# ELEN EE 6591: Smart Electric Energy - Energy Storage for the Electric Grid

**Description:** This graduate-level course offers a comprehensive exploration of Battery Energy Storage Systems (BESS) and their pivotal role in the ongoing transformation of the electric grid. It analyzes the evolving forces reshaping grid operations, shifting from traditional unidirectional central supply to dynamic, bidirectional power flows facilitated by large-scale BESS integration. Through a hybrid pedagogical approach, combining advanced theoretical lectures with hands-on, live on-site battery demonstrations, students will critically examine the multifaceted technical challenges impeding the widespread adoption of energy storage and critically evaluate potential solutions. Furthermore, the course will delve into the complex considerations inherent in the effective development, deployment, and operationalization of grid-scale energy storage projects, emphasizing their impact on grid resilience, reliability, and the integration of distributed energy sources.

**Prerequisite:** EE4511 Power Systems Analysis; Simulink Modeling.

**Instructor:** Dr. Mohamed Kamaludeen, Electrical Engineering.
**Office:** 633 Mudd.
**Office Hours:** Online (by appointment) and/or before class. You can email me at mkk2178@columbia.edu to setup an appointment. Please, include "[ELEN EE6591]" (without the quotes) in the subject line.

**Academic Load:** 3 hr./wk.; 3 cr.

**Time:** Thursday, 4:10pm – 6:40pm. This class will adapt to an asynchronous learning schedule. The first session will be in-person, followed by ad-hoc virtual session via Zoom. See the course timeline below for more details. I reserved the right to adjust the schedule.

**Location/Classroom:** XX Mudd

**Zoom Meeting ID**: Will be posted in Courseworks prior to Lecture.

**Textbook:** There is no textbook for this course. Relevant articles, journals and resources will be posted on Courseworks.

***Caution:***

- **Mandatory Off-Campus Sessions:** Be aware that this course includes required travel to designated battery facility locations within New York City (Queens, Brooklyn and/or Staten Island) for practical demonstrations and activities. Specific dates and logistics will be provided in advance.
- **High-Engagement Learning Model:** This course operates on a flipped classroom model and requires significant commitment to self-directed learning, independent research, and collaborative teamwork outside of scheduled class time. Students should anticipate dedicating substantial time to these activities.
- **Prerequisite Knowledge in Power Systems and Simulink Modeling:** A robust foundational understanding of power system engineering principles is essential for success in this course. Review of these fundamentals prior to the start of the course is highly recommended. Students should have working knowledge of Simulink modeling of power systems components.

***Course Topics:***

- Energy storage industry and technology overview.
- Grid Planning and DER integration.
- Energy Storage System (ESS) applications, economics and use cases.
- Advanced topics in electric power systems including smart grids, cybersecurity, microgrids and renewable energy integration etc.

***Student Learning Outcomes:*** Having successfully completed this course, you will be empowered to:

- **Master the full lifecycle of energy storage systems**: Gain a profound, practical understanding of the intricate design, strategic implementation, and optimized operation of cutting-edge energy storage solutions, positioning you with a comprehensive functional skillset in this critical field.
- **Drive the future of the power industry**: Acquire deep insights into the most timely and impactful shifts reshaping the power industry, including the transition to a smarter, cleaner, and electrified grid. You will learn to navigate and contribute to this monumental energy evolution.
- **Engage directly with real-world innovation**: Experience direct exposure to a live, grid-connected battery storage system, providing unparalleled practical insight into its operational dynamics and real-world application.
- **Become capable in diverse storage technologies**: Comprehend the full spectrum of energy storage technologies, assess their Technology Readiness Levels (TRLs), and conquer the multifaceted challenges associated with their seamless integration into the modern electric power grid.
- **Ensure grid resilience and stability**: Develop the advanced analytical skills necessary to critically assess and bolster power system stability, becoming a key contributor to maintaining reliable and robust electrical infrastructure.
- **Innovate with advanced simulation tools**: Harness the power of MATLAB/SIMULINK to simulate complex distribution systems, integrating grid-scale batteries and cutting-edge power electronic devices, thereby equipping you with essential skills for advanced grid modernization.

***Required Readings**:*

The research papers and relevant reading materials will be distributed throughout the course.

- Das, A., Wu, D., Bhatti, B. A., Kamaludeen, M. K. (2024, June 21). Approximate Dynamic Programming with Enhanced Off-Policy Learning for Coordinating Distributed Energy Resources. IEEE Transaction and Sustainable Energy, 15(3), 1614-1626. https://doi.org/10.1109/TSTE.2024.3361674
- Kamaludeen, M.K., et al.: Common direct current (DC) bus integration of DC fast chargers, grid-scale energy storage, and solar photovoltaic: New York City case study. IET Smart Grid. 115 (2024). https://doi.org/10.1049/stg2.12154.
- Kamaludeen, M.K., et al.: Grid-Scale Battery Systems for VAR Support in Con Edison Distribution Substations via Bi-Directional Smart Inverters. IET Smart Grid. 115 (2024). STG-2024-02-0029.
- Kamaludeen, M. K., Mohamed, A. A., Zafar, K., Esa, Y., Nyemah, E., Salmeron, L., Odie, S. (2023, December 21). Common direct current (DC) bus integration of DC fast chargers, grid-scale energy storage, and solar photovoltaic: New York City case study. *IET Smart Grid*. https://doi.org/DOI: 10.1049/stg2.12154
- Mohamed, A. A., Zafar, K., Vaidya, D., Salmeron, L., Kanwhen, O., Esa, Y., Kamaludeen, M. K. (2023, December 11). Grid Impact of Wastewater Resource Recovery Facilities-Based Community Microgrids. *IET Smart Grid*. https://doi.org/10.3390/smartcities6060152
- J. Kassakian, R. Schmalensee, "The Future of the Electric Grid," MIT, 2011, available online at: http://mitei.mit.edu/publications/reports-studies/future-electric-grid.
- Kamaludeen, Mohamed K., et al. "Dissecting the Levelized Cost of Storage — "Adders" for New York City." Sustainability - MDPI Journal, 23 Mar. 2022, pp. 1-18. https://www.mdpi.com/journal/sustainability, doi: Sustainability 2022, 14, 3768. https://doi.org/10.3390/su14073768.
- Kamaludeen, Mohamed K., et al. "ANALYZING VALUE STREAMS OF ENERGY STORAGE IN CON EDISON TERRITORY." EPRI - 3002022089, vol. 1, 4 June

2021, pp. 1-14, www.epri.com.

- Kamaludeen, Mohamed K, et al. "How Con Edison Is Planning for Accelerated Energy Storage Deployments and a Clean Energy Future." POWERGRID International, 27 Apr. 2021, www.power-grid.com/executive-insight/how-con-edison-is-planning-for-accelerated-energy-storage-deployments-and-a-clean-energy-future/.
- Kirn Zafar, Mohamed K. Kamaludeen, Yusef Esa, Ahmed Ali A. Mohamed, and Simon Odie, "Fault Analysis for DC Bus-Integrated ESS, EVSE, and PV," submitted to Energy Reports (EGYR-D-23-02193), 2023.

***Software Packages*†*:***

- MATLAB/SIMULINK. Students are expected to have a working knowledge of using this application.

† Instructions on how to install these software packages will be given in the class.

***Academic Integrity Policy:***

Academic integrity is paramount and strictly enforced within this course. Any form of plagiarism or cheating is unequivocally prohibited. During all examinations, mobile phones must be powered off and stowed away; their use as calculators or for any other purpose is strictly forbidden.

Engaging in academic dishonesty, including but not limited to copying content from the internet, collaborating inappropriately with peers, or unauthorized use of artificial intelligence platforms, places your academic standing in severe jeopardy. It is important to understand that instructors possess effective methods for detecting instances of plagiarism or unoriginal work.

Should you be found guilty of plagiarism or cheating on an examination, the minimum consequence will be a failing grade for the entire course. Furthermore, such infractions may lead to more severe penalties as outlined by University policy, including permanent notations on your academic transcript, suspension from the University, or even expulsion.

For a comprehensive understanding of the university's expectations and policies, you are required to review the Academic Integrity Policy of Columbia University at [https://www.cc-seas.columbia.edu/integrity/policy]. Adherence to these principles is not merely a recommendation but a fundamental requirement for all students.

***Attendance Policy:***

Consistent attendance is a critical component of success in this course, particularly for sessions involving project presentations and the mandatory in-field visits to battery sites. Your presence and punctuality for all classes are not merely encouraged, but are essential to your learning and the collaborative environment.

Punctual arrival for all classes is expected. Please be aware that I reserve the right to deny entry to the classroom for students who are late, as their delayed arrival can disrupt the learning experience for others and impede the flow of instruction.

Regarding project presentations, rescheduling is not automatically granted. Any request to reschedule a presentation is subject to my sole approval. To facilitate this process and demonstrate your commitment, you must notify me of your need to reschedule at least 24 hours in advance, to the extent that it is possible. Failure to adhere to these attendance and notification policies may result in significant academic disadvantages, including missed crucial information, inability to participate in practical components, and potentially adverse impacts on your grade. Your proactive engagement with these requirements is fundamental to your successful completion of the course.

***Miss Assignments:***

***"Life Happens Pass"-*** For <u>**one written assignment**</u> this semester you can get an automatic 48-hours extension on the due date, no questions asked. **You MUST inform Dr. Kamaludeen and the TA in writing (email) to get this pass.** All other assignments will get a 10% deduction per day of being late. It is to your benefit to turn in assignments on time. Most of the points are better than no points.

***Courtesy Policy:***
Eating and the use of unauthorized handheld electronic equipment is not allowed in the classroom.

***Disability Policy:***
The university is committed to providing appropriate academic accommodation to ensure all students have an equitable learning experience. If you have a disability that impacts your academic participation, the university strongly encourages you to register with the Disability Services office. This enables them to work with you to determine and implement reasonable accommodations in accordance with the Americans with Disabilities Act. Proactively connecting with the Disability Services office at Columbia University will help you access the support and resources available to facilitate your academic success.

***Evaluation and Grading Policy:***

| | |
|---|---|
| *Mid-Term Exam* | 25% |
| *Final Exam* | 30% |
| *Final Project: Presentation and Report* | 25% |
| *Attendance and Field Visit* | 10% |
| *Homework and Class Discussion* | 10% |

**Grading Scale**

| *Grade* | A+ | A | A- | B+ | B | B- | C+ | C | C- | F |
|---|---|---|---|---|---|---|---|---|---|---|
| *%* | ≥95 | 91-94 | 87-90 | 83-86 | 79-82 | 73-78 | 69-72 | 65-68 | 60-64 | ≤59 |

**Project: (25%)**
The final project requires students to undertake a comprehensive analysis and design of a grid-connected battery energy storage system (BESS). This project is divided into three core components:

1. **Site Selection and Deployment Analysis:**
   - Identify and thoroughly analyze a specific location suitable for BESS deployment, either within New York State or another chosen region.
   - This analysis must integrate the deployment techniques, site considerations, and application methodologies discussed in lectures and observed during battery site visits.
2. **Technical Modeling and Simulation:**
   - Develop a detailed model of the proposed grid-connected BESS using MATLAB/Simulink.
   - The model should clearly demonstrate the technical functionalities essential for the chosen application, validating system performance through simulation.
3. **Regulatory, Market, and Safety Assessment:**
   - Conduct a comprehensive study of the market drivers, relevant policies, safety standards, and permitting requirements critical for the successful deployment of the BESS at the selected location.
   - **Extra Credit Opportunity:** Integrate a detailed techno-economic analysis into your assessment, evaluating the financial viability and overall

economic impact of the proposed system.

**Deliverables:**
The project culminates in two primary deliverables:

- **Technical Paper:** A comprehensive report structured as a technical paper, outlining your findings, methodology, and conclusions. A standard template/example will be provided on Courseworks and should be at minimum 15-pages.
- **Presentation:** A formal 30-minutes group presentation summarizing your project and key results.

**Team Collaboration:**
Students are encouraged to form teams for this project. However, significant and demonstrable individual contribution from each team member is expected. The instructor reserves the right to modify team compositions or reassign individual students to ensure balanced workloads and effective collaboration. Further details regarding team sizes and formation guidelines will be provided during the semester.

**Homework's: (10%)**
These are due exactly 1 week from the assigned date. See course timeline below for details.

**Field Visits:**
This course includes two mandatory field visits to operational utility-scale battery systems, offering direct exposure to real-world applications.

**Key Field Visit Details:**

1. **Queens Facility (First Visit):**
   - **Location:** Con Edison site in Queens, NYC.
   - **System:** A 2 MW / 10 MWh Lithium Iron Phosphate (LFP) battery system, manufactured by BYD.
   - **Significance:** This is New York City's inaugural grid-connected battery system, operational for five years, primarily providing peak shaving services to the local network and substation.

2. **Brooklyn Facility (Second Visit):**
   - **Location:** Next to Con Edison Brownsville substation in Brooklyn, NYC.
   - **System:** A 5.8 MW / 23.2 MWh Tesla Megapack 2 LFP battery system.
   - **Applications:** This system performs various functions, including peak shaving under the BQDM program and possibly participation in ISO market services.

**Important Directives:**

- **Mandatory Personal Protective Equipment (PPE):** Proper Personal Protective Attire (PPE) is strictly required for entry and participation at both field visit sites.
- **PPE Requirements Discussion:** Specific details regarding the necessary PPE will be thoroughly discussed and reviewed in class prior to the first visit. Adherence to these requirements is non-negotiable for site access.

***Changes to the syllabus:***
I reserve the right to amend all policies stated above. Please make sure to check the class page on coursework regularly, where I will post announcements and any changes to the syllabus.

**Course Timeline**

| ELEN G6591 - Smart Electric Energy - Energy Storage for the Electric Grid  Course Syllabus and Timeline | | | | | |
|---|---|---|---|---|---|
| **Week #1** | **Date** | **Synchronous Learning** | **Topics** | **Project / Homework Assigned** | **Deliverables** |
| 1 | 9/4/2025 | In-Person | Syllabus + Evolution of the Electric Grid and Energy Storage | HW#1 | N/A |
| 2 | 9/11/2025 | Virtual | Energy Storage Deep Dive : Technologies, Operations, Use Cases and Degradation etc. | HW#2 | HW#1 |
| 3 | 9/18/2025 | In-Person | Grid Planning and DER Integration: Part 1 | HW#3 | HW#2 |
| 4 | 9/25/2025 | In-Person | Battery Site Visit 1: Con Edison Ozone Park Battery (2 Groups) - **BYD System** | N/A | HW#3 |
| 5 | 10/2/2025 | Virtual | Grid Planning and DER Integration: Part 2 | HW#4 | N/A |
| 6 | 10/9/2025 | In-Person | Final Project (Group) and Simulink Overview | Final Project (Group) | HW#4 |
| 7 | 10/16/2025 | **In-Person** | **Mid- Term Exam** | N/A | N/A |
| 8 | 10/23/2025 | In-Person | Battery Site Visit 2: Con Edison Brownsville Battery (2 Groups) - **Tesla System** | N/A | N/A |
| 9 | 10/30/2025 | Virtual | Clean Energy Electrification: Policy and Economic Valuation + DER VET Demonstration | HW#5 | N/A |
| 10 | 11/6/2025 | In-Person | Hydrogen + Long Duration Storage | HW#6 | HW#5 |
| 11 | 11/13/2025 | In-Person | Advance Grid Support Functionalities: Grid Following and Grid Forming Inverters* | HW#7 | HW#6 |
| 12 | 11/20/2025 | Virtual | Cybersecurity for Energy Storage Systems + Project Discussion/Q&A | HW#8 | HW#7 |
| 13 | 11/27/2025 | **No Class** | **Thanksgiving Recess** | N/A | HW#8 |
| 14 | 12/4/2025 | In-person | Final Project Presentation and Feedback; Course Evaluation | N/A | Final Project Presentation & Report |
| 15 | 12/11/2025 | In-person | Final Project Presentation and Feedback; Course Evaluation | N/A | Final Project Presentation & Report |
| 16 | 12/18/2025 | **In-Person** | **Final Exam** | N/A | N/A |

* I reserve the right to change this topic based on the progress and interest of the class.