Transforming the Global Power Sector
Open Tools and Data for Renewable Energy Integration

June 2023
Welcome to our webinar! Here are a few notes about using Zoom:

• This webinar is **being recorded** and will be shared with attendees.

• You will be **automatically muted** upon joining and throughout the webinar.

• Please use the **Q&A function** to ask questions to be addressed during the Q&A portions. You can find this function in your toolbar.

• Please use the **chat feature** to add comments and share input.

• If you have **technical issues**, please use the chat feature to message **Isabel McCan** or **Holly Darrow**.

• You can adjust your audio through the **audio settings**. If you are having issues, you can also dial-in and listen by phone, which can be found in your registration confirmation email.

Webinar Overview
Presenters

Karin Wadsack
Program Manager
National Renewable Energy Laboratory (NREL)

Galen Maclaurin
Senior Energy Researcher
National Renewable Energy Laboratory (NREL)

Kate Doubleday
Researcher
National Renewable Energy Laboratory (NREL)
1. Welcome and Housekeeping
2. Opening Remarks
4. Enabling Power Sector Transformation at Scale
5. Introduction to Production Cost Modeling (PCM)
6. Open-Source Tools for PCM Development
7. Overview of Sample Analysis and Training Materials
Agenda – Day 2

1. Recap of Day 1
2. Overview of PCM Workflow and Sample Analysis
3. Resource Visualization and Site Screening in RE Data Explorer
4. PCM Demonstration in Sienna\Ops
5. Open-Source Training Resources
6. Audience Q&A
7. Wrap Up
Opening Remarks

Karin Wadsack

National Renewable Energy Laboratory
Global Power System Transformation (G-PST) Consortium

**What?**
A global consortium focused on support to power system operators with advanced, low-emission solutions

**Why?**
To drive the development and transfer of the *technical and engineering knowledge* necessary for power system operators at the *speed and scale required* to support the global energy transition

**Who?**
Founding System Operators (FSOs)

Core Team
- Technical Institutes

Developing Country System Operators
- Indonesia, Ukraine, Vietnam, Thailand, India, South Africa, Pakistan, Morocco, Peru, Colombia, Panama, and others

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
Advancing Action in Five Key Areas

1. System Operator Research & Peer Learning
   - Perform cutting edge applied research to create novel system operator solutions and globally disseminate and infuse new insights through peer learning

2. System Operator Technical Assistance
   - Provide implementation support to scale established best practice engineering and operational solutions

3. Foundational Workforce Development
   - Build the inclusive and diverse workforce of tomorrow through enhanced university curriculum and technical upskilling for utility and system operator staff

4. Localized Technology Adoption Support
   - Adapt modern power system technologies to individual country contexts through testing programs and standards development activities

5. Open Data and Tools
   - Support rigorous planning, operational analysis and enhanced real-time system monitoring through open data and tools

CORE TEAM – All Core Team members contribute to all activity pillars

REGIONAL LEADS – Coordinate regional peer learning networks and country-level technical assistance delivery efforts for Africa, Asia, and Latin America and the Caribbean

INTERIM SECRETARIAT – Work program coordination, partnerships and support, outreach, etc.
The USAID-NREL Partnership

The U.S. Agency for International Development (USAID) and NREL partner with developing countries to decarbonize and transform energy systems around the world by addressing critical aspects of deploying advanced energy systems.

USAID-NREL PARTNERSHIP STRATEGIC PILLARS

Provision of demand-driven technical assistance through USAID Mission engagements, global knowledge platforms, and project implementation

- **ADVANCED & FRONTIER POWER SYSTEMS**
  - Utility-scale clean energy generation, transmission, distribution

- **INNOVATION & GRID INTERACTION IN BUILDINGS**
  - Energy efficiency, distributed generation, storage

- **ELECTRIC MOBILITY & SUSTAINABLE TRANSPORT**
  - Electric vehicles, charging infrastructure, hydrogen

- **INTEGRATED ENERGY SOLUTIONS**
  - Holistic energy sector scenario planning, impact assessments, and programming

- **JUST ENERGY TRANSITIONS**
  - Gender equity, air quality, resilience, job creation, energy access – foundational to all USAID-NREL activities

- **BEST-IN-CLASS ENERGY DATA & ANALYTICS**

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
The USAID-NREL Partnership’s global knowledge platforms provide free, state-of-the-art knowledge products, tools, and support on common and critical challenges to scaling up power, buildings, transport and integrated energy solutions.
Spotlight on Grid Integration Resources

- High-quality renewable energy data for decisions
- Integrated geospatial visualization
- Free data downloads

- Grid integration toolkit
- Best practice frameworks, case studies, and technical resources
- Variable Renewable Energy (VRE) Guidebook for Practitioners
High Quality Data for Renewable Energy Decision-Making

Galen Maclaurin

National Renewable Energy Laboratory
High-Quality Data Accelerates Energy Transitions

High-fidelity resource data

- Solar Irradiance
- Wind Speed

enables detailed modeling and analysis

- Site Evaluation
- System Performance & Costs
- Power System Modeling

and informs decision makers to answer complex questions.

- Transmission Planning
- Project Development
- Long-term Energy Planning
- Policy Design
**Motivation and Objectives**

**DEMOCRATIZING DATA:** Growing need for free timeseries wind and solar resource data across the globe to support:
- Project feasibility assessments
- Regional and national target setting
- Detailed power systems modeling
- Assessment of PV-Wind complementarity

**OBJECTIVES:** Provide high-quality, publicly available wind and solar resource data

**VALUE PROPOSITION:** Capture important atmospheric processes for the wind energy community:
- High-accuracy, meso-scale wind flow
- Sub-hourly to interannual resource variability
- Accurate vertical wind profile (wind shear)
- Ramping rates at fine temporal scales

![Figure Credit: Ryan King, NREL](image)
Solar Data Development Algorithm

NREL’s Physical Solar Model (PSM)

• Characterizes absorption and scattering of solar radiation from clouds and aerosols
• Models the transfer of solar radiation through Earth’s atmosphere
• Considers interactions with atmospheric constituents (e.g., CO₂, O₃, H₂O) and land surface
• Visit [https://nsrdb.nrel.gov/](https://nsrdb.nrel.gov/) for more information.

Illustration by Billy Roberts, NREL
Himawari Satellite Imagery

• Cloud characteristics are a key to estimate absorption and scattering of the incoming solar radiation
• Imagery from the Japanese Meteorological Agency’s (JMA’s) Himawari 7 and 8 satellites
• NREL partnered with the University of Wisconsin to model cloud type, optical thickness, and properties.
Southeast Asia Solar Resource Data

Released in February 2021:

• High fidelity solar radiation data covering SE Asia and much of the Indo-Pacific region.

• 10-years of high spatial and temporal resolution data and a Typical Meteorological Year (TMY) data set.

• Easily accessible, free, and open data.
NREL Wind Resource Data

NREL Wind Data - Asia
- Central Asia – 2015
  - 2km, 15 minute - Kazakhstan
  - 9km, 15 minute - other countries
- South Asia – 2017
  - 3km, 5 minute
  - India, Sri Lanka, Nepal, Bhutan
- Southeast Asia 2007-2021
  - 3km, 15 minute
  - Association of Southeast Asian Nation (ASEAN) countries and Bangladesh
A New Paradigm for Wind Resource Assessment

Combine cutting edge techniques in numerical weather prediction and machine learning

Weather Research and Forecasting (WRF) Model + Generative Adversarial Networks (GANs) = Meso-Scale Wind Resource Timeseries Data

Figure Credit: Mel Shapiro, NCAR

Figure Credit: Ryan King, NREL

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
ERA5 Global Weather Model
30 km resolution
Modeled Data
Satellite Data
Ground-measured Data
Contains dozens of weather variables

WRF Regional Model
Physics models incorporate:
- High-resolution terrain
- Sea surface temperature
- Land cover (surface roughness)
and more...

GANs Machine Learning
3 km resolution
Generator
WRF 9 km
Downscales WRF output
GANs 3 km
Compares to real-world examples
Real-world examples 3 km

WIND Toolkit
Southeast Asia
ERA5 30 km resolution
WTK 3km resolution

Figure Credit: Billy Robert, NREL
Renewable Energy (RE) Data Explorer

- A user-friendly geospatial visualization tool for analyzing renewable energy potential and informing decisions.
- Open data download repository for high-quality renewable energy resource data.
- Support for renewable energy decision-making.
**RE Data Explorer** was developed to support data-driven renewable energy analyses that can inform key renewable energy decisions globally.

Access the **RE Data Explorer Data-Driven Decisions webpage** to learn how renewable energy data can support informed renewable energy target setting, policy making, investment, and power sector planning.

Leverage the **Renewable Energy Data, Analysis, and Decisions: A Guide for Practitioners** to enhance your capability to make informed and effective renewable energy decisions using high-quality renewable energy data.
Additional Resources

Learn more about renewable energy resource data developed for the Southeast Asia region.

Developing Southeast Asia Solar Resource Data to Support the Clean Energy Transition in the Region

High-Resolution Southeast Asia Wind Resource Data Set

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
VRE Challenges

Variable renewable energy (VRE) resource challenges:

• Variable and uncertain
• Not “dispatchable”
• Does not provide inertia (without synthetic inertia controls)
Walter’s Premise

“The large scope and focus on today’s dominant conventional energy forms [in existing models] do not allow a detailed treatment of the more important issues for wind energy technologies.”

From: Short, W., N. Blair, D. Heimiller, and V. Singh (2003). Modeling the long-term market penetration of wind in the United States
What is grid integration?

**Grid integration** is the practice of power system planning, interconnection, and operation that enables efficient and cost-effective use of variable renewable energy (VRE) while maintaining the stability and reliability of the grid.
Access the Grid Integration Toolkit on Greening the Grid to unlock an extensive collection of expertly assembled and annotated resources that can facilitate your understanding of the key topics for integrating variable renewable energy into the grid.

Check out the Variable Renewable Energy Grid Integration Guidebook for Practitioners to gain a comprehensive understanding of strategies and good practices for conducting a high-quality grid integration study.
Four Pillars of Power System Reliability

Capacity
Power generation and transmission capacity must be sufficient to meet peak demand for electricity.

Flexibility
Power systems must have adequate flexibility to address variability and uncertainty in demand (load) and generation resources.

Frequency
Power systems must be able to maintain steady frequency.

Voltage
Power systems must be able to maintain voltage within an acceptable range.
Relevant grid decision timescales span 15 orders of magnitude.

Adapted from A. Von Meier
Relevant grid decision timescales span 15 orders of magnitude.
Relevant grid decision timescales span 15 orders of magnitude.
Relevant grid decision timescales span 15 orders of magnitude.

Adapted from A. Von Meier.

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
Relevant grid decision timescales span 15 orders of magnitude.

Production cost models (PCMs) simulate operations for planning.
Sources of Flexibility

Relative Economics of Integration Options

- Involuntary Load Shedding
- Chemical Storage
- Transmission Expansion
- Coal Ramping
- CT and CCGT Gas Ramping
- Transmission Reinforcement
- Pumped Hydro Storage
- Thermal Storage

Option costs are system-dependent and evolving over time

Type of Intervention

- Markers
- Load
- Flexible Generation
- Networks
- Storage

System Operation

- Strategic RE Curtailment
- Expanded Balancing Footprint/Joint System Operation
- Sub-hourly Scheduling and Dispatch
- RE Forecasting
- Grid Codes
Introduction to Production Cost Modeling (PCM)
PCM for System Planning

Enabling Elements
- Implementation of known effective solutions
- Data collection
- Modeling expertise

Grid Integration Analysis
- Revise parameters for generation and transmission expansion to ensure reliability and cost-effectiveness
- Optimal generation resource location and operation to meet future demand
- Transmission expansion planning

Capacity Expansion
- Future generation and transmission scenarios

Production Cost
- Revise operational parameters to ensure system stability
- Cost/benefit analysis of system operations

Power Flow
- "Interest periods" of system stress
- Technical feasibility/reliability analysis

Policy Development
# Example Outcomes: India Case Study

## RE Integration Strategies

<table>
<thead>
<tr>
<th>Normal Operations</th>
<th>Coordinated Scheduling and Dispatch</th>
<th>Coal Plant Flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>State-level dispatch, 55% minimum generation</td>
<td>Regional</td>
<td>National</td>
</tr>
<tr>
<td>230,000 INR Crore Annual Production Cost</td>
<td>2.8% Savings annually</td>
<td>3.5% Savings annually</td>
</tr>
<tr>
<td>1.4% Renewable energy curtailment</td>
<td>1.3% Renewable energy curtailment</td>
<td>0.89% Renewable energy curtailment</td>
</tr>
</tbody>
</table>

**FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.**

**India Renewable Integration Study**

Global Power System Transformation Consortium | 44
Developer Context: Project Development

Idea development

The idea development phase consists of brainstorming and idea generation activities to give the project a more rounded shape.

The main purpose of this phase is to flesh out selected business ideas and structure the rest of the project.

Concept development

The concept development phase usually consists of two stages and related studies:

i. a prefeasibility study (PFS)
ii. a feasibility study (FS).

The PSF is a rougher version of a FS. The purpose of a PFS is to discard unattractive ideas and choose the best among many.

Business development

The business development phase usually consists of two stages:

i. a validation stage
ii. a preparation stage

The best feasible idea is validated with detailed analyses of design and operations. Sourcing of permits and licenses follows.

Project execution

The project execution phase entails construction and installation of the plant, plus any other civil work needed for the project operations.

The number of possible projects shrinks during the project development phase, as different options are assessed. One (or a subset) of initial ideas will go to execution.

Source(s): Danish Energy Agency Prefeasibility Study Guidelines
Developer Context: Project Development

The concept development phase usually consists of two stages and related studies; a prefeasibility stage and study (PFS) and a feasibility stage and study (FS).

RE Data Explorer can aide prefeasibility study & resource prospecting

PCM can study impact of operations on project feasibility
- Bidding strategies
- Curtailment
- Local emissions displacement

Prefeasibility study vs Feasibility study

Scope
A prefeasibility study scans a series of options and determines the best one in the set. The feasibility study analyzes in depth the best solution from the prefeasibility phase.

Uncertainty
Uncertainty in the prefeasibility study is often much higher than for the feasibility study, e.g., -35% to +65% for PFS, and -22% to +35% for FS for Capital Cost.

Financing
Financial security is usually not mandatory for a PFS (though a preliminary assessment is generally made), whereas financial bankability must be ensured at the end of the FS.

Source(s): Danish Energy Agency Prefeasibility Study Guidelines
Structure of an Optimization Problem

"Find the lowest cost dispatch for a load given the constraints..."

"Maximize the stability margin of the system such that ..."

\[ \min_u \ g(x, u) \]
\[ \text{s.t.} \quad x \in \mathcal{X} \]
\[ u \in \mathcal{U} \]

GAMS, AMPL, Pyomo, JuMP, Yalmip, CVX

LP
MILP
LQP
QPQC
SOCP
SDP
NLP
CPLEX
Mosek
Gurobi
Ipopt
NLOpt
Knitro

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
Building PCM Problems

Cost Function: Linear, Polynomial, Piece-wise Linear.

Device and Branch Level Model: Generator Limits, Storage Capacity, Branch Power Flow.

Network Model: Copper plate model or nodal flow balance.

Services Model: Reserves, Area Exchanges, Reactive Power Control Areas.

Feedforward Model: Reserves Commitments, Area Exchanges, Reactive Power Control Areas.

\[ f^k(\cdot) = \min_{\bar{u}^k_t} C_{f^k}(\bar{u}^k_t) \]

s.t.  \[ H^D_{f^k} (\bar{u}_t, \bar{u}_{t-1}, \bar{x}_{t-1}, \bar{\rho}_t, \Phi^k | t) \leq 0 \]

\[ H^B_{f^k} (\bar{u}_t, \bar{u}_{t-1}, \bar{x}_{t-1}, \bar{\rho}_t, \Phi^k | t) \leq 0 \]

\[ H^N_{f^k} (\bar{u}_t, \bar{u}_{t-1}, \bar{x}_{t-1}, \bar{\rho}_t, \Phi^k | t) = 0 \]

\[ H^S_{f^k} (\bar{u}_t, \bar{u}_{t-1}, \bar{x}_{t-1}, \bar{\rho}_t, \Phi^k | t) \leq 0 \]

\[ H^F_{f^k} (\bar{u}_t, \bar{u}_{t-1}, \bar{x}_{t-1}, \bar{\rho}_t, \Phi^k | t) \leq 0 \]
Unit commitment and economic dispatch

optimization horizon: 48 hours
Unit commitment and economic dispatch

rolling forward in 24 hour increments
The state of the system at time t=0 is dependent on:

1. Generator commitment status: on/off
2. If “on”: hours of continuous operation; current ramp rate
3. If “off”: hours since last operation (minimum shut down duration)
Unit commitment and economic dispatch

- Intertemporal Unit-Commitment & Economic Dispatch (UC/ED)
  Mixed Integer Programming problem (MIP)
- Sequential UC/ED Steps
Data Needs for PCM

**Generator data:**
- Bus location
- Minimum/maximum power levels
- Ramp limits
- Thermal plants:
  - Fuel type and heat rate curve
  - Minimum up time/down time
- Hydro plants:
  - Reservoir or river-flow data
- Storage plants:
  - Energy capacity
  - State-of-charge limits
- Eligible reserve categories
- Fuel cost data or market bids

**Transmission network data:**
- Bus and branch topology
- Bus voltage level
- Line power flow limits
- Line reactance

**Time-series data:**
- Time-coincident load, wind, and solar time-series
  - Power data or resource data + a model
  - Hourly and/or sub-hourly resolution
  - Plant/bus, zonal, or area spatial resolution
- Require 2 time-series data sets to model forecast uncertainty using UC/ED:
  1. Forecast posted day-ahead, hour-ahead, 5-minute-ahead, etc.
  2. Realizations

**System/operator data:**
- Reserve categories and requirements

See the [VRE Guidebook for Practitioners](#) (page 52) for a complete list of data requirements for PCM modeling.
Open-Source Data for PCM

Historical time-series data:
- **RE Data Explorer** Southeast Asia Wind data, Asia/Pacific Himawari and Puerto Rico Solar data
- **National Solar Radiation Database** (NSRDB)
- Wind Integration National Dataset Toolkit (North America)
- System operators often post historical hourly demand (for example, **National Grid Corporation of the Philippines Operations Data**)

Historical and real-time weather forecasts:
- European Centre for Medium-Range Weather Forecasts

Cost data:
- **NREL Annual Technology Baseline** (US)

Transmission network data:
- BetterGrids
- DR POWER
- openmod
- Texas A&M University synthetic networks

Plant operating characteristics:
- World Resources Institute Global Power Plant Database
- Industry and academic publications, such as IRENA’s Flexibility in Conventional Power Plants brief
- US EPA National Electric Energy Data System (NEEDS)
- US EIA **Form 923** and **Form 923**
Open-Source Tools for PCM Development

NREL System Advisor Model (SAM) and Sienna
Today’s Workflow

High-fidelity resource data

- Plant Specifications
- Plant Losses

System Advisor Model (SAM)

- Electricity Production
- Costs, Compensation, Financing, Incentives

= Levelized Cost of Energy (LCOE), Net Present Value, Payback Period

Results

- Hourly Locational Marginal Prices (LMPs)
- Transmission Line Flows
- Generator Set Points, RE curtailment

Thermal Generator Data

+ Transmission Constraints

Demand Time-Series

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
System Advisor Model (SAM)

Free software that enable detailed performance and financial analysis for renewable energy systems

- Open-source code
- Extensive documentation and user support
- Evaluate financial metrics for different markets
- Parametric and uncertainty analysis
- View and export key results

https://sam.nrel.gov/
https://pvwatts.nrel.gov/
Overview of SAM Capabilities

Technologies
- Photovoltaics
- Battery Storage
- Wind power
- Concentrating solar power
- Marine energy and tidal systems
- Fuel cells
- Geothermal
- Biomass
- Solar water heating

Financial Models
- Behind-the-meter
  - Residential, Commercial
  - Third-party ownership
- Power purchase agreements
  - Single owner
  - Equity flips
  - Sale-leaseback
- Merchant plants
- Simple LCOE calculator
Accessing SAM

1. Online through the PVWatts® Calculator
   - For quick ballpark calculations

2. Download the GUI
   - For detailed modeling of individual plants

3. Programmatically
   - To develop your own application around SAM or run SAM through Python

4. Through reV, the Renewable Energy Potential Model
   - For very large batch processing and scenario development

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
Open-source ecosystem for power system modeling, simulation and optimization

Sienna\Data
Efficient intake and use of energy systems input data
Developed to support modeling with large shares of inverter-based sources
Formerly known as SIIP
https://github.com/NREL-Sienna

Sienna\Ops
Simulation of system scheduling, including sequential problems for production cost modeling

Sienna\Dyn
Simulation of power system dynamic response to disturbances and contingencies
Sienna’s three core applications use combinations of packages in the Julia Programming Language.

**Sienna\Data**
Input data intake and handling
- PowerSystems.jl
- PowerSimulations.jl
- PowerGraphics.jl
- PowerNetworkMatrices.jl
- PowerSystemsCaseBuilder.jl

**Sienna\Ops**
System scheduling simulations
- PowerSystems.jl
- PowerSimulations.jl
- PowerFlows.jl
- PowerAnalytics.jl
- PowerGraphics.jl

**Sienna\Dyn**
Dynamic response simulations
- PowerSystems.jl
- PowerSimulationsDynamics.jl
- PowerGraphics.jl

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE, DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
Sienna\Ops: PCM for Large Systems

The system achieves up to 45% instant penetration of solar power at certain hours of the day.

<table>
<thead>
<tr>
<th>Generator Type</th>
<th>Installed Capacity Original System [MW]</th>
<th>Installed Capacity Modified System [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>938.04</td>
<td>21,031.9</td>
</tr>
<tr>
<td>Gas Turbines</td>
<td>76,572.1</td>
<td>76,572.1</td>
</tr>
<tr>
<td>Steam Turbines</td>
<td>23,568.2</td>
<td>23,568.2</td>
</tr>
<tr>
<td>Hydro</td>
<td>1,326.72</td>
<td>15,81.22</td>
</tr>
<tr>
<td>Wind Power</td>
<td>15,089.0</td>
<td>14,755.4</td>
</tr>
</tbody>
</table>
How effective are reserve requirements, market designs, and generator controls at handling wind, solar, load, and generator availability forecast errors to maintain supply/demand balance?

- Enables the assessment of system reliability
- Improves upon the scalability and PCM integration of existing state-of-the-art
- System performance evaluation capabilities
  - Reserve product adequacy
  - Ancillary service provision from emerging technologies
  - Forecasting techniques
  - Market design

FOR INTERNAL USE ONLY – DO NOT DISTRIBUTE. DO NOT CITE OR REFERENCE. This work is not for distribution or commercial purposes. The methodology, formula, and analysis used and presented in this document and the views herein do not necessarily represent the views of, nor are they endorsed by the U.S. Department of Energy or the U.S. Government, or any agency thereof.
Is the system stable against perturbations from setpoint transitions, fluctuations in generator and demand injections, and contingencies?

- Existing commercial tools can address these questions for select models and under a fix set of solution algorithms.

- Sienna\Dyn provides a scalable solution (open-source) to assess stability under evolving (low-inertia) grid conditions.
Visualizations with PowerGraphics.jl

- **Plot types**: bar, stack, line, (coming soon: networks)
- **Data**: System, Operations results, (coming soon: dynamics results)
- **Backends**: GR (static), PlotlyJS (basic interactivity)
Sienna Resources

Package documentation includes Quick Start Guides and Tutorials:

- **PowerSystems.jl**
- **PowerSimulations.jl**
- **PowerSimulationsDynamics.jl**
- **PowerGraphics.jl**

NREL Team: [sienna@nrel.gov](mailto:sienna@nrel.gov)

Slack: [https://nrel-sienna.slack.com](https://nrel-sienna.slack.com)
Other Open-Source Planning Tools

Production cost modeling:
- GridPath

Capacity Expansion:
- Caliope/Engage
- Switch
- GenX.jl
- ReOpt
- PyPSA

Load flow:
- MATPOWER
- PANDAPOWER
- PowerModels.jl

Dynamics:
- Sienna\Dyn (PowerSimulationsDynamics.jl)
- ANDES
- PowerDynamics.jl
- Dynawoo

Distribution scale:
- OpenDSS
- GridLab-D
- PowerModelsDistribution.jl

See [https://g-pst.github.io/tools/](https://g-pst.github.io/tools/)
Key Takeaways

- Power system *flexibility* is key for integrating VRE
- Time-series production cost modeling can quantify the benefits of many sources of operational flexibility
- For system operators, PCM is key to operations and planning:
  - Minimize operating & reserve costs on a daily, hourly, subhourly basis
  - Study & anticipate impacts of VRE scenarios on operations
- For developers, PCM can help determine site feasibility:
  - Transmission-constrained curtailment, market bidding strategies (hybrid/storage), locational cost and emissions impacts
- Open-source data and models reduce cost and difficulty of site prefeasibility and feasibility studies
Case Study: Cambodia

PowNet (2021):
- Open-source, hourly-resolution operational model
- Includes transmission lines and generators
- [https://github.com/Critical-Infrastructure-Systems-Lab/PowNet](https://github.com/Critical-Infrastructure-Systems-Lab/PowNet)

Modified from Chowdhury et al. 2020
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Recap of Day 1</td>
</tr>
<tr>
<td>2</td>
<td>Overview of PCM Workflow and Sample Analysis</td>
</tr>
<tr>
<td>3</td>
<td>Resource Visualization and Site Screening in RE Data Explorer</td>
</tr>
<tr>
<td>4</td>
<td>PCM Demonstration in Sienna\Ops</td>
</tr>
<tr>
<td>5</td>
<td>Open-Source Training Resources</td>
</tr>
<tr>
<td>6</td>
<td>Audience Q&amp;A</td>
</tr>
<tr>
<td>7</td>
<td>Wrap Up</td>
</tr>
</tbody>
</table>
Preparing for Tomorrow’s Session (Optional)

- The code for the case study production cost modeling demonstration is available on Github: [https://github.com/NREL-Sienna/PSI-Cambodia](https://github.com/NREL-Sienna/PSI-Cambodia)
- An explanation of the demonstration is available in the [PSI-Cambodia README](https://github.com/NREL-Sienna/PSI-Cambodia), including some of the installation instructions below.
- **Instructions for installing software for the three open-source tools we will be using:**
  1. RE-Data Explorer: Can be accessed online without any installation
  2. System Advisor Model (SAM): We will run SAM in Python using the PySAM wrapper, as well as designing plant specifications in the SAM GUI:
     1. Download the SAM GUI
     2. Install Python
     3. Activate the environment as described in the [PSI-Cambodia README](https://github.com/NREL-Sienna/PSI-Cambodia) (step 2.c in the README)
  3. Sienna: Sienna is written in the Julia programming language
     1. Install Julia
     2. Activate the environment and run literate.jl as described in the [PSI-Cambodia README](https://github.com/NREL-Sienna/PSI-Cambodia) (step 3 in the README)
- For more information, visit [Variable Renewable Energy Grid Integration Studies: A Guidebook for Practitioners](https://www.nrel.gov/analysis/variable_rweg studies/guidebook/index.html).

You can visit these resources at: [https://globalpst.org/transforming-the-global-power-sector-open-data-and-tools-for-renewable-energy-integration/](https://globalpst.org/transforming-the-global-power-sector-open-data-and-tools-for-renewable-energy-integration/)
Thank you!