



Benjamin Lynch¹

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: lynch.be@northeastern.edu

Umit Coskun

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: a.coskun@northeastern.edu

Gregory Kowalski

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: g.kowalski@northeastern.edu

Laurent Lessard

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: l.lessard@northeastern.edu

Yiannis Levendis

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: y.levendis@northeastern.edu

Bala Maheswaran

First Year Engineering,
Northeastern University,
Boston, MA 02115
e-mail: b.maheswaran@northeastern.edu

Hameed Metghalchi

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: m.metghalchi@northeastern.edu

Hossein Noorian

School of Management,
Wentworth Institute of Technology,
Boston, MA 02115
e-mail: noorianh@wit.edu

Inclusion of Concentrated Solar Thermal Power in Northeastern University's Mechanical Engineering Curriculum

Global energy consumption continues to surge, demanding a transition from fossil fuels to cleaner and more sustainable alternatives. A variety of renewable energy sources—solar, wind, hydro, and geothermal—are critical to this transformation, with each offering diverse and regionally adaptive solutions. Among these sources, solar energy has become a dominant force through both photovoltaic (PV) and solar thermal technologies. While PV systems remain the leading force in regard to rapid deployment and decentralized applications, concentrated solar thermal power (CSTP) systems offer a unique advantage of thermal energy storage. Thermal energy storage offers an affordable and efficient form of dispatchable electricity generation and industrial process heat. Despite its benefits, CSTP remains a niche and is vastly underrepresented in engineering curricula across the United States. This article presents a comprehensive initiative at Northeastern University to address this educational gap by systematically institutionalizing CSTP content across nine mechanical engineering courses from the first year through the graduate level. Through hands-on projects, advanced simulations, and heliostat-focused design challenges, engineering students gain practical and theoretical exposure to CSTP technologies. By aligning curriculum development with the goals of the Department of Energy (DOE) and Heliostat Consortium (HelioCon), Northeastern University establishes a replicable model for integrating CSTP education and preparing a new generation of engineers to meet the growing demands of the clean energy transition. [DOI: 10.1115/1.4069389]

Keywords: alternative energy sources, biomass conversion, clean energy, design engineering, energy, mechanical engineering, renewable energy, robot kinematics, solar, solar reactor, solar receiver, solar thermal power, sustainable engineering, thermal energy storage

¹Corresponding author.

Manuscript received August 2, 2025; final manuscript received August 9, 2025; published online September 16, 2025. Tech. Editor: Hameed Metghalchi.

Rifat Sipahi

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: R.Sipahi@northeastern.edu

Yustianto Tjiptowidjojo

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: y.tjiptowidjojo@northeastern.edu

Yasin Yazicioglu

Department of Mechanical and Industrial
Engineering,
Northeastern University,
Boston, MA 02115
e-mail: y.yazicioglu@northeastern.edu

Introduction

Concentrated solar thermal power (CSTP) systems utilize large arrays of self-orienting mirrors (heliostats) to deliver high fluxes onto a small solar receiver. From there, an energy (heat) transfer medium, commonly molten salts, sCO_2 , particles, or air, absorbs the solar radiation as thermal energy, raising the temperature to between 600 and 800 °C [1]. Three common commercial architectures exist as (1) power-tower heliostat fields, (2) parabolic troughs, and (3) dish-engine systems, while linear Fresnel and next-generation particle towers are also emerging [2,3]. By the end of 2023, global CSTP capacity reached approximately 7 GW, with approximately 75% of the cumulative capacity being attributed to solar troughs [4]. While Spain and the United States currently lead the world in installed capacity, China's research and development pipeline is positioning them to overtake both Spain and the United States by 2030 [5].

In modern power-tower configurations, heliostat fields occupy anywhere between 30% and 50% of the cost of installation, making their cost reduction a primary goal of the Department of Energy (DOE) [6]. The thermal output of CSTP systems is often routed through a Rankine or Brayton cycle to produce electricity to be fed to the grid, or supplied directly as industrial process heat [7,8].

Since the thermal energy is captured first, CSTP plants often couple directly with molten-salt thermal energy storage (TES) providing anywhere between 15 and 24 h of long-duration storage and relatively low cost compared to the 4–6 h of lithium-ion battery storage seen in photovoltaic (PV) systems [9,10]. Other energy (heat) transfer media, such as ceramic/sand and supercritical CO_2 , are being evaluated for next-generation CSTP systems for use in thermochemical or industrial process integration [11].

The Solar Energy Technologies Office (SETO) has set a 2030 leveled-cost-of-energy target of \$0.05/kWh for dispatchable CSTP, as well as a cost target for heliostats of \$50/m² [12,13]. To structure a pipeline which spans across both industry and academia, SETO launched the Heliostat Consortium (HelioCon) in 2021, publishing a roadmap highlighting several critical gaps in the field of CSTP: metrology, advanced manufacturing, controls, and—as the focus of this article—resources, training, and education (RTE) [14]. This report highlights that RTE through university partnerships and workforce expansion are critical pillars toward the overall cost reduction strategy.

While the DOE continues to make a push toward the development of CSTP technology, CSTP remains an academic blind spot in most United States-based engineering programs. HelioCon's

roadmap identifies multiple *Tier 1* (must-address) RTE gaps, including a lack of centralized public heliostat/CSTP knowledge sources and limited university outreach. Additionally, an expansion of the heliostat workforce is needed to mitigate commercial deployment risks [15].

Several universities across the US have worked to address these gaps with funding provided by HelioCon and the Department of Energy to aid in these initiatives. Some examples include Rice University's "A Brighter Future" initiative [16], University of Nevada's Operating Surface Angle Measurement System (OSAMS) project [17], and the University of Wisconsin—Madison's Predictive and Optimized Control of Heliostats for Future Solar Fields (PROMETHEUS) project [18].

Northeastern University is taking a multifaceted approach to integrating CSTP content. To actively advance CSTP knowledge, Northeastern University faculty and graduate researchers have focused on several subsets of CSTP topic areas. The thermodynamic optimization of solar-powered Brayton recompression cycles using molten-salt TES has been explored [19–23]. Additionally, Northeastern teams have pioneered iron powder combustion systems for carbon-free energy generation [24].

Aside from pure research, Northeastern University has set objectives to institutionalize CSTP into Northeastern University's College of Engineering's Mechanical Engineering curriculum through HelioCon Request for Proposal (RFP) funding. The two projects, "An Educational Program on Concentrated Solar Power and Heliostats for Power Generation and Industrial Processes" and "Advancing University Level Education on Heliostat Design and Operation," focus on accomplishing this set of objectives and are the focus of this article.

When taken together, the trend reveals a mismatch between the increasing recognition of federal agencies of CSTP being essential toward a decarbonized grid and the marginalized representation of CSTP in engineering curricula. HelioCon's roadmap emphasizes that without targeted educational investment, the corresponding shortfalls from lack of knowledge access will be detrimental to the progress of nationwide CSTP adoption. This article responds to the targeted RTE gap by documenting how Northeastern University is taking both deliberate and systemic action to embed CSTP content across nine key courses, from first-year engineering classes to the final year capstone engineering class and graduate-level courses. In doing so, Northeastern University aligns itself with the broader workforce and educational objectives outlined by SETO, the DOE, and HelioCon, establishing a replicable and

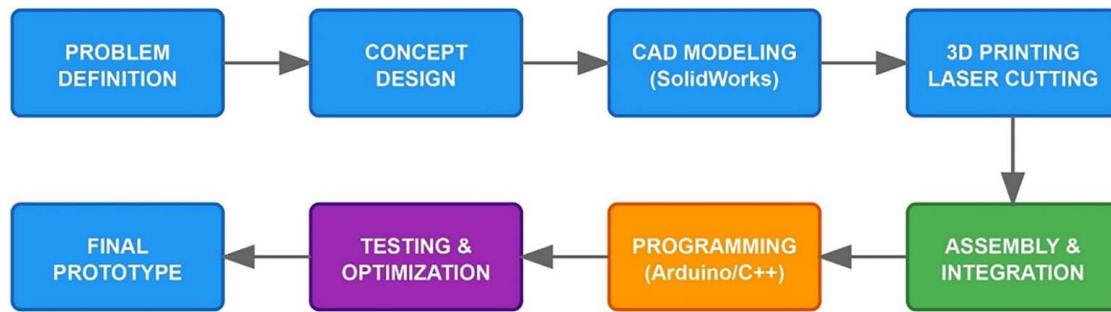


Fig. 1 Engineering design process flow

referenceable model for other institutions seeking to better equip future engineers with critical CSTEP knowledge.

These courses are: GE1501 and GE1502 Cornerstone of Engineering, ME3460 Robot Dynamics and Control, ME4550 Mechanical Engineering Design, ME4555 Systems Analysis and Control, MEIE4701 and MEIE4702 Capstone Design 1 and 2, ME5680 Applications of Concentrating Solar Thermal Power, and EMGT6305 Financial Management for Engineers.

GE1501 and GE1502 Cornerstone of Engineering

Introduction and Objective. The Heliostat Model Assembly activity represents a significant hands-on learning experience within Northeastern University's Cornerstone of Engineering curriculum. This activity bridges theoretical knowledge of solar energy systems with practical engineering design and construction, providing freshman engineering students with exposure to CSTEP technology while developing essential engineering skills including 3D modeling, prototyping, and system integration.

The Heliostat Model Assembly activity is designed to introduce students to solar concentration principles through the construction of a functional heliostat prototype. A heliostat is a device that tracks the sun's movement throughout the day and reflects sunlight onto a specific target, forming the foundation of concentrated solar power systems used in utility-scale renewable energy generation.

The primary objective of this activity is to provide students with a comprehensive understanding of how heliostats enhance solar power systems through practical, hands-on engagement. Students are challenged to construct a miniature heliostat model that demonstrates the core functionality of real heliostat systems used in commercial solar power plants.

Engineering Design Process. The activity requires students to integrate multiple engineering disciplines and technologies. The construction process involves:

Materials and components:

- Mirrors for light reflection
- 3D-printed structural components
- Laser-cut precision parts
- Motors for automated tracking
- Pivot mechanisms for directional control
- ARDUINO microcontrollers for system control
- Various sensors for sun tracking and positioning

Design and manufacturing process: Students must follow a systematic approach from concept to prototype, utilizing modern engineering tools and methodologies. The process, shown in Fig. 1, includes:

- (1) *Initial design phase:* Students begin with conceptual design, moving from paper prototypes to digital 3D models.
- (2) *Computer-aided design (CAD) modeling:* Detailed design work using SOLIDWORKS to create precise component specifications.
- (3) *Rapid prototyping:* Utilization of 3D printing and laser cutting technologies available in the First-Year Engineering Learning & Innovation Center.
- (4) *System integration:* Assembly of mechanical, electrical, and control systems.
- (5) *Programming:* Implementation of ARDUINO-based control algorithms for sun tracking.
- (6) *Testing and optimization:* Evaluation of prototype performance and iterative improvements.

Educational Integration and Learning Outcomes. The heliostat activity aligns with multiple course objectives outlined in the Cornerstone of Engineering curriculum:

Engineering design process application: Students apply the complete engineering design process, from problem identification through solution implementation and testing. This hands-on experience reinforces theoretical concepts covered in weeks 1–14 of the course schedule.

Technical skills development:

- *CAD and 3D modeling:* Students develop proficiency in SOLIDWORKS, creating detailed technical drawings and 3D assemblies.
- *Programming:* Implementation of control algorithms using ARDUINO and C++ programming concepts learned earlier in the course.
- *Manufacturing:* Practical experience with 3D printing and laser cutting technologies.
- *System integration:* Understanding of how mechanical, electrical, and software components work together.

Communication and documentation: The activity includes comprehensive documentation requirements, including detailed procedures, design rationale, results analysis, and identification of system inefficiencies with proposed improvements as shown in Fig. 2.



Fig. 2 Required components and deliverables



Fig. 3 Assessment criteria

Assessment and Presentation Requirements. The heliostat activity culminates in both written and oral presentation components as shown in Fig. 3:

Written report: Teams must submit a comprehensive report including:

- Title page with team member identification
- Detailed procedural documentation from initial concept through final prototype
- Complete design specifications and rationale
- Results analysis and performance evaluation
- Critical assessment of system inefficiencies
- Proposed design improvements and modifications
- SOLIDWORKS simulation tutorial and design documentation

Oral presentation: A 10-min presentation utilizing multimedia tools to communicate:

- Project summary and heliostat model overview
- Key insights gained about the engineering design process
- Technical challenges encountered and solutions developed
- System performance analysis and identified limitations
- Recommendations for future improvements

Integration With Course Structure. The heliostat activity occurs during week 10 of the fall and spring semester, strategically positioned when students have developed sufficient background in

- Engineering design methodology (weeks 1–7)
- SOLIDWORKS proficiency (weeks 5–8 graphics curriculum)
- ARDUINO programming (weeks 1–10 SparkFun activities)
- C++ programming fundamentals (weeks 1–7 programming curriculum)

This timing ensures students possess the necessary technical skills while providing a capstone experience that synthesizes multiple course components.

Broader Educational Impact. The heliostat activity serves multiple educational purposes beyond technical skill development:

Sustainability awareness: Students gain a practical understanding of renewable energy technologies and their engineering challenges, fostering awareness of sustainable engineering practices.

Systems thinking: The activity requires students to consider how individual components interact within a larger system, developing crucial systems engineering perspectives.

Innovation and creativity: Students must solve complex technical challenges creatively, often developing unique solutions to tracking, positioning, and control problems.

Team collaboration: As a team-based activity, students develop collaborative skills essential for professional engineering practice.

Conclusion. The Heliostat Model Assembly activity, shown in Fig. 4, represents an exemplary integration of theoretical knowledge with practical application. By combining renewable energy technology with hands-on engineering design, students gain valuable experience in problem-solving, technical communication, and system integration. The activity successfully bridges multiple engineering disciplines while introducing students to emerging technologies in sustainable energy systems.

This comprehensive approach to engineering education, emphasizing both technical competency and practical application, prepares students for advanced engineering coursework and professional practice. The heliostat activity demonstrates how well-designed hands-on experiences can enhance student engagement while developing essential engineering skills and sustainable technology awareness.

The success of this activity depends on continued access to modern fabrication facilities, updated equipment, and integration with evolving renewable energy technologies, ensuring students remain current with industry practices and emerging technological trends.

ME3460 Robot Dynamics and Control

Introduction and Objective. Multi-degree-of-freedom of Heliostat motivated curriculum development in our Robot Dynamics and Control (ME3460) course. The primary objective in ME3460 is to recognize Heliostat as a kinematic system, resembling a robotic manipulator and thus leveraging forward/inverse kinematics (FK/IK) to explain Heliostat motion, or prescribe a desired motion. The developed curriculum aims to build on FK/IK concepts by placing them in the context of Heliostat operation, thereby providing students with direct exposure to CSTP technology.

Curriculum Development in ME3460. Two core skills needed to master the motion of manipulator-type robotic systems are FK and IK. These two concepts are thoroughly taught in ME3460. To this end, treating a Heliostat as a robotic system, two homework questions were designed to address FK and IK. Specifically, these questions were focused on:

- **FK:** The corners A, B, C, and D of a Heliostat (Fig. 5) may house sensors to measure light intensity; hence, it is critical to know the positions of these corners in the reference frame. This homework question is motivated by this knowledge and asks the students to consider a Heliostat with two degrees-of-freedom, in elevation and azimuth directions. Given the dimensions of a Heliostat as well as the elevation and azimuth angles, the students are asked to utilize FK tools to calculate where the corners A, B, C, and D are in the reference frame.
- **IK:** For motion control purposes, IK presents critical knowledge, building upon FK. To this end, students in this assignment are asked to calculate what elevation and azimuth angles are needed to render the Heliostat in a particular “pose,” that is, the Heliostat corners are positioned to desired locations in the reference frame.

Educational Integration and Learning Outcomes. The assignments around the heliostat helped support several learning outcomes. In ME3460, students demonstrated knowledge in:

- **FK:** Understanding of multiple moving frames and their geometric relationship to the reference frame; understanding of rotation and translation in describing the relationship between two frames; understanding of Denavit-Hartenberg notation; construction of homogeneous transformation



Fig. 4 Course learning objective integration

matrices to express the coordinate transformations between two frames.

- *IK*: Utilization of FK knowledge along with homogeneous transformation matrices to back calculate the formulation expressing desired elevation and azimuth angles in terms of given locations of the Heliostat corners.

While the designed assignments in ME3460 were at the undergraduate level, instructors teaching at the graduate level can potentially repurpose these assignments for more advanced-level students. Overall, the assignment on FK requires background on the basics of vector calculus, linear algebra, homogeneous transformation, and the concept of Denavit–Hartenberg. These concepts in

combination with lectures on IK will suffice to assign the homework problem on IK.

Assessment. Student work was assessed by grading student submissions in Gradescope. Utilization of Gradescope permitted a refined understanding of how well the students solved the problems and in what areas they need improvement.

For ME3460, in Spring 2025, the course was offered in one section, with an enrollment of 42 students. Student performance in each of the areas was as follows:

- *FK*: In this assignment, 42 students submitted work. The average percentage of points students earned in the Heliostat

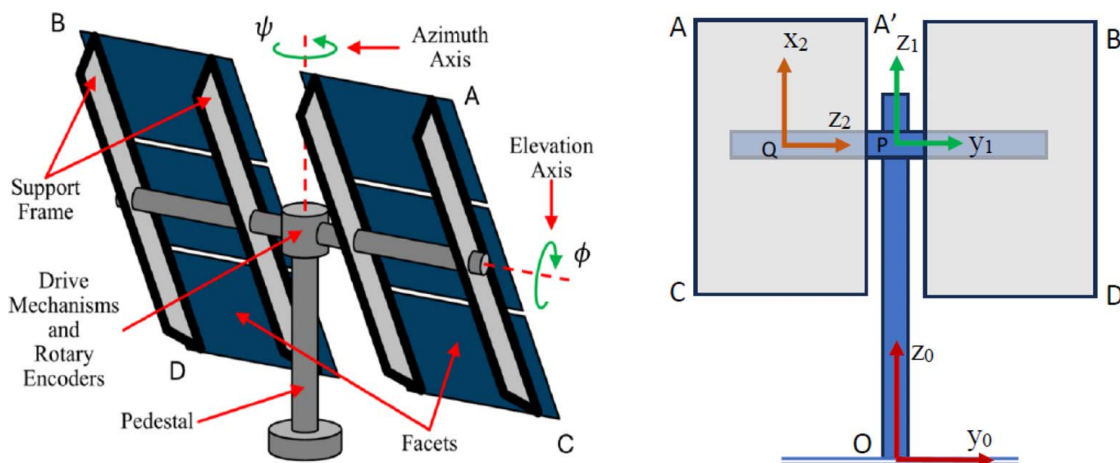


Fig. 5 Left: rear view (image credit: [25]). Right: front view; simplified model of the heliostat.

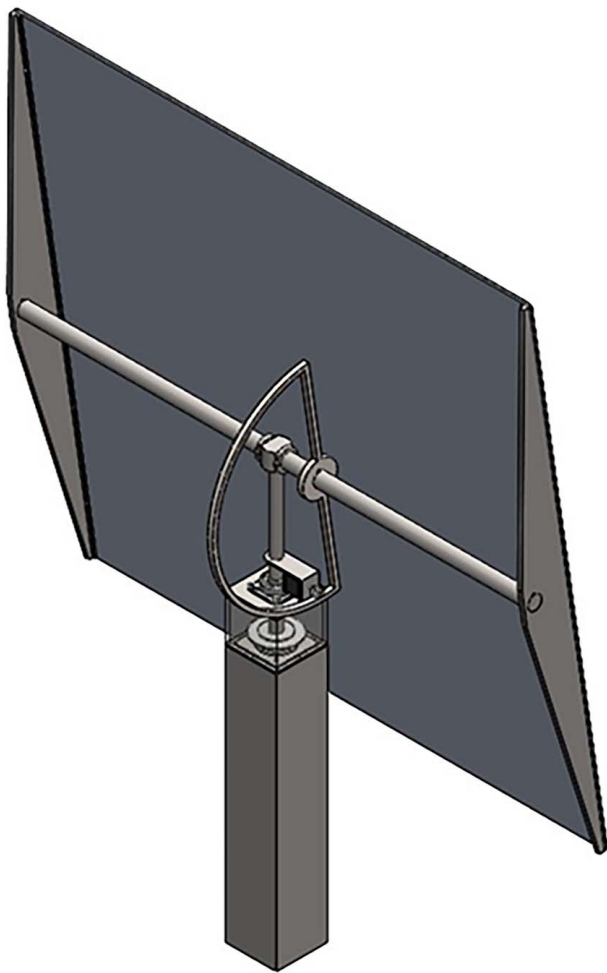


Fig. 6 First heliostat project assembly

question was 86%. Seven students scored full points, and 29 of them 80% or higher. One of the common errors was due to sign mistakes when filling out the Denavit–Hartenberg table. This error then propagated into subsequent steps. While students showed they fundamentally understood how to fill out the table, they missed the correct sign convention.

- *IK*: In this assignment, 40 students submitted work. The average percentage of points students earned in the Heliostat question was 94%. The first part of the assignment was related to a general parametric solution, which all the students got correctly. In the second part, where the students were asked to compute the solution, three students lost points, with minimal errors such as using sine versus cosine, or using the arctan function instead of the arctan2 function.

Broader Educational Impact. Heliostat technology offers many opportunities for efficient and sustainable energy generation. To realize these opportunities, it is critical that engineers from multiple disciplines combine their expertise to perfect such technology. For example, it is critical to accurately measure the sun's incidence angle to then automatically control the Heliostat elevation and azimuth angles to effectively focus the sunlight onto the collector tower. While this aspect emphasizes the need for sensing and control, Heliostat technology in addition requires precise electromechanical design from materials, machine design, and electronics to a thorough understanding of how the culmination of these disciplines influences heat transfer and ultimately electricity generation. Overall, Heliostat technology provides a strong foundation upon which robotics concepts can be motivated in engineering education.

To this end, educators can create impactful teaching materials covering vector algebra, transformation matrices, kinematics in multiple frames, forward and inverse kinematics, as well as feedback control combined with robotic trajectory tracking. These topics can be put in the context of Heliostats to not only teach key engineering principles but also to train the next-generation engineers on the fundamentals of Heliostats, and in general on sustainable energy generation.

Conclusion. We have designed two homework problems addressing key areas in robotics, put in the context of Heliostats. These problems were assigned to students in ME3460 Robot Dynamics exposing 42 engineering students to the concept of Heliostats and how two key concepts, FK and IK, learned in this course could help us understand, analyze, and investigate the kinematics of Heliostats. Future work will focus on creating additional homework problems.

ME4550 Mechanical Engineering Design

Course Overview and Objectives. ME4550: Mechanical Engineering Design is a four-credit upper-level undergraduate course offered at Northeastern University. This course aims to act as a pivotal point for students as they move from basic engineering concepts to real-world mechanical design challenges. Emphasizing open-ended design methodologies, ME4550 assists students in rigorously applying stress analysis, failure theories, and fatigue considerations when designing machine components. Students work with a variety of mechanical parts, including shafts, gears, springs, bearings, threaded fasteners, and bolted joints, fostering a comprehensive understanding of how theoretical concepts are utilized in real mechanical systems.

A key aspect of ME4550 is the focus on collaborative, team-oriented design projects that simulate industry-standard design cycles. Students utilize the analysis techniques they have learned to conceptualize, model, and assess mechanical systems, ultimately resulting in the development of design portfolios that showcase both technical skills and the reasoning behind their design choices.

CSTP Project Integration and Learning Objectives. To support the initiatives of the Department of Energy and the Heliostat Consortium (HelioCon) aimed at developing heliostat design expertise in US academic institutions, two student groups were assigned projects focused on heliostat design for the Spring 2025 semester. These projects met important course goals, which included:

- Investigating commercial product architectures along with their performance standards and
- Implementing the complete design process of a mechanical system, including analysis, modeling, and documentation.

This project introduced students to the broader field of CSTP by requiring them to create mechanical designs pertinent to advanced heliostat systems.

Heliostat Design #1: Spur Gear-Driven 9 m² Mirror System. The first group developed a heliostat, depicted in Fig. 6, featuring a reflective area of 9 m² that employs 3M SMF 1100 film affixed to a backing plate made of 12 mm-thick aluminum. Their design emphasized precise solar tracking using a dual-axis drivetrain, which includes custom antibacklash spur gear assemblies for both azimuth and elevation adjustments. The drivetrain also featured electromagnetic braking systems to maintain positional stability.

The structural framework was made from A500 structural steel and engineered to withstand wind gusts of up to 60 mph for durations of 3 s. Key load-bearing components, such as the 0.6 m tall, 60 mm diameter azimuth shaft and the 3 m long, 80 mm diameter mirror frame shaft, were designed with a minimum mechanical safety factor of 1.5. The project's durability in harsh environments



Fig. 7 Second heliostat project assembly

was taken into account, with material choices and mechanical layout assessed for effective long-term operation in sandy and desert settings. Students performed comprehensive loading analyses on three essential parts: the azimuth shaft, the mirror frame shaft, and the mirror backing plate. These analyses guided geometric design decisions and confirmed adherence to safety and performance requirements.

Heliostat Design #2: Precision Lead-Screw Array for Sun Tracking. The second group developed an innovative design that substituted conventional gear-based tracking systems with a three-lead-screw arrangement, each featuring high-precision ball joints and driven by female-threaded motors. This approach provided omni-directional positioning through the coordinated actuation of the lead screws and evenly distributed the mirror's weight to reduce deflection.

As illustrated in Fig. 7, the mirror system included a 1 m^2 reflective surface, supported by a welded metal frame and secured to a tripod base that was bolted into a concrete foundation. The structure was designed for high-wind stability, with the lead-screw setup providing both a mechanical advantage and precise angular control. The implementation of a low-power (1 hp) motor synchronized with the gradual, predictable movement of the sun enabled efficient and cost-effective operation.

Students performed structural and motion analyses of the lead-screw assembly, focusing specifically on load uniformity, motor torque requirements, and environmental stability. This project familiarized students with new design concepts in heliostat tracking that emphasize precision and simplicity rather than conventional gear-driven systems.

Educational Impact and Relevance to CSTP. By focusing on two primary design initiatives related to heliostat system development, ME4550 effectively incorporated CSTP-related technical challenges into the mechanical engineering curriculum. These projects allowed students to gain practical experience in designing mechanical subsystems for solar applications, enhancing their skills in:

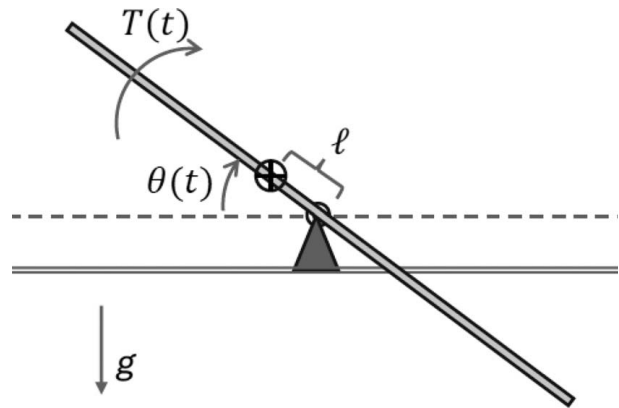


Fig. 8 A single-degree-of-freedom heliostat with mass imbalance, subjected to gravity and actuated by an input torque

- Selecting and analyzing mechanical components while considering environmental constraints
- Controlling motors with precision for renewable energy uses
- Assessing structural integrity and material performance in the face of wind loading
- Developing system-level thinking for scalable deployment in the field

These design opportunities reinforce the Department of Energy's commitment to growing the pipeline of heliostat engineering talent. Additionally, they provide a reproducible framework for integrating CSTP content into fundamental mechanical engineering courses across the nation.

ME4555 Systems Analysis and Control

Introduction and Objective. Dynamical modeling, analysis, and control needs for Heliostats motivated curriculum development in our Mechanical Engineering program for ME4555 System Analysis and Control course. ME4555 is a core course in the program, taken mostly by junior and senior level students each semester. The developed curriculum aims to build on course materials, while putting these materials into context with Heliostats providing students with exposure to CSTP technology. The primary objective in ME4555 is to emphasize the importance of modeling, dynamic response, and motion control.

Curriculum Development in ME4555. ME4555 at Northeastern is built upon three main areas: modeling, analysis, and control, taught sequentially, each taking up approximately a third of a semester. A homework problem has been designed to emphasize each of the areas. Specifically, these questions were focused on:

- *Modeling:* In this assignment, the students were provided with a single-degree-of-freedom Heliostat model with a mass imbalance, subjected to gravity, actuated by a torque input and undergoing angular displacement shown in Fig. 8. The students were asked to develop the nonlinear equation of motion and linearize the equation about a given equilibrium.
- *Analysis:* In this assignment, the students were asked to incorporate a DC motor at the hinge in Fig. 8, develop the equations of motion in the linear case, and obtain the transfer function that describes the relationship between the motor input voltage and the angular displacement. Students were next tasked to study the time response of angular displacement for a given voltage profile, using MATLAB.
- *Control:* In this assignment, the students were asked to design a control logic based on a proportional-integral-derivative (PID) controller that renders the Heliostat motion in a particular manner.

Educational Integration and Learning Outcomes. The assignments around the heliostat helped support several learning outcomes. In ME4555, students demonstrated knowledge in:

- *Modeling:* Development of free-body diagrams, implementation of Newton's second law of motion, recognizing that the dynamics is nonlinear, and implementing the small motion assumption to linearize the dynamics.
- *Analysis:* Integrating motor dynamics into Fig. 8 with additional equations of motion, recognizing that the dynamics is linear time-invariant hence it can be converted to the Laplace domain, successfully manipulating the Laplace equations to derive the transfer function, and implementation of the transfer function in MATLAB.
- *Control:* Constructing a feedback control loop, incorporating PID controller gains as parameters into the system transfer function, implementing pole placement ideas to identify the numerical values of the controller gains, and implementing root locus concepts to investigate how changes in a control parameter could affect the control performance.

While there exist similar courses in the US in both mechanical, aerospace, and electrical engineering programs, these courses may vary in terms of coverage and the sequence of the materials delivered. Overall, the assignment on modeling should be considered when a course covers mathematical modeling. The assignment on analysis could be utilized in systems and/or controls courses, where the goal is to investigate "open-loop" response by building upon Laplace transforms and transient dynamics. Lastly, the assignment in controls requires additional background on feedback control diagrams, effects of pole locations on system dynamics, and linear stability.

Assessment. Student work was assessed by grading submissions in Gradescope, which permitted a refined understanding of how well the students solved the problems and where they needed improvement. In Spring 2025, the course was offered in three sections, with enrollments in the order reported: 58, 35, 56, totaling 149 students. Student performance in each of the areas was as follows:

- *Modeling:* A total of 144 students submitted the assignment, and the average score on the Heliostat problem was 90%. About 54% of students answered the question correctly, while 35% did not correctly identify the nonlinear term due to mass imbalance. Remaining errors were limited to a maximum of 6% of students.
- *Analysis:* A total of 138 students submitted the assignment, and the average score on the Heliostat problem was 86%. About 45% of students answered the question correctly. Common errors included missing time simulations (30% of students), incorrect identification of the steady-state value (23%), and contradictions within submitted solutions (9%).
- *Control:* A total of 135 students submitted the assignment, and the average score on the Heliostat problem was 91%. About 47% of students earned full points. The most challenging part involved root locus concepts: 47% of students lost points for not finding the correct condition on the derivative controller gain, and 21% misread pole locations from the root locus plots.

Broader Educational Impact. Heliostat technology offers many opportunities for efficient and sustainable energy generation. To realize these opportunities, it is critical that engineers from multiple disciplines combine their expertise to perfect such technology. For example, it is critical to accurately measure the sun's incidence angle to then automatically control the Heliostat elevation and azimuth angles to effectively focus the sunlight onto the collector tower. While this aspect emphasizes the need for sensing and control, Heliostat technology in addition requires precise electro-

mechanical design from materials, machine design, and electronics to a thorough understanding of how the culmination of these disciplines influences heat transfer and ultimately electricity generation. Overall, Heliostat technology provides a strong foundation upon which multidisciplinary engineering development can be motivated in engineering education. To this end, educators can create impactful teaching materials in courses involving mathematical modeling, systems analysis, mechatronics, and control design in the context of Heliostats to not only teach key engineering principles but also to train the next-generation engineers on the fundamentals of Heliostats, and in general on sustainable energy generation.

Conclusion. We have designed several homework problems addressing key areas in mathematical modeling, system analysis, and controls in the context of Heliostats. These problems were assigned to students in M 4555 System Analysis and Control exposing 149 engineering students to the concept of Heliostats and how materials learned in the course could help us understand, analyze, and investigate controlled motion of Heliostats. Future work will focus on creating additional homework problems addressing mechanical modeling, comparison of various controllers for their tracking performance, ramp tracking and steady-state error calculations, and frequency response.

MEIE4701 and MEIE4702 Capstone Designs 1 and 2

At Northeastern University, the Capstone Mechanical Engineering Design is the final required course for the bachelor's degree in Mechanical Engineering; it provides the opportunity for students to integrate their curricular and experiential journeys into a multisemester team project with a real-world outcome. The Capstone experience applies the engineering sciences and other knowledge domains to the design of a system, component, product, process, and/or set of research inquiries. The students bid for or develop their team's particular design project with the approval of the appropriate faculty. In the project assignment process, design teams are self-formed or configured of students with similar interest areas. Each project includes the use of open-ended problems, development and application of research and design methodologies, formulation of design problem statements and specifications, generation and consideration of alternative solutions, along with safety, usability, and feasibility considerations, and detailed system descriptions. It also includes realistic constraints such as economic factors, sustainability, along with global and social impact, to name a few. Throughout the Capstone experience, students are also challenged to think and act as a "team" and to consider how notions of diversity, equity, inclusion, and belonging affect their decisions, actions, and results.

During the two-year duration of this work, six student capstone teams were launched to investigate heliostat-related innovations. These Capstone projects included:

Deformable Heliostat, Phase 1 Project. Typically, heliostats consist of a reflective surface and two actuators that tilt the mirror as the sun moves throughout the day to continuously concentrate light on a stationary target. Current heliostats are not on track to meet the Department of Energy's 2030 goal of 5¢/kWh, so this team set out to explore how a continuously deforming reflective surface can help meet that goal.

The Deformable Heliostat, as shown in Fig. 9, features an acrylic mirror that is pulled into a concave shape using a linear actuator. This curvature increases the concentration and intensity of light as opposed to the standard flat heliostat. Upon multiple iterations and testing, the team determined that this deformable model was successful by the following metrics: increasing concentration up to 45.72%, minimizing the effects of aberrations, and increasing intensity by a factor of 7.5. This model paves the way for further research into deformable solutions in heliostat technology and has the potential to be used in utility-scale heliostat arrays.

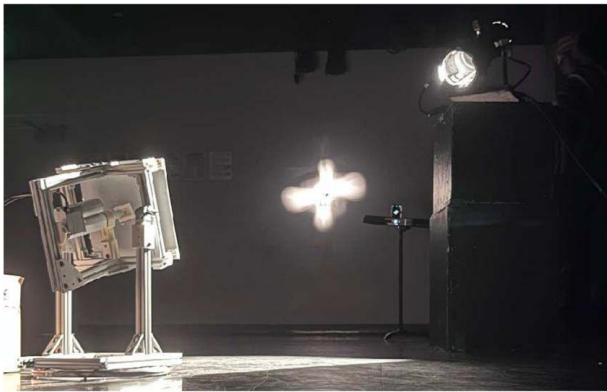


Fig. 9 Deformable heliostat phase I

Deformable Heliostat, Phase 2 Project. Central receiver systems (CRS) use thousands of heliostats, or sun-tracking mirrors, to concentrate light onto a central tower to produce electricity. Current reports estimate CRS could see a 50% increase in overall efficiency simply from design and cost improvements of its heliostats. To achieve this goal and help further the transition to renewable energy, this team designed a different heliostat that also used deformation of the mirror surface as an alternative to traditional sun-tracking methods.

This heliostat features an acrylic mirror that can be manually deformed at each corner, shown in Fig. 10. This deformation creates off-axis parabolic shapes which can shift the focal point of its reflection as the sun moves over certain distances throughout the day. The curvature of the mirror also increases the concentration of light as opposed to the standard flat heliostat. Through iteration, simulation, and testing, this team determined that a deformable heliostat can complement traditional methods to increase efficiency and concentration of a CRS plant.

Heliostat Sun Tracker Project. Heliostats are movable mirrors that function by reflecting concentrated sunlight at a target to create thermal energy and produce electricity. They are used in a wide array of concentrating solar thermal power (CSTP) plants and follow a programmed movement throughout the day. This open-loop system can lead to the misalignment of the sunlight rays on the target, and these tracking errors decrease the overall efficiency of the heliostat.

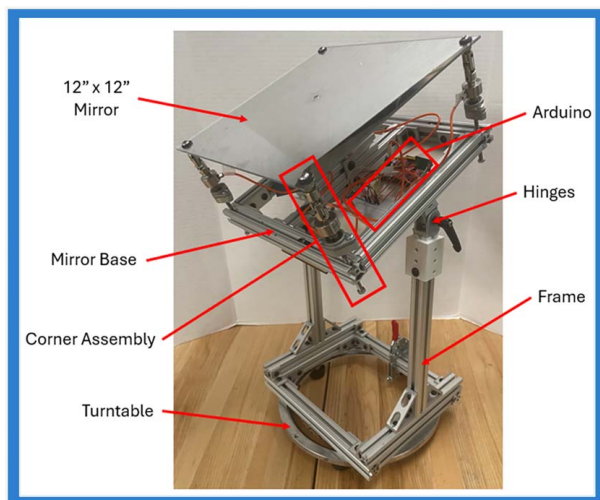


Fig. 10 Deformable heliostat phase II

A possible solution includes employing a closed-loop tracking system, shown in Fig. 11, where the light values from photoresistors are used to correct tracking errors. In this phase of the project, the team designed a mirror that could track the position of the sun throughout the day, a first step to achieving this goal. This was accomplished with the assistance of stepper motors connected to the heliostat's metal frame. Changes of the sun's azimuth and elevation angles were followed diurnally. However, this system did not reflect sunlight on a target.

Heliostat Sun Tracker and Tower Tracker Project. Existing CSTP fields use an open-loop system, relying on astronomical data to focus the sunlight. However, if a heliostat's position were to change due to weather or environmental conditions, open-loop heliostats have no way to check if they are aiming at the receiver. Therefore, this team developed a closed-loop heliostat system to improve the accuracy and efficiency of heliostats. To achieve this goal, three primary units, a solar tracker that detects the location of the sun, a self-moving mirror that reflects the light to the target, and a receiver that acts as a locating beacon for the mirror and a target for the reflected sunlight, are shown in Fig. 12.

The solar tracker's algorithm uses feedback from four lux sensors to find the azimuthal and zenith angles of the sun; it then sends those angles to the mirror, which uses those inputs to calculate the bisecting vector between the sunlight and the receiver to reflect the light at the target. To improve the precision of solar tracking, a cap was added to the solar tracker, which blocked the sunlight unless the rays were normal to the lux sensors within 0.1 deg. Limit switches and proximity sensors were added to both the mirror and the tracker to decrease error accumulation over time, using a homing sequence. Lastly, a beacon was added to the receiver, which the mirror can use to detect its position. It was estimated that, at scale, if the mirrors are ideally positioned, then the power production of the plant could potentially increase.

Solar Dish—Biomass Pyrolyzer Project. Rising global temperatures have caused an increase in forest fires devastating neighborhoods, depleting natural resources, and harming wildlife. These



Fig. 11 Closed-loop heliostat system

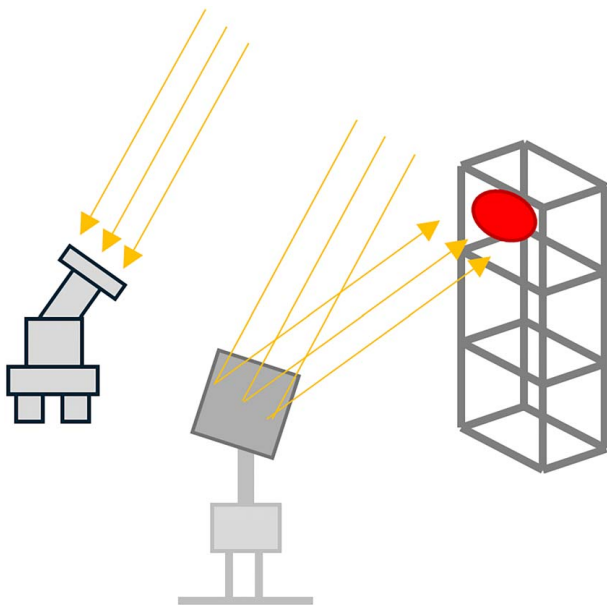


Fig. 12 Heliostat tower-beacon tracking system diagram

fires can cause such damage due to excess biomass found on forest floors. Therefore, this project aims to mitigate the harm caused by these fires by incentivizing the cleanup of pine needles from forest floors. A solar pyrolyzer, shown in Fig. 13, was built to convert this biomass to a useful resource. The team adopted a concentrating solar dish and designed a feeder system to control the flowrate of chopped pine needles via an auger. The collected solid product consisted of charred pine needles. Outdoors testing showed that the new system could reach a temperature of at least 550 °C, well above the necessary minimum needle pyrolysis temperature of 300 °C to generate biochar.

Solar Trough—Biomass Pyrolyzer Project. This project aims to design, build, and test a uniaxial rotating parabolic solar



Fig. 13 Solar pyrolyzer dish



Fig. 14 Parabolic trough collector

thermal trough to pyrolyze dried pine needles into biofuel products including biochar, bio-oil, and biogas. The main advantage of the trough over the dish is that it enables continuous feeding of the biomass. The main disadvantage is that it attains lower temperatures.

A parabolic trough collector shown in Fig. 14 reflects sunlight onto a focal tube facilitating a seamless feeding process and a moderate temperature pyrolysis process that can yield the highest ratio of biochar relative to other products (bio-oil and biogas). The system consists of the parabolic trough collector system and its mechanical fixtures, a continuous feeder mechanism to move the pine needles through the pyrolysis chamber, and a collection device for the bio-oil and biochar produced. By rotating the trough to follow the relevant motion of the sun throughout the day, the production of biochar was optimized. This allowed for the greatest conversion of solar energy to the heat needed for the thermal pyrolysis of the pine needles at the focal tube of the reflective parabolic trough of the pyrolyzer. The maximum attained temperature in the tube was 350 °C.

ME5680 Applications of Concentrating Solar Thermal Power

Introduction. Applications of Concentrating Solar Thermal Technologies is a graduate-level course designed to provide an in-depth understanding of the design, performance, and real-world applicability of the CSTP system. With global interest growing in clean and dispatchable energy technologies, CSTP has emerged as a niche but crucial area of innovation and deployment. This course helps to equip students with the tools to analyze, simulate, and optimize CSTP systems by integrating thermofluidic principles, solar resource forecasting, geometric optics, and material science.

Students will explore a wide range of CSTP components—from heliostats and parabolic troughs to receivers and thermal energy storage systems, and compare their performance and feasibility against other renewable energy technologies like photovoltaic systems. The course emphasizes technical competence as well as the practical evaluation of solar resource availability and system feasibility in diverse geographic contexts.

ME5680 is one of the few graduate courses in the US devoted solely to CSTP system analysis and design, developed as part of DOE-supported efforts to expand CSTP education.

Course Delivery and Content Breakdown. ME5680 is delivered through two weekly 100-min lectures across a 14-week semester, combining theory with real-world design applications. The course is highly interactive and project-based. Each student selects a specific geographic location—often their hometown—and performs a detailed feasibility analysis for CSTP deployment at that site. This includes calculating direct normal irradiance (DNI), sunrise-to-sunset solar availability, collector incidence angles, tracking optimization, and energy capture potential. Advanced simulations incorporate shaping and pointing errors, mirror reflectance properties, and antireflective coatings based on American Society for Testing and Materials (ASTM) standards.

Evaluation is based on class participation (15%), homework (25%), take-home exams (25%), and a final term project (35%), allowing students to demonstrate both theoretical knowledge and applied engineering judgement. A week-by-week content breakdown is provided below.

The chosen textbook is: *Concentrating Solar Thermal Energy: Fundamentals and Application*, by Gilles Flamant, Wiley, 2022, ISBN: 9781789450798.

Week 1	Introduction: what are solar concentrating power systems (CSTP); history of concentrated solar applications. Review: system definitions, concentration factors, combined convection, and thermal radiation losses.
Week 2	Type of CSTP applications, current developments, emerging new generation CSTPs current cost factors and trends. Introduction to Sun-Earth system.
Week 3	Prediction of Sun's position, sunrise/sunset times. Prediction of air mass, attenuation of radiation.
Week 4	Prediction of terrestrial incident solar radiation. Key metrics for solar energy measurement; Sun's angle, ISO DNI, DNI of solar disk, circumsolar radiation. Solar radiation measurement techniques and difficulties.
Week 5	Solar radiation forecasting techniques. Defining the concentrating factor, the maximum reachable temperature in a concentrating system, and the assessment of concentrating errors. Quantification of parabolic trough concentrators.
Week 6	Optical quantification of heliostat fields, simulation techniques for heliostat fields. Introduction to solar receivers and solar receiver types.
Week 7	Thermal analysis of parabolic trough receivers, analysis of absorber tube with a protective glass, governing equations, and solution strategies
Week 8	Characteristics of parabolic trough receivers, finding temperature distribution via iterations. Review of radiative exchange via radiosity and view factors.
Week 9	Thermal model for cavity receivers, and solution strategies. Take-home Exam 1.
Week 10	Energy flow rates and their distribution in a cavity receiver. Influence of cavity design on the optical efficiency of cavity receivers. Properties of heat transfer fluids in CSTP systems. Estimation of convective transfer coefficients and pressure drops based on the choice of heat transfer fluids. Thermal energy storage (simulation) and cost factors.
Week 11	Molten salts, liquid metals, and gases as heat transfer fluids, and their impact on convective transfer coefficients. Introduction to optical metrics within the relevant spectral range.
Week 12	Achieving desired optical functions; transparent layers, absorptive layers, antireflective coatings, selective coatings
Week 13	Introduction to thermal energy storage systems. Molten-salt storage systems. Thermocline systems, steam accumulators, and storage systems based on phase change materials.
Week 14	Hybrid PV-CSTP systems. Review of the photovoltaic effect. High temperature PV-CSTP receivers. Strategies based on spectral splitting. Emerging PV-CSTP hybrid strategies.
Week 15	Final project.

Conclusion. By the end of ME5680, students will have a thorough technical and practical understanding of how CSTP systems operate, how their performance is quantified, and how they can be realistically implemented in various settings. The course fosters the ability to critically assess CSTP's advantages in energy storage, hybridization with PV, and integration with advanced industrial processes like biogas manufacturing. Graduates of this course will be well-prepared to contribute to the advancement of solar thermal technologies in both academic and industrial contexts.

EMGT6305 Financial Management for Engineers

Introduction. The Financial Management for Engineers (EMGT6305) course is an elective course at the Mechanical and Industrial Engineering Department at the School of Engineering at Northeastern University. This course used to be offered once a year, but after my involvement with this course, the popularity of the course has steadily increased among graduate students in different majors at the School of Engineering due to the word of mouth among students. In recent years, this course has traditionally been offered every semester, including summer-one semester in both the traditional (in-person) and online format. The interesting aspect of the online version of this course is a bit different.

Course Delivery. Basically, I lecture and cover the course material in the on-ground course with the presence of students in the course. At the same time, my lecture is being recorded and will be available to the online section early in the morning of the following day. Since the department is very supportive of me and this course, depending on the enrollment of the course, which at its peak time had 152 students enrolled in this course, and I, along with the support and assistance of four different teaching assistants (TAs) was able to administer this course. In selecting the TAs for this course, I follow a rigorous process to identify and select them. One of the requirements for consideration for a TA job is the ideal candidate should achieve a score of 100 either in the mid-term and ideally in the cumulative final exam.

Course Objectives and Structure. The primary objectives of the course are to provide engineering students with an understanding of financial management, strategies, tactics, and techniques to develop the skills and to understand the financial implications of a wide variety of business and engineering decisions in different types of business organizations.

It is a well-known assumption and practice that the prerequisite of the first finance course is financial accounting. However, in this course, since none of the students had taken financial accounting before registering for this course, it is a challenging situation for me to make sure that students in this course become familiar with the basic principles of financial accounting. In doing so, I cherry-pick certain aspects of financial accounting along with their real-life applications in corporate America.

This way, students will become familiar with the financial accounting concepts in the first four sessions or about 14 h at the beginning of this course, which will help students to digest many concepts in the field of finance later. Along the way, at the beginning of every session, many major economic and financial news were discussed in class, by giving students ample time to ask questions. In the process, students are reminded that as the potential leader in different positions in a corporation, they should be familiar with both fiscal and monetary policies and be able to distinguish and even predict them under an inflationary and recessionary environment. Along the way, students were reminded about the impact of some political decisions, such as the outcome of a presidential election and its consequences in the execution of both fiscal and monetary policies. In fact, the possibility of having one party in charge of the executive branch and another party in charge of the

Legislative branch has been discussed in class. Most importantly, what would be the impact of those policies or lack if any changes of those policies may have a resounding impact on both domestic and international markets.

The specific segment of this course, which has an absolute relationship with the subject of concentrated solar power (CSTP), mainly rests on the concept of capital budgeting in finance and its different methods. Here, I will introduce students to many challenges that corporations face prior to making a holistic decision on this issue. The process starts with the executive branch and its policy priority (if any) in this area. Students will be reminded about the specific impact of tax policies/incentives and the monetary policy of the Federal Reserve System. This includes the impact of these decisions on the cost of capital for corporations. The issue will be expanded on the interaction of the probability of the occurrence of different incoming annual cash flows, coupled with the impact of specific tax policies, and the retention value of an investment at the end of its useful life. Along the way, the most recent improvement of the technology in this area is discussed in the course.

Concentrated Solar Power Methodology

- Class lecture combined with class discussions about the impact of the following issues:
- Weather, the suitable physical locations
- Technology
- Government (Federal, State, and local) policies and regulations
- Political issues, such as national and local trends
- Economics, such as interest rate, unemployment rate, inflation rate, balance of payment, etc.
- Competition
- International
- Understanding and calculations of the cost of capital
- The introduction and understanding of the concept of capital budgeting and its different methods

Example Project. ABC Company is very committed to using concentrating solar power (CSTP) in its operation.

ABC Company has hired a nationally known commercial real estate company to assist it in identifying 3000 acres of land near the border of Alabama and Florida. The current price of undeveloped land in this part of the state of Alabama or Florida is \$40,000 an acre. The cost of developing a portion of the land and making it commercially available is estimated to be \$20 million. ABC Company is hoping that it will get the State of Alabama or Florida's approval to provide two exit ramps out of the nearby interstate highway to facilitate its investment in this project.

Based on the internal study of ABC Company's Treasury Department, if ABC Company invests \$100 million in this project, then it will realize the following annual savings (Table 1) in terms of cash flow in its operation. The overall outcome of this investment is heavily dependent on how one of the States of Alabama or Florida would partially support ABC Company's efforts in initiating this valuable project. As a result of this consideration, its impact on the annual cash flow will differ substantially. Therefore, as a consultant to the ABC Company, you are asked to offer your advice on implementing which of the following investments.

- Calculate each project's payback period (2 points).

Table 1 Alabama versus Florida CSTP annual project savings

Year	Alabama project	Florida project
1	\$57,000,000	\$38,000,000
2	\$42,000,000	\$65,000,000
3	\$68,000,000	\$76,000,000

- Compute the net present value of each project when the firm's weighted average cost of capital is 8% (2 points).
- Internal rate of return—your choice, based on your answer to part B (2 points).
- Modified internal rate of return—your choice, based on your answer to part B (2 points).
- Discuss how the chance of political events and the passage of a favorable tax rate will impact the above methods (2 points).

Summary

As global energy demand continues to rise, a necessary transition from fossil fuels to more renewable sources must take place. While technologies like PV, wind, hydro, and geothermal play pivotal roles in this shift, CSTP stands out for its potential to provide dispatchable and long-duration thermal storage. Despite its value, CSTP remains underrepresented in US engineering curricula. This article details Northeastern University's comprehensive initiative to close that educational gap by integrating CSTP across nine mechanical engineering courses, from the first-year level to graduate education. The curriculum includes:

- Hands-on heliostat projects in first-year engineering courses (GE1501 and GE1502),
- Kinematics-based heliostat modeling in robot dynamics and control (ME3460),
- Full-cycle heliostat mechanical design projects in Mechanical Engineering Design (ME4550),
- Dynamic modeling and PID control of heliostats in Systems Analysis and Control (ME4555),
- Heliostat and solar receiver innovations in Capstone Design Projects (MEIE1701 and MEIE4702),
- Graduate-level simulation and performance analysis of CSTP systems in Applications of Concentrated Solar Thermal Technologies (ME5680), and
- Assessment of financial and policy-based decision-making related to CSTP investments in Financial Management for Engineers (EMGT6305).

By aligning with US DOE and Heliostat Consortium (HelioCon) goals, Northeastern University serves as a pillar for integrating CSTP education into engineering curricula and aiding in addressing critical workforce and training gaps identified in national roadmaps. The program fosters interdisciplinary learning, hands-on design, systems thinking, and technical communication—helping to prepare the next generation of engineers to lead in the solar thermal energy transition.

Acknowledgment

This work was funded by the Heliostat Consortium for Concentrating Solar-Thermal Power funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office agreement number 10303. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Conflict of Interest

The authors declare that they have no conflicts of interest. This article does not involve research with human or animal participants; therefore, informed consent is not applicable.

Data Availability Statement

The authors attest that all data for this study are included in the article.

References

- [1] Flamant, G., 2022, *Concentrating Solar Thermal Energy*, John Wiley & Sons, Hoboken, NJ.
- [2] National Renewable Energy Laboratory, 2024, "Concentrating Solar Power Basics" [Online]. <https://www.nrel.gov/research/re-csp>, Accessed July 31, 2025.
- [3] Kraemer, S., 2025, "Sandia's Gen-3 Particle-Based CSP Demo to Debut This Fall, SolarPACES," Jun. 4 [Online]. <https://www.solarpaces.org/sandias-gen-3-particle-based-csp-demo-to-debut-this-fall/>, Accessed July 31, 2025.
- [4] Rodat, S., and Thonig, R., 2024, "Status of Concentrated Solar Power Plants Installed Worldwide: Past and Present Data," *Clean Technol.*, **6**(1), pp. 365–378.
- [5] China Solar Thermal Alliance, 2025, "Blue Book of China's Concentrating Solar Power Industry 2024" [Online]. <https://www.solarpaces.org/wp-content/uploads/2025/03/Chinas-CSP-blue-book-2024.pdf>, Accessed July 31, 2025.
- [6] Zhu, G., Augustine, C., Mitchell, R., Muller, M., Kurup, P., Zolan, A., Yellapantula, S., et al., 2022, "Roadmap to Advance Heliostat Technologies for Concentrating Solar-Thermal Power," U.S. Department of Energy.
- [7] Kurup, P., and Turchi, C., 2025, "Initial Investigation Into the Potential of CSP Industrial Process Heat for the Southwest United States," National Renewable Energy Laboratory [Online]. <https://docs.nrel.gov/docs/fy16osti/64709.pdf>, Accessed July 31, 2025.
- [8] Raghavan, K., 2024, "Concentrating Solar-Thermal Technologies for Industrial Process Heat" [Online]. <https://www.energy.gov/sites/default/files/2024-12/itiac-march-2024-raghavan-seto.pdf>, Accessed July 31, 2025.
- [9] Chen, X., Zhang, Z., Qi, X., Ling, X., and Peng, H., 2018, "State of the Art on the High-Temperature Thermochemical Energy Storage Systems," *Energy Convers. Manage.*, **177**, pp. 792–815.
- [10] National Renewable Energy Laboratory, 2024, "Commercial Battery Storage Electricity|2024|ATB|NREL" [Online]. https://atb.nrel.gov/electricity/2024/2023/commercial_battery_storage, Accessed July 31, 2025.
- [11] Kraemer, S., 2021, "Can a New Kind of CSP Be a Game Changer?" SolarPACES [Online]. <https://www.solarpaces.org/can-a-new-kind-of-csp-be-a-game-changer/>, Accessed July 31, 2025.
- [12] U.S. Department of Energy, 2022, "2022 SETO Peer Review—Concentrating Solar-Thermal Power Review Summary" [Online]. <https://www.energy.gov/eere/solar/2022-seto-peer-review-concentrating-solar-thermal-power-review-summary>, Accessed July 31, 2025.
- [13] Kurup, R., Akar, S., Glynn, S., Augustine, C., and Davenport, P., 2019, "Cost Update: Commercial and Advanced Heliostat Collectors," National Renewable Energy Laboratory [Online]. <https://docs.nrel.gov/docs/fy22osti/80482.pdf>, Accessed July 31, 2025.
- [14] Zhu, G., Augustine, C., Farrell, T., Kesseli, D., Tsvankin, D., Yellapantula, S., Zolan, A., et al., 2023, "Heliostat Consortium Annual Report: 2023," U.S. Department of Energy.
- [15] Mitchell, R., Zhou, Y., Grabel, M., Zhu, G., and Sment, J., 2024, "Resources, Training, and Education Under the Heliostat Consortium: Industry Gap Analysis and Building a Resource Database," *ASME J. Sol. Energy Eng.*, **146**(6), p. 064501.
- [16] Rice University, 2025, "Building a Brighter Future, Sustainability Institute" [Online]. <https://si.rice.edu/news/2024/building-brighter-future>, Accessed July 31, 2025.
- [17] Ringle, E., 2025, "DOE Consortium Awards \$3 Million for 6 Projects to Advance Heliostat Technology and Workforce for Commercial Readiness," National Renewable Energy Laboratory [Online]. <https://www.nrel.gov/news/detail/program/2024/doe-consortium-awards-3-million-for-six-projects-to-advance-heliostat-technology-and-workforce-for-commercial-readiness>, Accessed July 31, 2025.
- [18] Heliostat Consortium, 2025, "Heliostat Consortium Annual Report 2024" [Online]. <https://docs.nrel.gov/docs/fy25osti/91036.pdf>, Accessed July 31, 2025.
- [19] You, D., Tatli, A. E., Ghanavati, A., and Metghalchi, H., 2022, "Design and Analysis of a Solar-Energy-Driven Tri-generation Plant for Power, Heating, and Refrigeration," *ASME J. Energy Resour. Technol.*, **144**(8), p. 082105.
- [20] Tatli, A. E., You, D., Ghanavati, A., and Metghalchi, H., 2023, "Insight Into Recompression Brayton Cycle," *ASME Open J. Eng.*, **2**, p. 021023.
- [21] Tatli, A. E., You, D., and Metghalchi, H., 2024, "Optimizing Supercritical Carbon Dioxide Cycles Performance With Respect to Split Ratio and Intermediate Pressure," *ASME Open J. Eng.*, **3**, p. 031026.
- [22] Tatli, A. E., You, D., and Metghalchi, H., 2024, "Effects of Intermediate Pressure and Split Ratio on Supercritical Modified Recompression Cycles Performance," *ASME Open J. Eng.*, **3**, p. 031015.
- [23] You, D., Tatli, A. E., and Metghalchi, H., 2025, "A Brayton Pumped Thermal Energy Storage System Based on Supercritical Carbon Dioxide Recompression Reheating Discharge Cycle," *ASME Open J. Eng.*, **4**, p. 041002.
- [24] Patel, S., Metghalchi, H., and Levendis, Y. A., 2025, "Energy and Exergy Analyses of Power Generation Cycles Using Powdered Iron as a Fuel Source," *ASME Open J. Eng.*, **4**, p. 041021.
- [25] Salgado-Plasencia, Eugenio, Carillo-Serrano, Roberto V., Rivas-Araiza, Edgar A., and Toledano-Ayala, Manuel, 2019, "SCADA-Based Heliostat Control System with a Fuzzy Logic Controller for the Heliostat Orientation," *Appl. Sci.*, **9**(15), pp. 1–18.