



SMART - Site Specific Visualization and Decision Support

Science-informed Machine Learning to Accelerate
Real Time (SMART) Decisions in Subsurface Applications

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FECM/NETL Carbon Management Research Project Review Meeting

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SMART Visualization and Decision Support Platform (SVDSP)

Key Project participants

LLNL

- Kayla Kroll
- Chris Sherman
- Gina Geffers
- David He
- Joe Morris
- Chaoyi Wang
- Josh White

NETL

- David Morgan
- Veronika Vasylykivska
- Gavin Liu
- Gabe Creason
- Derek Vikara
- Kolawole Bello
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PNNL

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- Seunghwan Baek
- Ashton Kirol

SMART Visualization and Decision Support Platform (SVDSP)

Unified Simulation Module

CO₂ Storage Site Performance Overview

1

Induced Seismicity Module

Build decision-making intuition for end-users using fast simulation approaches relating to:

- Seismic hazards
- Detected anomalies
- Induced seismicity risk

2

Virtual Learning Module

Leverage ML-based rapid forecasting models to evaluate effects of reservoir management decisions

3

Real-time Forecasting & Operational Control Module

Integrates monitoring data to generate real-time updates and visualizations of CO₂ storage performance.

Provide actionable decision support to improve or modify operations or monitoring strategies.

4

Risk and Economic Analysis Module

Translate ML-based modeling forecasts generated from geologic, operational, and observational data into meaningful metrics related to risk and economic insights.

SMART Visualization and Decision Support Platform (SVDSP)

Goals ⇒

- Translate updated workflows, integrated ML approaches and technical results from Tasks 3, 4 and 5 into clear, actionable decision support for developers, regulators and other stakeholders.
- With stakeholder feedback, develop quantitative operational, risk and economic performance metrics to generate useful outputs for visualization and decision support during CO₂ injection and PISC.

Sub-task 6.1: Induced Seismicity Module

Sub-task 6.2: Virtual Learning Module

Sub-task 6.3: Real-time Forecasting and Operational (RTFO) Control Module

Sub-task 6.4: Economic and Risk Module

Sub-task 6.5: Integration into SMART Visualization and Decision Support Platform (SVDSP)

Technical Approach/Project Scope

High-level Project execution plan / Project schedule summary including key milestones

- **Write design document (complete 4/30/2023)**
- **Develop prototype decision support modules using unified data and visualization platform (1/31/2024)**
- **Apply to Illinois Basin Decatur Project (3/31/2024)**

6.1.1	Decision tree platform -design specs and programming	LLNL	LLNL	1	5	6/1/2023	10/31/2023
6.1.2	Imaging and modeling data infusion into ORION and results visualization	LLNL	LLNL	4	8	9/1/2023	1/31/2024
6.2.1	VLE platform design specs and programming	PNNL, NETL	PNNL	1	8	6/1/2023	1/31/2024
6.2.2	Imaging and modeling data infusion into VLE module and results visualization	PNNL, NETL	NETL	6	10	11/1/2023	3/31/2024
6.3.1	RTFO platform design specs and programming	PNNL	PNNL	1	8	6/1/2023	1/31/2024
6.3.2	Imaging and modeling data infusion into RTFO module and results visualization	PNNL	PNNL	6	10	11/1/2023	3/31/2024
6.4.1	EcoR module design specs and programming for Cost Analysis	NETL	NETL	1	8	6/1/2023	1/31/2024
6.4.2	EcoR module design specs and programming for Risk Analysis	NETL	NETL	1	8	6/1/2023	1/31/2024
6.4.3	Imaging and modeling data infusion into EcoR module and results visualization – Cost Analysis	NETL	NETL	6	10	11/1/2023	3/31/2024
6.4.4	Imaging and modeling data infusion into EcoR module and results visualization for Risk Analysis	NETL	NETL	6	10	11/1/2023	3/31/2024
6.5.1	Integrated platform design specs and programming - SDSP	PNNL, NETL, LLNL	NETL	1	8	6/1/2023	1/31/2024
6.5.2	Demonstration of end-to-end SDSP applicability to IBDP site	NETL	NETL	6	10	11/1/2023	3/31/2024

Sub-Task 6.1 – Induced Seismicity Module

Goal ⇒ Offer insight to the implications of operational decisions on potential induced seismic activity

- Complete the development of the updated Decision Tree Platform (updated design specifications, programming), ORION version 1.x, for integration of methodologies into an ensemble forecast based on pressure, stress, and operational parameters
- Evaluate operational management strategies and the duration of the seismic PISC period at the IBDP site

Element 6.1.1: Decision Tree Platform Design Specs and Programming

Element 6.1.2: Imaging and Modeling Data Infusion into ORION and Results Visualization

Responsible organizations: LLNL

Induced Seismicity - Design

 = Improvement via SMART over Baseline

Task 4 Outputs

ML-based Inverted reservoir properties (LLNL, PNNL, ?)

- Permeability
- Porosity
- Fluid pressure
- Fault orientation, friction

Fluid injection data

- Location, rate (Operators)

ML informed advanced, near real time seismic catalog data (LANL)

- Location, timing, magnitude

Task 5 Outputs

Operational parameter optimization workflows (LLNL)

ML and/or reduced order models of in-situ fluid pressure, stress, and seismic forecasts (LLNL, LBNL)

NRAP Linkages

Open-IAM fluid pressure predictions (PNNL, LLNL)

Physics, statistical forecasting models (LLNL, LBNL)

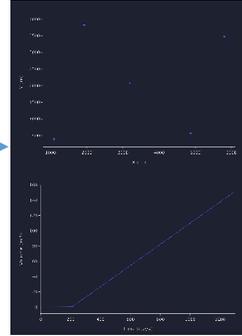
SOSAT stress, friction estimates (PNNL, LLNL)

EDX Linkages

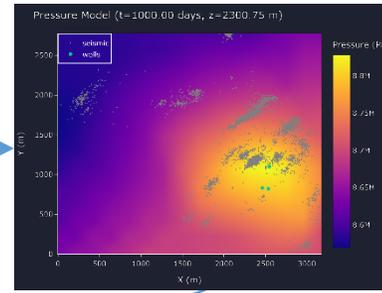
Hosting of seismic, pressure, well data, configuration examples

Deployment of cloud-enabled module?

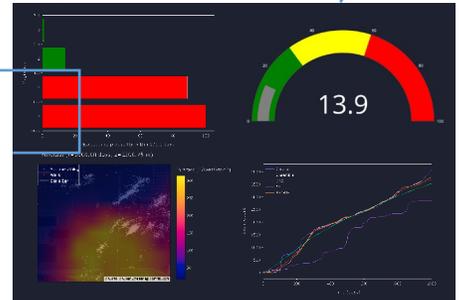
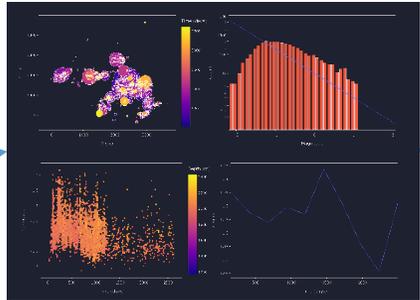
Operational Parameter Update



Fluid pressure/stress forecast



Seismic forecast models



Task 6 Outputs

Ported to web-based interface (LANL)

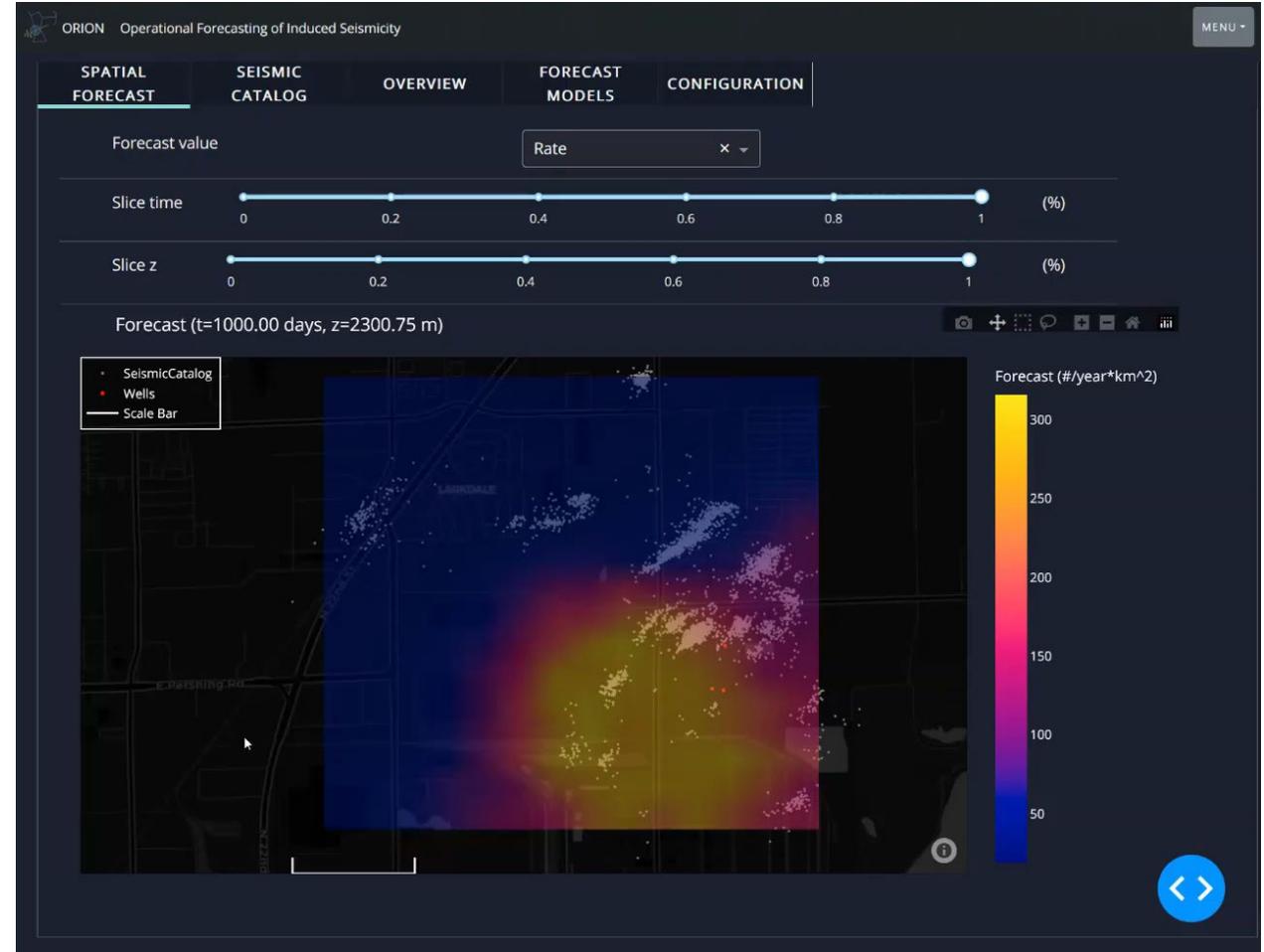
Seismic forecasts, conditional alerts, modified traffic light system, operational management suggestions (LLNL)

Seismic PISC evaluation criteria (LLNL)

Induced Seismicity – User Interface

Status

- IBDP seismic dataset integrated into ORION
 - Phase II early win!
- Developed and implemented ORION with STRIVE
- Video (right) shows IBDP data use case run and step through tabs.



Sub-Task 6.2 – Virtual Learning Environment (VLE) Module

Goal ⇒ Develop tools to inform decision making by summarizing data for key outputs from ML-derived physical simulation algorithms.

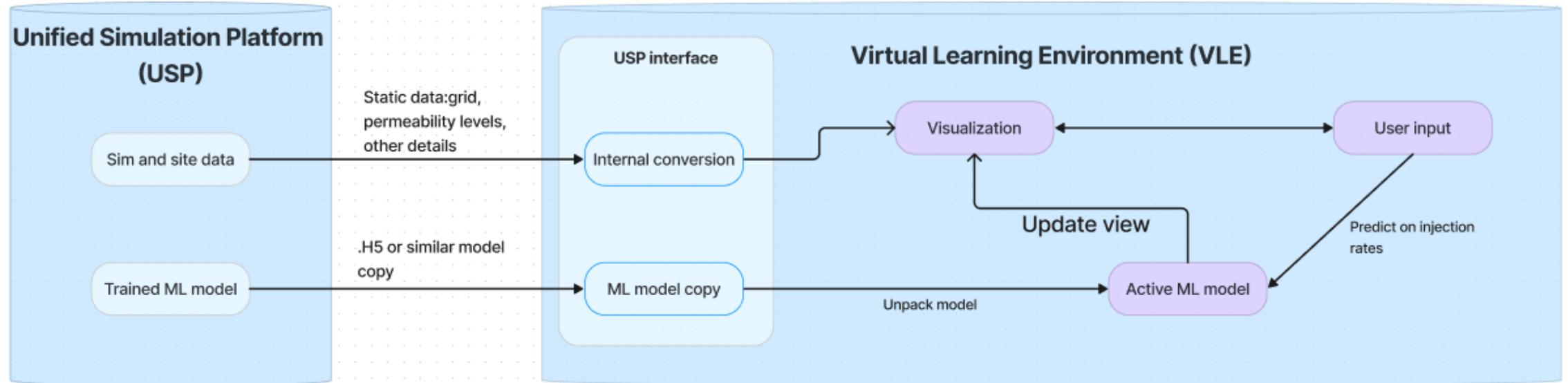
- Build upon phase I work by adding additional data summary and display.
- Demonstrate VLE using IBDP data pulled from USM and integrated into SVDSP

Element 6.2.1: VLE Module Design Specs and Programming

Element 6.2.2: Imaging and Modeling Data Infusion into VLE Module and Results Visualization

Responsible organizations: PNNL and NETL-LRST

Virtual Learning Environment (VLE) - Design



Virtual Learning Environment (VLE) – Mockup

1. VLE landing page

Virtual Learning Environment (VLE)

CARBON SEQUESTRATION

Data-to-insights: Learn and explore 'what-if' scenarios with few steps or clicks

New proje...

User Input

Interactivity

Interrogation

Create New Project

Load Existing...

Use-cases/Examples

Quick demo

Class-VI doc links

Video links of VLE demos

Class VI Permit Application Outline

This document provides an overview of the items and the associated activities an applicant must complete during the development of an application to start carbon sequestration (CS) for geologic sequestration (GS) under the US Class VI program. In addition to a detailed index to the Class VI guidance documents that cover the development of the information needed for a complete Class VI application, please note the general application items and activities listed herein reflect EPA's recommendations for complying with the relevant Class VI rule requirements. It is advised that applicants are notified that the elements and activities are not intended to be a substitute for the specific requirements of the Federal Class VI Rule and demonstrate that an applicant's proposed project complies with these US permitting authorities about the specific needs for their project and review the [Class VI Rule](#) with the [EPA website documents](#), which are available on EPA's web site in order to gain a full understanding of the Class VI permit application process.

Item	Activity and Purpose	Evidence Reference
Characterize the geologic setting of the proposed GS site to demonstrate that the Class VI well will be sited in an area with a suitable geologic setting, consisting of an injection zone and sufficient capacity to receive the CO ₂ and a confining zone that is free of permeable beds or fractures. The information will satisfy the requirements of 49 CFR 248.202(a)(2)(i), (2)(ii), and (2)(iii). For additional information, see the Class VI Rule , Guidance Site Characterization Guidance , and Subsurface Appraisal in Planning, the Application and Construction of Geologic Storage .	<ul style="list-style-type: none"> Regional geology and geologic structure <ul style="list-style-type: none"> Provide a description of the geologic setting, including the injection zone and USGS, the thickness and general extent of formations, and the presence of fractures in the injection zone and the confining zone. Provide a description of the geologic setting, including the injection zone and USGS, the thickness and general extent of formations, and the presence of fractures in the injection zone and the confining zone. 	<ul style="list-style-type: none"> Section 2.1.1, 2.1.2, and 2.1.3 of the Geologic Site Characterization Guidance Section 2.1.1, 2.1.2, and 2.1.3 of the Geologic Site Characterization Guidance
<ul style="list-style-type: none"> Faults and fractures <ul style="list-style-type: none"> Describe the location, orientation, and extent of faults and fractures in the injection zone. 	<ul style="list-style-type: none"> Provide water chemistry data on all water-bearing formations to identify USGS, confirm that the injection zone is not a USGS, and describe the water quality in any permeable beds and fractures in the injection zone and the confining zone. 	<ul style="list-style-type: none"> Section 2.1.1, 2.1.2, and 2.1.3 of the Geologic Site Characterization Guidance
<ul style="list-style-type: none"> Hydrologic and hydrogeologic information <ul style="list-style-type: none"> Describe the hydrologic balance between the proposed injection formation and any USGS, spring, and other wells in the salt to support an understanding of the water resources near the proposed well. 	<ul style="list-style-type: none"> Provide water chemistry data on all water-bearing formations to identify USGS, confirm that the injection zone is not a USGS, and describe the water quality in any permeable beds and fractures in the injection zone and the confining zone. 	<ul style="list-style-type: none"> Section 2.1.1, 2.1.2, and 2.1.3 of the Geologic Site Characterization Guidance
<ul style="list-style-type: none"> Geotechnical data <ul style="list-style-type: none"> Provide geotechnical information on soils and rocks in the injection zone and the confining zone to identify potential interactions that could affect the stability of the injection zone and the confining zone, and address CO₂ storage capacity estimates. 	<ul style="list-style-type: none"> Provide water chemistry data on all water-bearing formations to identify USGS, confirm that the injection zone is not a USGS, and describe the water quality in any permeable beds and fractures in the injection zone and the confining zone. 	<ul style="list-style-type: none"> Section 2.1.1, 2.1.2, and 2.1.3 of the Geologic Site Characterization Guidance

Sub-Task 6.3 – Real-Time Forecasting and Operational (RTFO) Control Module

Goal ⇒ Provide real-time actionable decision support to improve operation and risk management strategies during geological carbon sequestration operations.

- Forecast future reservoir performance based on historical monitoring data.
- Optimize storage efficiency by varying injection strategies.

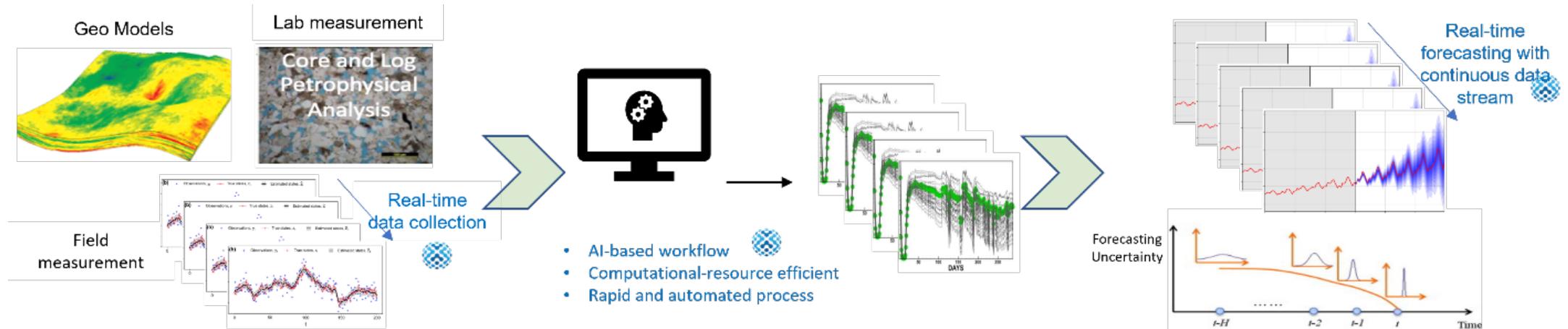
Element 6.3.1: RTFO Module Design Specs and Programming

Element 6.3.2: Imaging and Modeling Data Infusion into RTFO Module and Results Visualization

Responsible organizations: PNNL

Real-Time Forecasting Design

Expected module inputs and outputs



Input

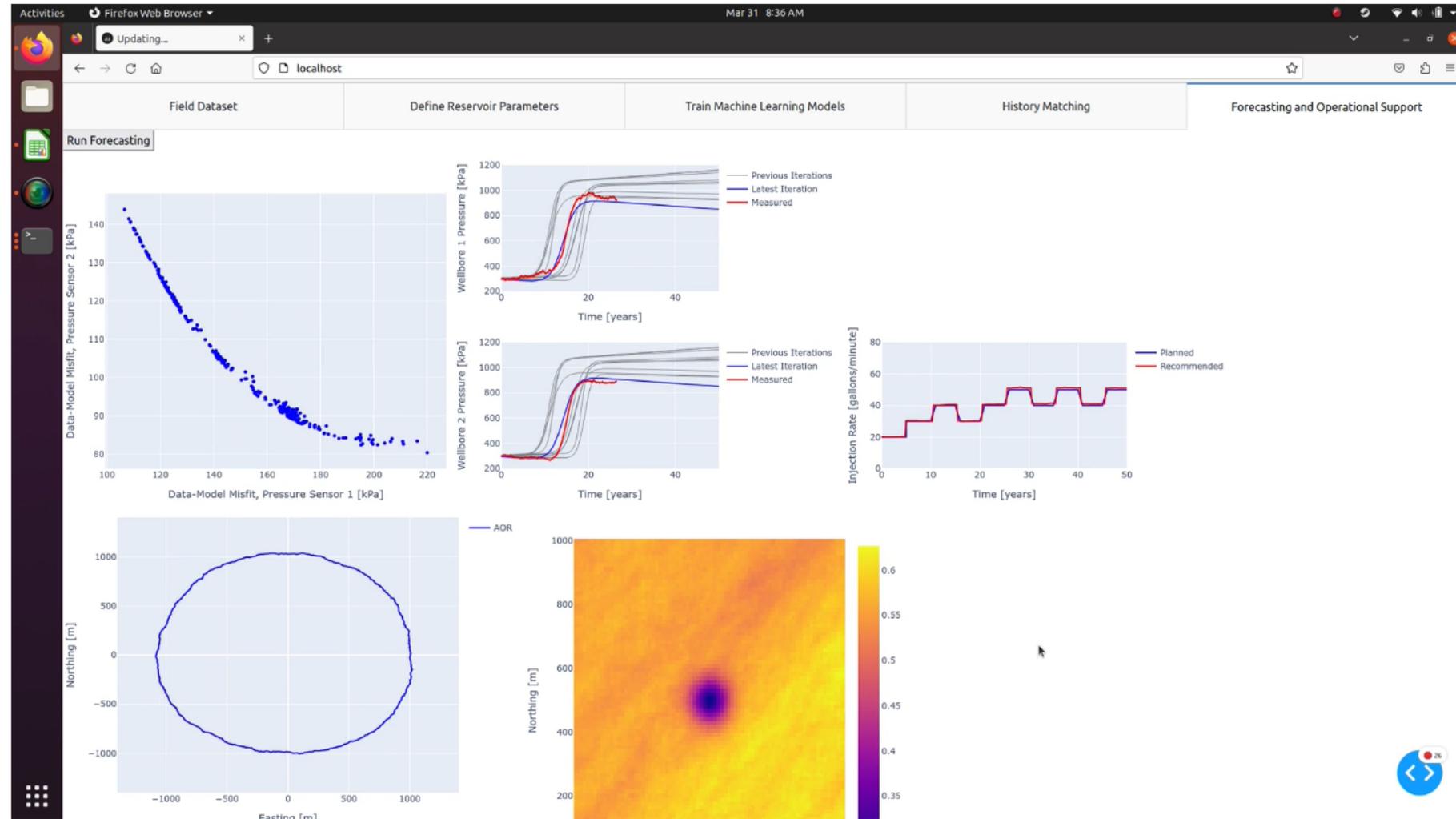
- ML reservoir model
- History-matching algorithm and hyper parameters
- Field measurement data
- Calibrating parameter types and ranges
- Well locations
- Optimization algorithm and hyper parameters

Output

- History-matched reservoir models
- Forecasting of CO₂ and pressure with the history-matching reservoir models
- Optimized conditions (e.g., injection rate schedule) and objectives (e.g., operational cost, risk threshold)

Real-Time Forecasting and Operational Control GUI

- History-matching algorithms (upper middle) attempt to fit reservoir simulations (blue lines) to real-time measured field data (red lines)
- Pareto graph (upper left) shows tradeoff relationship as no reservoir yet found can explain both sensor readings equally well
- Area of review (lower left) and uncertainty reduction (lower middle) continuously update as new data and simulations come in
- Planned injection schedules are compared to algorithm-recommended injection schedules, which also update in real time



Sub-Task 6.4 – Economic and Risk Module (EcoR)

Goal ⇒ Translate ML-based modeling forecasts generated from geologic, operational and observational data into meaningful metrics related to:

- Potential risk of fluid leakage out of the storage formation
- Engineering economic assessment of storage operations

Element 6.4.1: EcoR Module Design Specs and Programming for Cost Analysis

Element 6.4.2: EcoR Module Design Specs and Programming for Risk Analysis

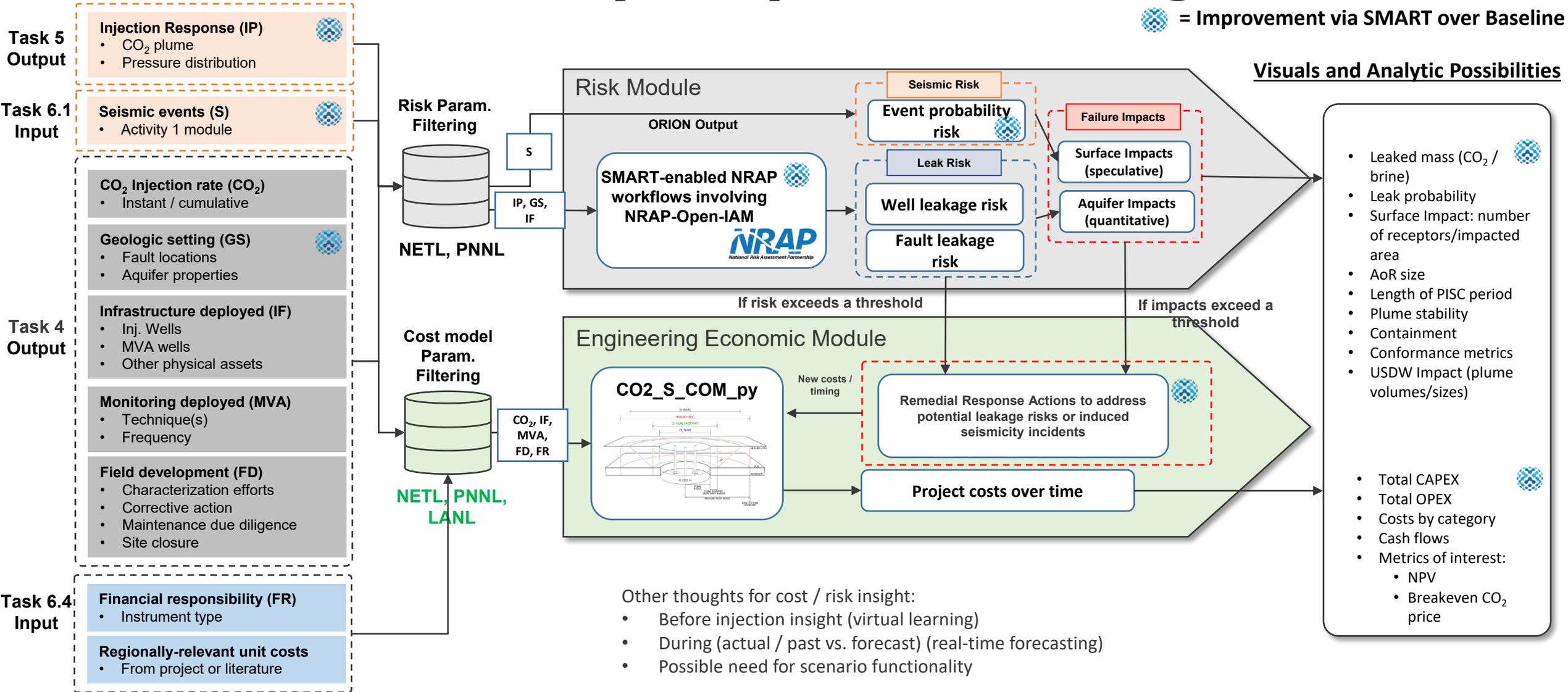
Element 6.4.3: Imaging and Modeling Data Infusion into EcoR Module and Results Visualization – Cost Analysis

Element 6.4.4: Imaging and Modeling Data Infusion into EcoR Module and Results Visualization – Risk Analysis

Responsible organizations: NETL for 6.4.1 and 6.4.3 and NETL-LRST for 6.4.2 and 6.4.4

Economic and Risk (EcoR) Module Design

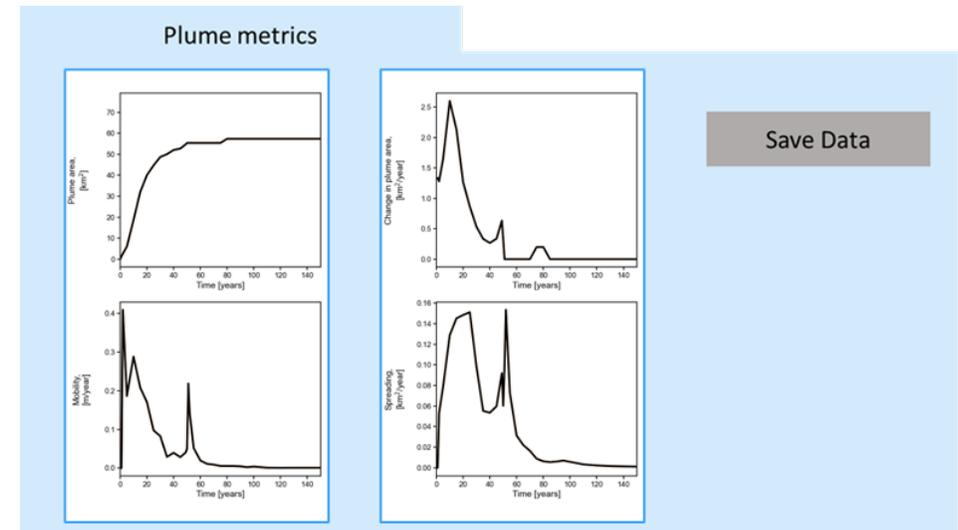
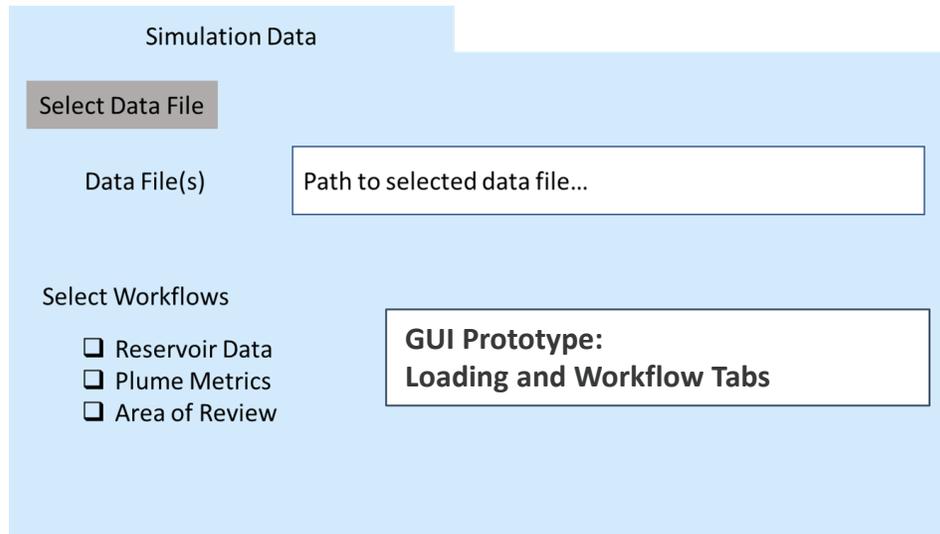
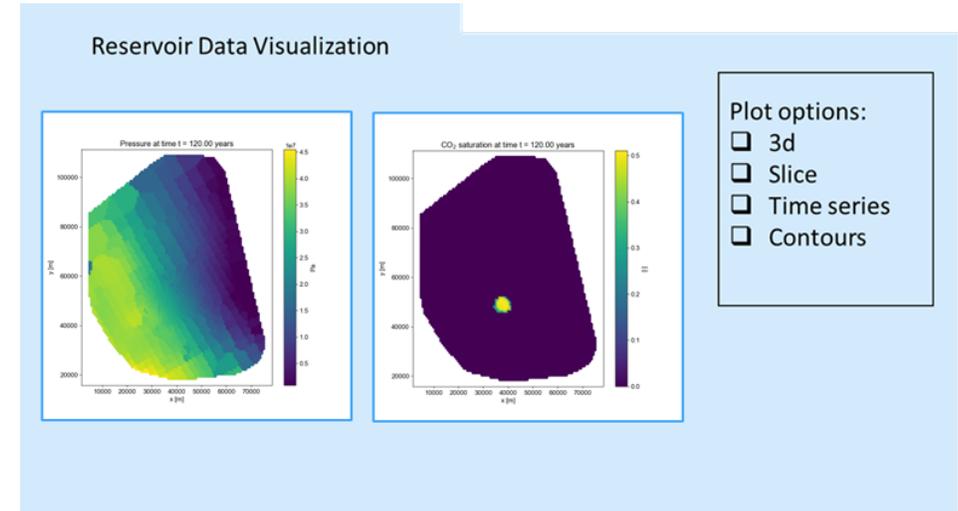
 = Improvement via SMART over Baseline



SMART Risk Module

Status Updates

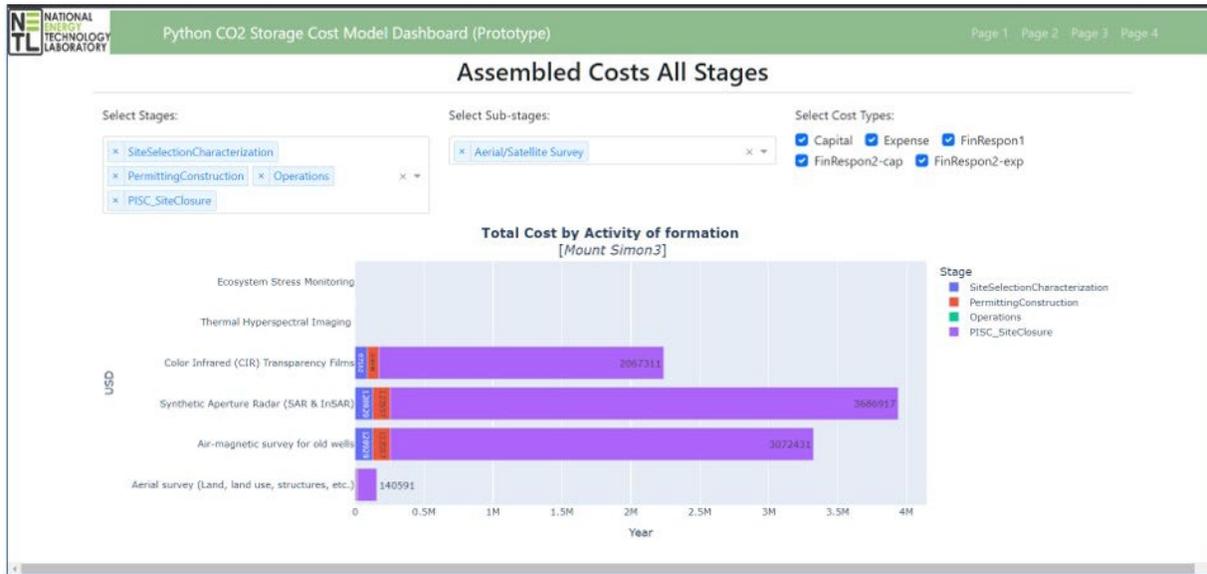
- Testing existing data (e.g., SACROC, IBDP) from SMART Phase I and II to identify potential use cases/available risk metrics
- Converted existing data into NRAP-Open-IAM accepted format
- Utilizing and updating the existing functionality in NRAP-Open-IAM:
 - updated lookup table reservoir and plume stability components to handle 2D/3D data;
 - added option for alternative data formats of the lookup tables
 - NRAP's work on coupling of NRAP-Open-IAM and ORION can benefit development of risk module.



SMART Engineering Economic Module

Status Update

- Starting point is Python version of FECM/NETL CO₂ Saline Storage Cost Model (CO2_S_COM_py)
- Currently implementing modifications needed to allow the model to use outputs from other NRAP and SMART tools
- Created a prototype dashboard using Plotly/Dash



Sub-Task 6.5 – Integration into SMART Visualization and Decision Support Platform (SVDSP)

Goals ⇒

- Combine individual modules (USM, ORION, VLE, RTFO, EcoR) into the integrated overarching SVDSP suitable for end-user application
- Develop the STRIVE abstraction layer between the modules and Plotly Dash graphics library to ensure a consistent user interface
- Demonstrate the use of the SVDSP using data from IBDP site

Element 6.5.1: Integrated Platform Design Specs and Programming – SVDSP

Element 6.5.2: Demonstration of End-to-End SVDSP Applicability to IBDP Site

Responsible organizations: PNNL, NETL, LLNL and NETL-LRST for 6.5.1 and NETL-LRST and NETL for 6.5.2

SMART Visualization and Decision Support Platform (SVDSP)

Challenges

- **Challenges using conventional methods**

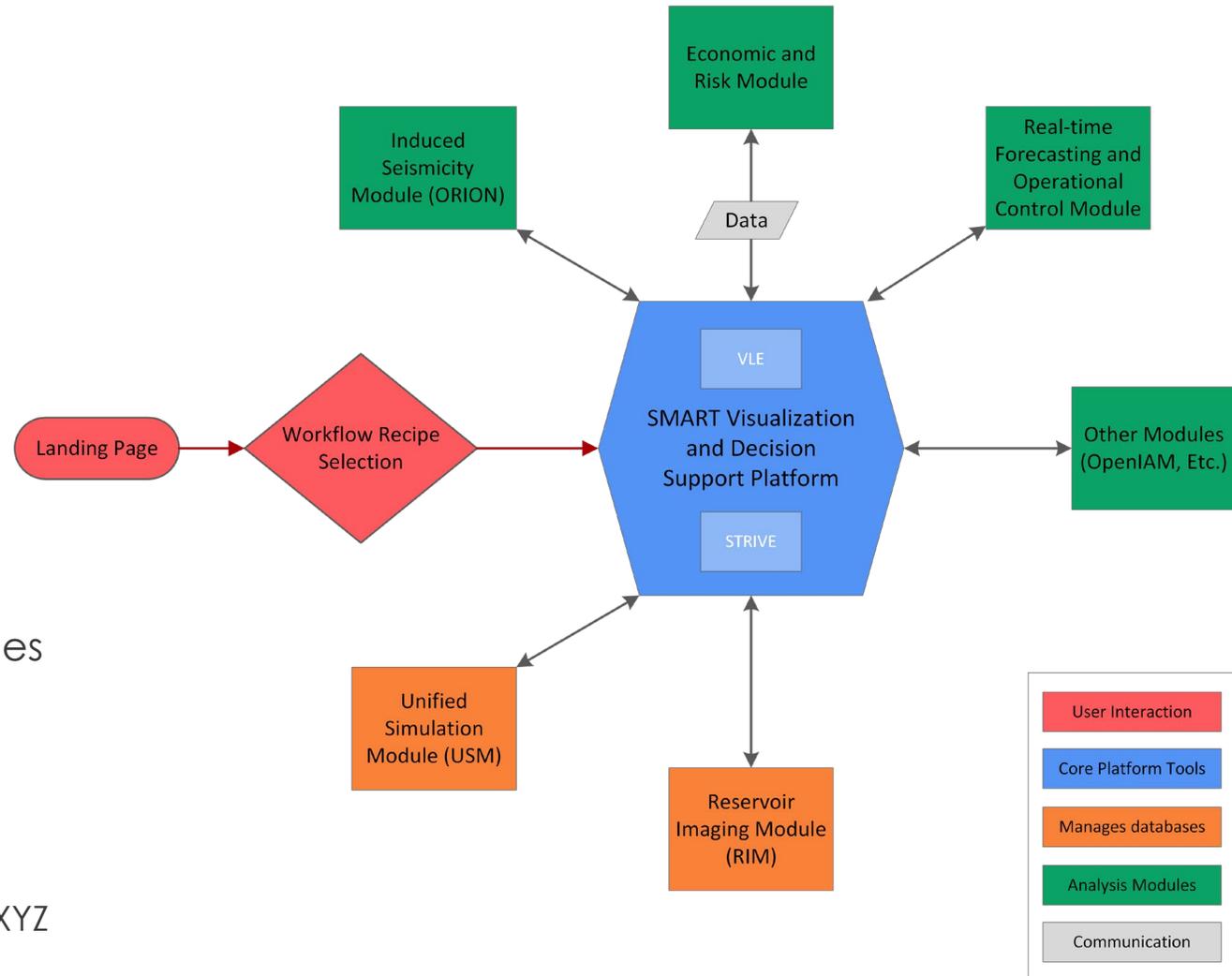
- Several tools for decision support and visualization have been created
- Each has a unique user interface
- Each piece of desktop software must be installed separately
- Input data formats are not consistent

- **SMART will unify these tools into a cohesive, web-based framework**

- Visualization library of 2D and 3D plotting methods using Plotly Dash
- STRIVE will act as an interface between modules and visualization library

- **SVDSP uses a hub-and-spoke model**

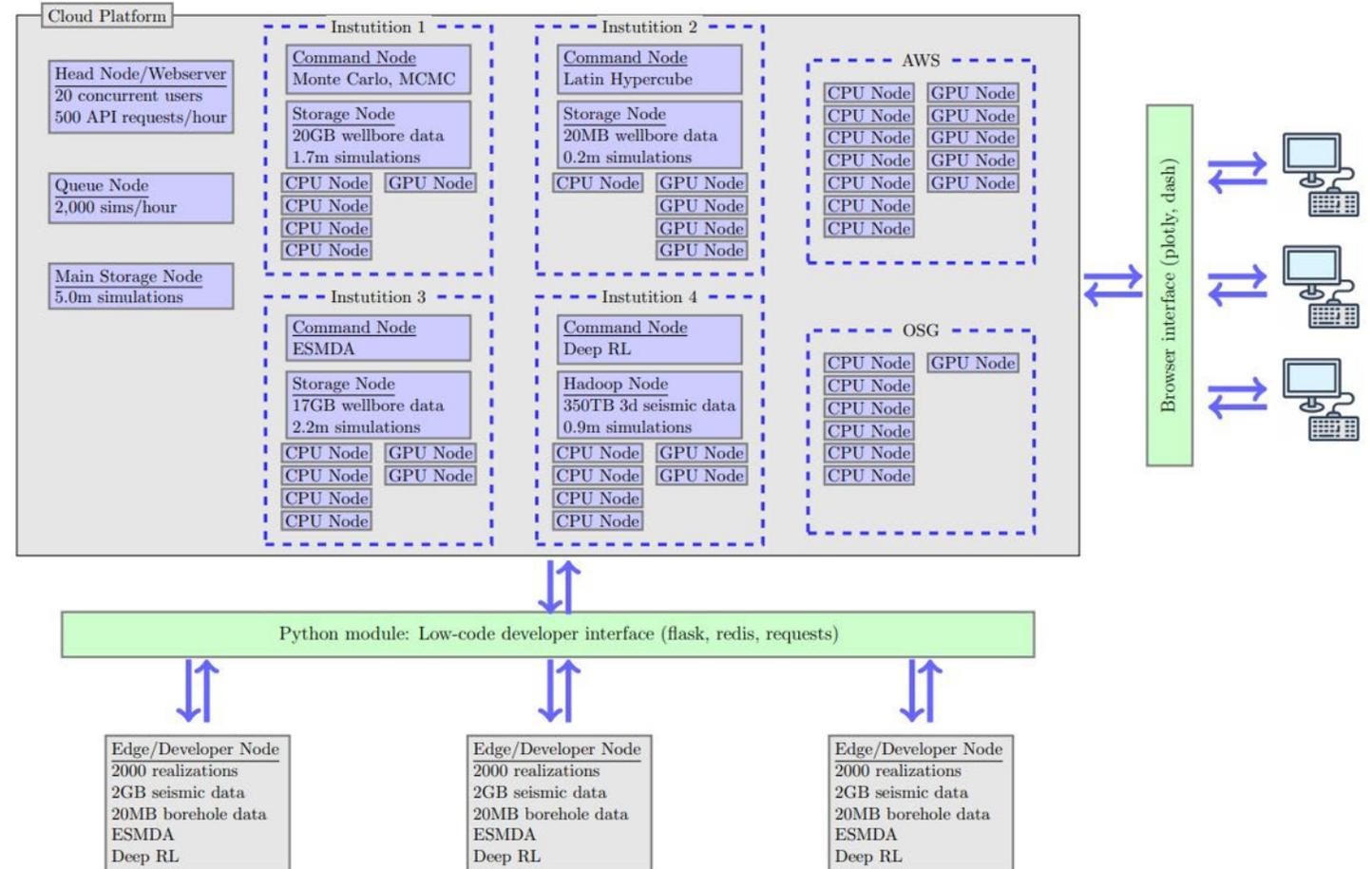
- Recipes include step-by-step instructions for performing a specific task
 - E.g.: "Ask USM to download pre-trained model XYZ from EDX"



Next Steps

After Project/Scale-up potential

- **The SVDSP is designed to be flexible**
 - can be run on desktop hardware to avoid sharing sensitive data, or
 - could be deployed on a cloud platform for scalability
 - browser interface for both desktop or cloud-based implementations



SMART Visualization and Decision Support Framework (SVDSP)

Contribution to commercial-scale CCS deployment

Selected Use Cases

- Induced Seismicity
 - An operator plans to inject fluids and they want to develop an intuition of how pressure changes impact seismic hazard
- Virtual Learning Environment
 - User queries for what-if scenarios through ML model predictions
- Real-time Forecasting
 - A site operator updating a site-specific reservoir model in real time
- Operational Control
 - A site operator maximizing CO₂ injection rate within risk thresholds (e.g., pressure build-up)
- Containment Risk
 - User selects location of saved individual or ensembled (multiple) realizations of input data (e.g., pressure and saturation) and defines a threshold. The platform calculates plume stability metrics for all provided quantities of interest.
- Economic
 - Assuming the user can select an injection scenario and monitoring program, the engineering economic module will be able to calculate the revenues, costs and financial performance of that injection scenario, including key financial metrics

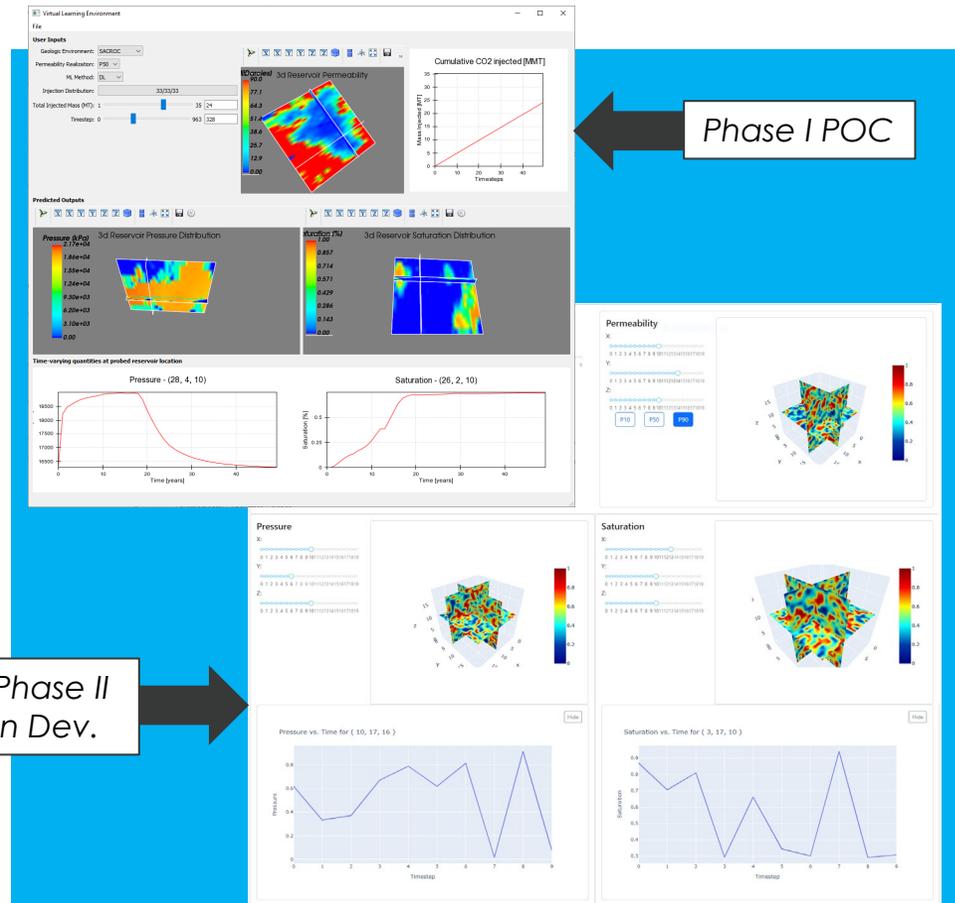
Technical aspects of VLE – User Interface

Status

The **Virtual Learning Environment (VLE)** is an exploratory tool which uses ML predictions to rapidly inform an end user of how a given reservoir simulation would likely change in response to altered inputs (i.e., “What-if” scenarios)

Phase II development will:

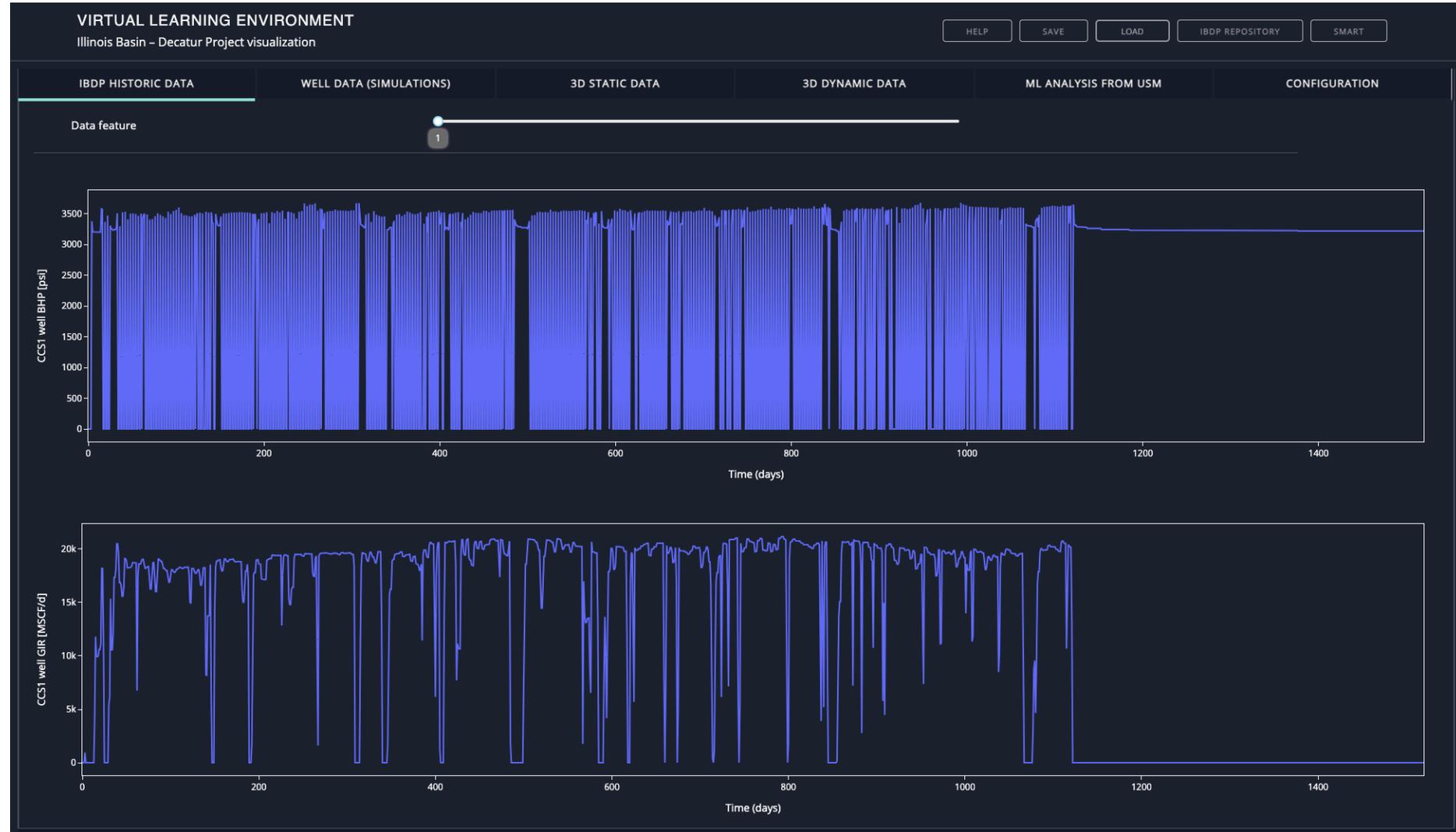
- Encompass Phase I behavior
 - Explore *predicted* changes in pressure and saturation over time given injection rate and permeability profile
 - Additional framing data (AoR) likely to be integrated
- Be migrated to an online environment
- Import ML data from Unified Simulation Module (USM)
- Act as a “landing page” for other modules



Integration of VLE with USM – User Interface

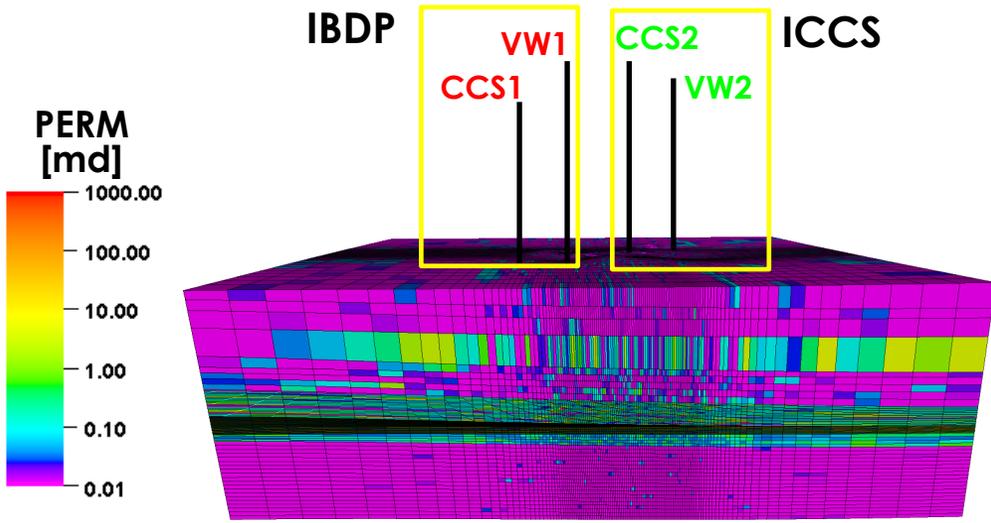
Status

- VLE as a “Landing Page”
 - Previous functionality still present, but encapsulated as a one “module” amongst several
 - Intent is still for a coarse-level, “what-if” support, only incorporating other modules
- Will utilize inter-module communication
 - Move “state” data from VLE level to full module
 - VLE is *not* replacing any modules but acting as a gateway



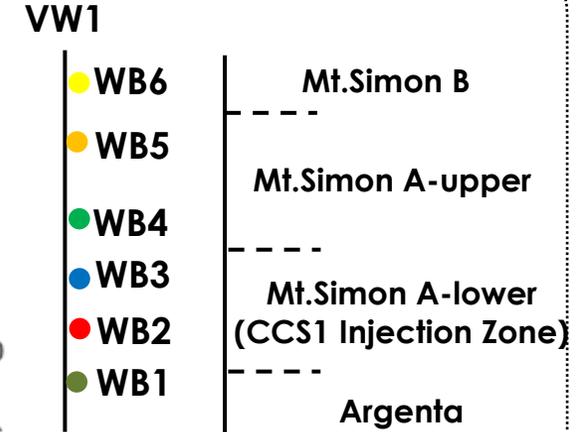
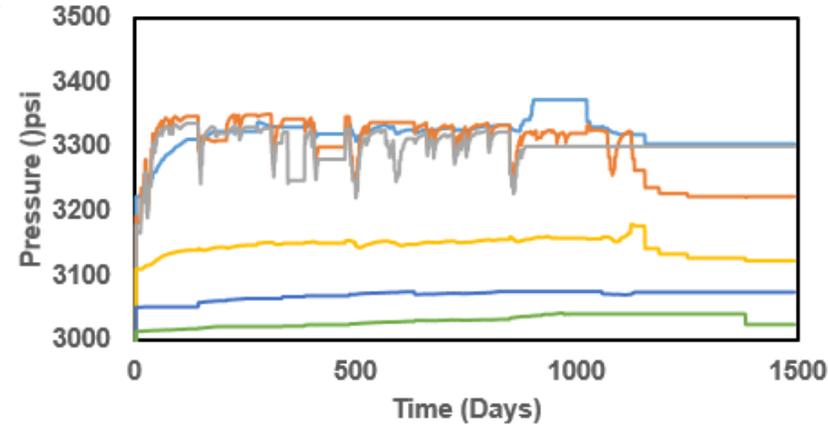
Use-case: IBDP Model Description and Data Availability through VLE and USM

Status



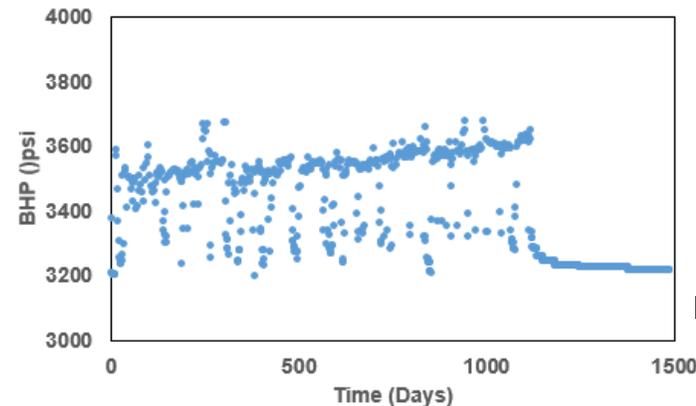
- Grid: 126 * 125 * 110 (1.73 Million Cells)
- ECLIPSE Compositional Model (E300)
- CO2STORE Module
- Simulation Period: 2011-2015
- Run Time: 1.5 hours with 16 Cores Parallel run

Observed data



Behind-casing pressure (Monitor Well)

Location of behind-casing sensors



Bottom-Hole Pressure of Injection Well

Moving forward – Building on early Phase-II wins!!

Status

• Key Development Challenges

- User Interface will need to be rebuilt for online presentation
- Architecture will need to be updated for multi-user/session operation
- Conventions for interoperation between modules will need to be defined
 - USM → VLE (through STRIVE)
 - VLE ↔ Other Modules (through STRIVE)

• Key Gaps

- Where will the data/models/tools live?
 - EDX cloud is likely the answer
- How should “coarse” versions of modules be implemented?
 - This may look very different for different modules

• New Opportunities through STRIVE + EDX + USM

- Demonstration of how utilization of ML models can bridge the gap between research and application
- Inter-module communication development will lead to a more cohesive, unified presentation of the SMART platform

[STRIVE documentation](#) [STRIVE Integration Walkthrough](#) [Widget API](#) [Figure API](#) [General](#) [Contributing to STRIVE](#) [More](#) ▾



SMART Tools Rapid Visualization Environment (STRIVE)

STRIVE

About

Welcome to the SMART Tool Rapid Visualization Environment (STRIVE) documentation.

The SMART Tools Rapid Visualization Environment (STRIVE) package provides tools for generating a modern-looking, flexible, and efficient graphical user interface (GUI) in python. Instead of requiring developers to write their own custom GUI-code, STRIVE relies on a set of simple API entries on objects to create and manage pages, figures, and widgets. This approach is adapted from the GUI framework originally implemented in [ORION](#).

The STRIVE API is designed to be independent of the selected GUI frontend. In its initial version, STRIVE is supporting the [Plotly Dash framework](#).

See [PDF documentation](#).

Getting Started

To begin working with STRIVE, you should first clone the repository. If you have not done so already, setup your account on gitlab and ask a STRIVE developer for access to the repository. You may also want to create/upload an ssh key to your account (see the [gitlab documentation](#) for details).

Once you have a local copy of STRIVE, you can install it into your python environment using pip. Note: we recommend using a [virtual python environment](#) to avoid conflicting with other work you may be doing.

```
cd /some/local/path
git clone git@gitlab.com:doe-smart/phase-2/strive.git
cd strive
python -m pip install --upgrade .
```

User Guide

[STRIVE Integration Walkthrough](#)

[Widget API](#)

[Figure API](#)

☰ On this page

STRIVE

About

Getting Started

User Guide

Developer Guide

Indices and Tables

Acknowledgements

📄 Show Source

Questions?



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