRL ranges of identified and benchmarked labs

Appendix I: Test Facility Equipment List

The equipment lists provided in this appendix are largely adapted from the facility websites. The list for the RIT Battery Prototyping Center and a list of recommended equipment by Massachusetts-based Ionic Materials (see header note on UMich Battery Lab Equipment List) were provided by Representative Solomon Goldstein-Rose.

RIT Battery Prototyping Center (NY-BEST)

	Coin-cell Scale	Cylinder/Pouch-cell Scale
Mixing	Flaktek Speedmixer 150.1 FV. Buhler Homogenizing Disper DH-2.5[1]	Bhuler Hivis HM-2P-01. Buhler Laboratory Disk Mill
	Primix FILMIX 56-L	
	Malvern Kinexus Rheometer	
Coating	MTI blade coating system	TBD
Calendaring	TOB: 150C[2]	Independent Machine Company Calendar system: 150C
Electrode Prep	Coin-cell punches Steel rule die custom punches and press	Slitting machine by Independent Machine Company or Delta Mod. Sovema SoLith RPN300
Cell Assembly	Pred Materials coin cell crimper and coin cell disassembly tool	Sovema SoLith CWM150 (for 18650 cells). Sovema SoLith Automatic Cell Winder (for prismatic cells)
Testing	Add 64 channels to pilot-scale system	Bitrode system (32-channel,1A,0-5V). Arbin System (32-channel,5A,0-5V). Both in Thermal channel
Characterization	Hitachi S900 (scanning electron) Brookfield Viscometer[3] Amatek VersaSTAT 4 (Impedence analysis) Bruker D2 PHASER (tabletop X-ray diffractometer) Vacuum Atmospheres Glovebox HORIBA Raman (spctrometer) TA Instruments DSC series (Differential Scanning Calorimeter) TA Instruments TGA series (thermogravimetric analyzer) TA instruments DMA series (Dynamic Mechanical Analyzer) Netzch MMC 274 Nexus + High Temperature Coin Cell Module	

[1] We could not find this particular Buhler unit online.
[2] We could not find the company TOB online.
[3] Brookfield offers a wide array of viscometers.

UMich Battery Lab

Note: We received a list of suggested equipment from the private company Ionic Materials that was identical to the list of equipment from UMich Battery Lab, except without the Beckman Coulter LS 13 320, TA Instruments DSC series, TA Instruments TGA series, and Micromeritics Surface Area Analyzer.

	Coin-cell Scale	**Cylinder/Pouch-cell Scale**
Mixing	Buhler Hivis 3D-5	Buhler Hivis 2P-03
	Primix FILMIX 56-30	
	TA Instruments Discovery HR-2 Rheometer	
Coating	Mathis Labcoater LTE-S	CIS: Multicoating Type[1]
Calendaring	CIS: 150C[1]	CIS: 2kN/cm, 150C[1]
Electrode Prep	CIS: Manual electrode punches[1] mPlus notching system (electrode punch)[2]	CIS: slitting machine[1] mPlus notching system (electrode punch)
Cell Assembly	Toyo TOSMAC Crimping Machine for Small Cells[3]	KOEM cell winder for 18650 cells. mPlus packaging machines for 18650 and pouch cells
Testing	Maccor (24-channel,50A,0-5V or 72-channel,10A,0-5V) in thermal chamber	Maccor (48-channel,150µA-5A,0-5V or 96-channel,30µA-1A,0-5V) in thermal chamber
Characterization	Thermal Hazard Technology Accelerated Rate Calorimeter Luna OBR 4600 (fiber optic strain and temp sensing) Hitachi S3500N (SEM w/ EDAX) Princeton Applied Research VS-SCEM (scanning electrochemical probe microscope) Solartron 1260, Solartron ModuLab (impedance analyzers) Rigaku MiniFlex 600 Benchtop X-ray Diffractometer Vacuum Atmospheres Genesis (glovebox) HORIBA Raman (spctrometer) Beckman Coulter LS 13 320 (laser diffraction particle size analyzer) TA Instruments DSC series (Differential Scanning Calorimeter) TA Instruments TGA series (Thermogravimetric Analyzer) Micromeritics Surface Area Analyzer w/ BET[4]	

[1] CIS is a Korean company. We could not find them online.
[2] The lead at the Lawrence Berkeley Lab Battery Group suggested using machine crimping for higher-quality cells.
[3] UMich claims a Toyo system for de-crimping cells, but we could not find such a system online.
[4] Micromitics offers multiple surface-area analyzers with BET support.

UMD CALCE Battery Group

Electrical Characterization	Cadex C8000 Battery Test system Agilent 34970A Data Acquistion INL Battery Testing System Neware BTS4000 Arbin BT2000 Battery Test System Arbin BT-1
Environmental Chambers	MBRAUN Glove Box Workstation Yamato DVS 402 Thermo Temperature Humidity Chamber
Mechanical Testing	TA's Dynamic Mechanical Analyzer Data Physics 1D Electrodynamic Shaker Perkin-Elmer Differential Scanning Calorimeter Vibrotron 6D-Electrodynamic Shaker DAC Torsion Tester Mechanical Test System
Failure Analysis	Zeiss AxioCam MRc5 Optical Microscopy Agilent Foruier Transform Infrared Spectroscopy Nikon Atomic Force Microscopy Fischer X-ray Fluorescence Microscopy

University of Washington Clean Energy Testbeds

Roll-to Roll Printing	FOM Solar-X3 roll-to-roll printer
Fabrication	FOM R&D Sheet Coater FOM Mini Roll Coater New Long LS 34GX Screen Printer nScrypt 3Dn-300 Printer Nanonex NIL NX-B100 Nano-Imprint Lithographer Laurell Spin Coater Annealsys As-One 150 Rapid Thermal Processor Thinky ARV-310 Mixer Jelight 256 UV-Ozone Cleaner Xenon S-2100 Photonic Sintering (Flash Lamp) Setup Beckman-Coulter Allegra X-30 Centrifuge CEM Mars 6 Microwave Digestion System Temperature and Humidity Test Chambers MBraun Gloveboxes Environment Control Room
Characterization and Analysis Instrumentation	ThermoNicolet iS10 Fourier-Transform Infrared Spectrometer Bruker D8 Advance X-Ray Diffractometer OAI Trisolar Class AAA Solar Simulator Spire Spi-Sun Simulator 5100SLP Maccor Series 4200 M 16-Channel Automated Battery Test System Maccor Series 4000 96-Channel Automated Battery Test System Ametek Versastat4-500 Arbin HTPCE-2104 High Precision Coulombic Efficiency Tester Anton Paar MCR302 Rheometer Kuss DSA100S Drop Shape Analyzer Dektak XTL Profilometer NanoScience Instuments Phenom ProX scanning Electron Microscope with Energy-Dispersive X-ray Spectroscopy Mettler Toledo DSC 3+ Mettler Toledo TGA/DSC 3+ Olympus OLS4100 Nikon Eclipse LV150N Agilent Cary 60UV-Vis Litesizer 500
Systems Integration Instrumentation	Powin Energy Battery Energy Storage System Optal-RT Digital Simulator
Research Training Testbed	MTJ OTF-1200X-III Tube Furnace Quantum Design Dynacool Perkin Elmer Nexion 2000B Perkin Elmer LS 55 Agilent/Diablo Anlaytical- 5000A Real Time Gas Analyzer (RTGA) and 5777B Gas Chromatography

	Malvern zetasizer Nano ZS – Dynamic Light Scattering (DLS) Analyzer Angstrom Engineering NexDep Thermal Evaporator Golvebox-Integrated Sawatec: SM-150 SpinCoater Laurell Spin Coater Glove Box with Solar Simulator and EQE Oriel Verasol-2 Solar Simulator QEPVSI-b Measurement system Hohsen HSACC-10 Automatic Coin Cell Crimper Mbraun Argon Battery Glovebox Maccor 4000 64 channel multifunctional battery testing system Maccor MTC-020 battery-test temperature chambers

Appendix II: Test Facility Contact Information

For some of the facilities we contacted, we were forwarded to a second person. In these cases, we mark down the forwarded person second.

	Facility	Key Persons	Titles	Email	Phone
University Based Test Facilities	NY-BEST TCC	Davion Hill	Energy Storage Leader, DNV GL	Davion.m.hill@dnvgl.com	614-761-1214
	UMich Battery Lab	Greg Less	Senior Lab Manager	gless@umich.edu	734-764-2794
		Bruno Vanzieleghem	Assistant Director of Operations, UMich Energy Institute	brunov@umich.edu	734-764-9981
	UWash Clean Energy Testbeds	Michael Pomfret	Managing Director	mpomfret@uw.edu	206-685-6833
	UMD CALCE Battery Group	Roy Arunkumar	Administrator, UMD CALCE	rakumar@calce.umd.edu	301-405-5383
		Dr. Yinjiao (Laura) Xing	Research Associate	yxing3@calce.umd.edu	301-405-5316
	Penn State BATTERY	Timothy Cleary	Director	tcleary@engr.psu.edu	814-865-0500
DOE National Laboratory Based Test Facilities	Sandia National Lab			partnerships@sandia.gov	
	Argonne National Lab	Ben Schiltz	JCESR Communications Lead	bschiltz@anl.gov	630-252-5640
	National Renewable Energy Lab	Ahmed Pesaran		ahmad.pesaran@nrel.gov	
		Matthew Keyser		matthew.keyser@nrel.gov	
	Lawrence Berkeley National Lab	Kate Britton	Senior Administrator, Energy Storage and Distributed Resource Division	kmbritton@lbl.gov	510-495-8894
		Vince Battaglia	Lead, Battery Group	vsbattaglia@lbl.gov	510-495-8894
	Idaho National Lab	Nicole Stricker	Communications Lead	nicole.stricker@inl.gov	208-526-5955
		Eric Dufek	Lead, Energy Storage Group	eric.dufek@inl.gov	208-526-2132
	Pacific Northwest National Lab	Gordon Graff	Commercialization Manager	gl.graff@pnnl.gov	509-375-6786
Other	Fraunhofer CSE Grid Integration Group	Matt Kromer	Director, Grid Integration Group	mkromer@cse.fraunhofer.org	
		Christian Hoepfner	Center Director	choepfner@cse.fraunhofer.org	617-575-7250