Machine Learning for Subsurface Energy Storage: Physics-Informed Neural Networks and Neural Operators

Summer Research Projects 2026

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Preferred Background: Geosciences, Physics, Mathematics, Computational Sciences

Number of Projects: 2 independent projects

Period: Flexible start from April 2026, 6 weeks full-time equivalent

Location: UiO Department of Geosciences in collaboration with SINTEF

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Background and Motivation

The global energy transition requires massive-scale geological storage of hydrogen (H_2) and carbon dioxide (CO_2) in subsurface porous formations. Understanding the complex multiphysics processes, including reactive transport, phase behavior, and geomechanical interactions, is critical for safe and efficient storage operations, particularly in challenging or emerging less-mature environments.

Traditional numerical simulations of these processes are computationally intensive, often taking days or weeks for high-fidelity models. **Physics-Informed Neural Networks (PINNs)** and **Neural Operators** represent a paradigm shift, offering orders of magnitude faster performance while maintaining accuracy by directly encoding physical laws into the learning architecture.

This summer research program offers M.Sc. students the opportunity to work at the cutting edge of scientific machine learning, accelerating subsurface energy research, and contributing to climate change mitigation strategies.

Research Areas

Project 1: Physics-Informed Neural Networks with Constraint Enforcement

Scientific Focus: PINNs solve partial differential equations (PDEs) by incorporating physical laws as loss functions. Recent advances distinguish between:

- **Soft constraints:** Physical laws added as penalty terms in the loss function
- **Hard constraints:** Physical laws strictly enforced through network architecture design

Research Objectives:

- Implement PINNs with uncertainty quantification for coupled reactive transport equations in porous media
- Compare soft vs. hard constraint methods for mass conservation and thermodynamic consistency
- Apply to H_2 or CO_2 injection scenarios with mineral dissolution/precipitation reactions
- Investigate novel loss function weighting strategies and adaptive sampling techniques

Key Innovation Areas:

- Inverse modeling: Infer permeability fields and reaction kinetics from limited monitoring data
- Uncertainty quantification using Bayesian PINNs
- Transfer learning across different geological formations
- Multi-fidelity modeling combining PINNs with sparse high-resolution simulations

Project 2: Neural Operators for Subsurface Energy Applications

Scientific Focus: Neural Operators (e.g., Fourier Neural Operators - FNO, DeepONet) learn mappings between infinite-dimensional function spaces, enabling:

- Mesh-independent predictions
- Resolution-invariant learning
- Rapid solution of parametric PDEs across varying initial/boundary conditions

Research Objectives:

- Develop Neural Operator models for subsurface flow and transport problems
- Train on synthetic and real-field datasets
- Enable real-time forecasting of CO_2 and/or H_2 gas behavior
- Explore Graph Neural Operators for complex geological media

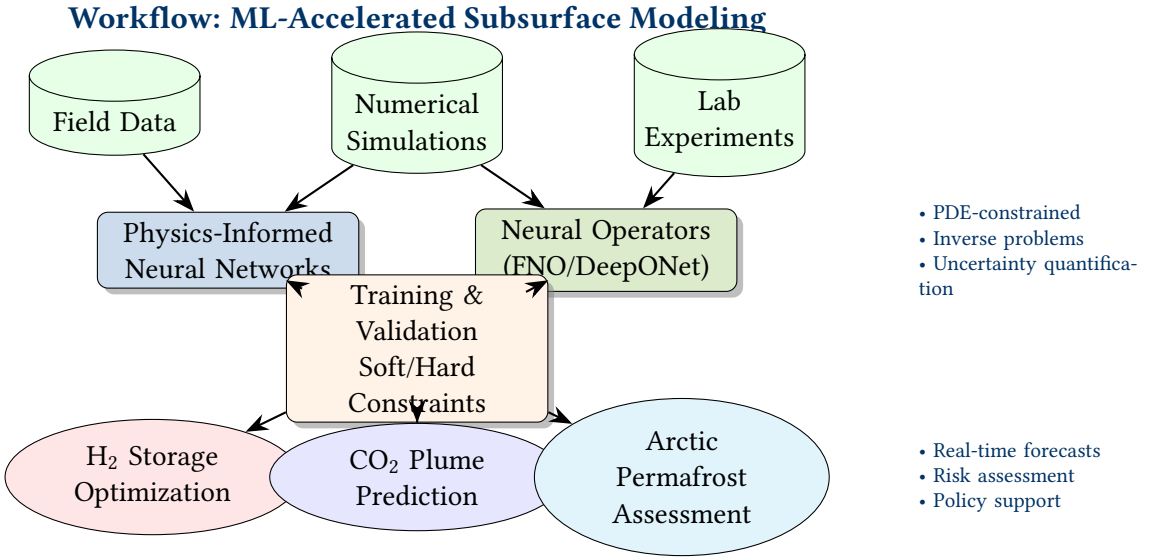


Figure 1: Integrated workflow combining data sources, machine learning architectures, and subsurface energy and environmental applications.

Expected Outcomes and Deliverables

Technical Deliverables:

- Open-source Python codebase (PyTorch) with documentation
- Trained models for at least one subsurface application case study
- Comprehensive benchmark comparing ML methods vs. traditional numerical solvers
- Jupyter notebooks demonstrating model usage and visualization

Scientific Outputs:

- Technical report (20-30 pages) documenting methodology, results, and insights
- Conference-style presentation to research group (and UiO:Energy stakeholders)
- Potential co-authorship on peer-reviewed publication (depending on results)
- Contribution to ongoing research projects in subsurface energy storage

Skills Development:

- Advanced ML: neural network architectures, training strategies, hyperparameter optimization
- Scientific computing: numerical methods for solving PDEs
- Geoscience applications: familiarity with subsurface fluid flow, reactive transport, geomechanics
- Research skills: literature review, experimental/numerical test design, technical writing

Students will gain experience in frontier research combining traditional geosciences with cutting-edge artificial intelligence, preparing them for careers in academia, energy industry, or climate technology sectors. The projects offer meaningful, supervised research within active research groups, ensuring valuable learning outcomes and potential for continued collaboration.