Utility and Grid Operator Resources for Future Power Systems Webinar Series

Transmission and Distribution Coordination

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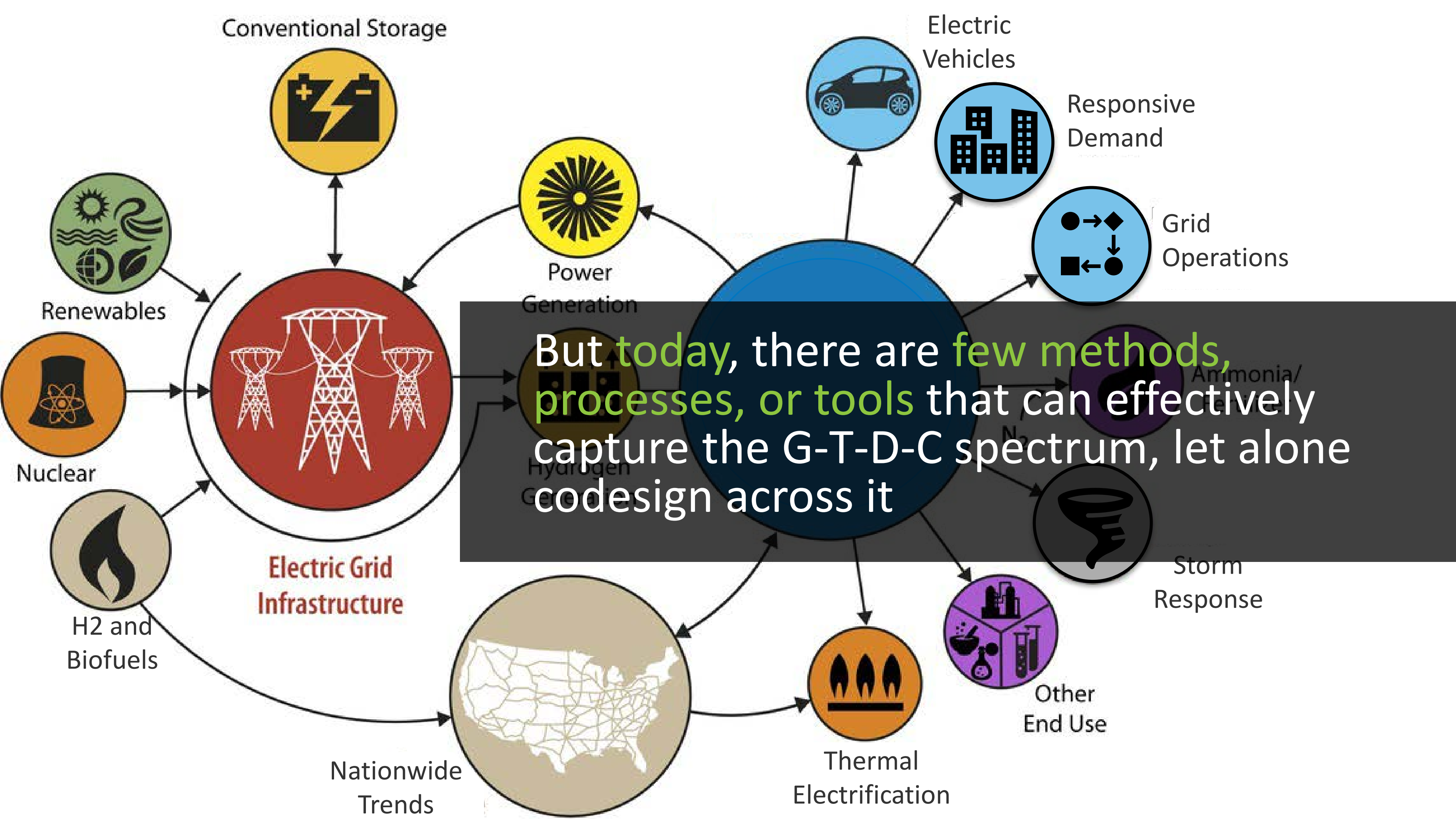
National Renewable Energy Laboratory (NREL)
NREL Webinar Series
June 17, 2025

Photo by Josh Bauer, NREL 61725

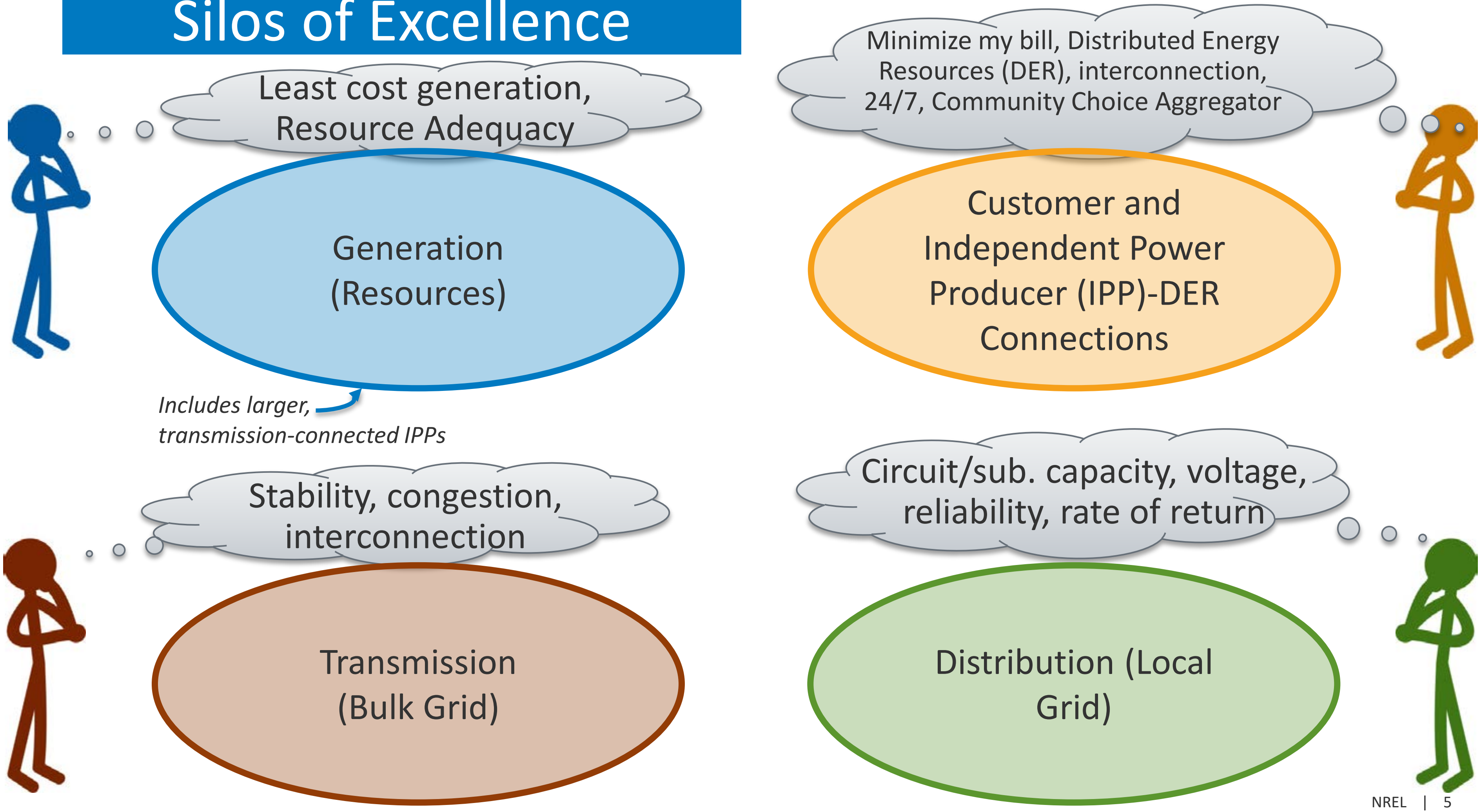
Planning the future grid and interconnected energy system requires balancing generation (G), transmission (T), distribution (D), and customer (C) resources while also increasingly capturing engineering details in planning



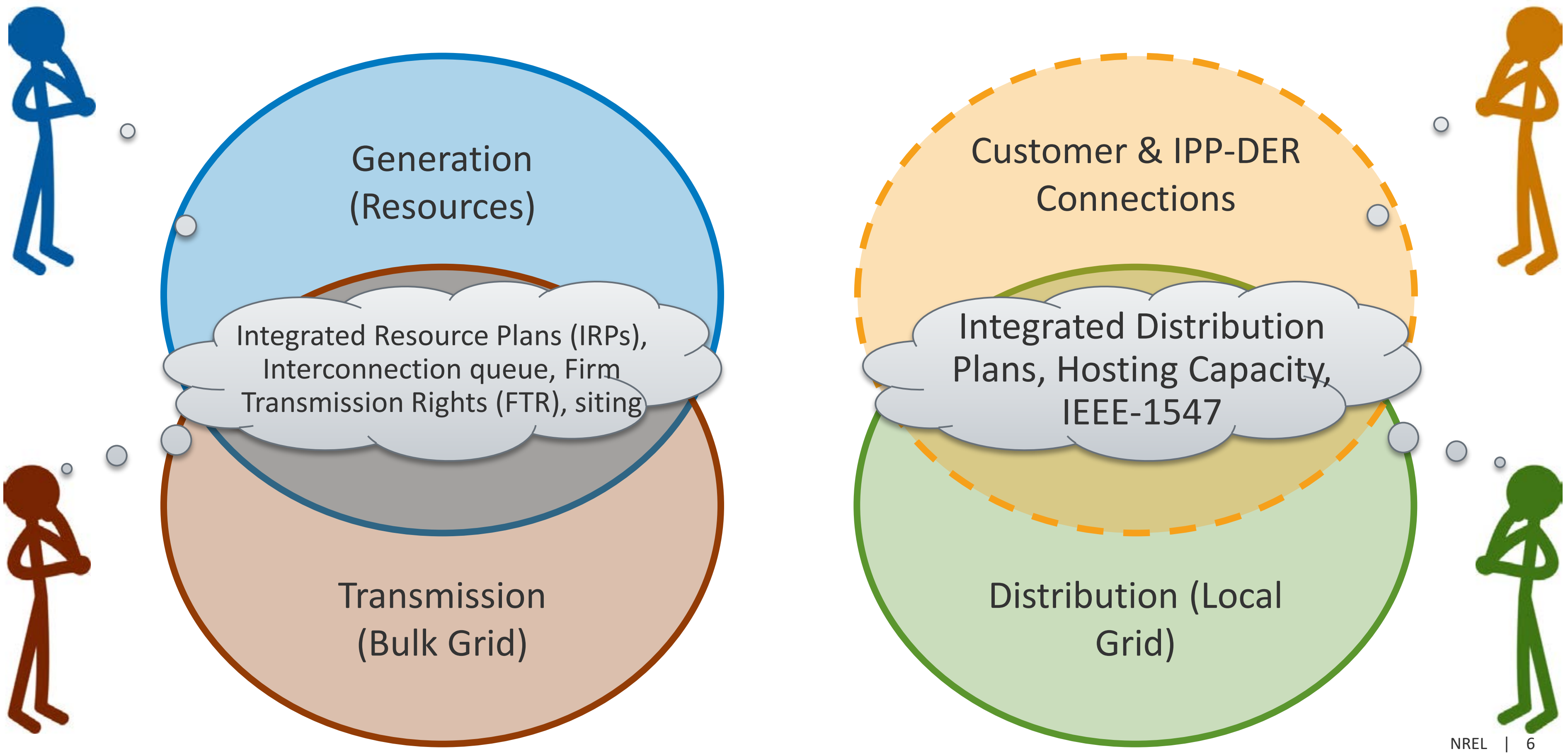
But today, there are few methods, processes, or tools that can effectively capture the G-T-D-C spectrum, let alone codesign across it


There are many opportunities to create new approaches for holistic G-T-D-C planning of reliable and affordable electric grid-connected future energy systems

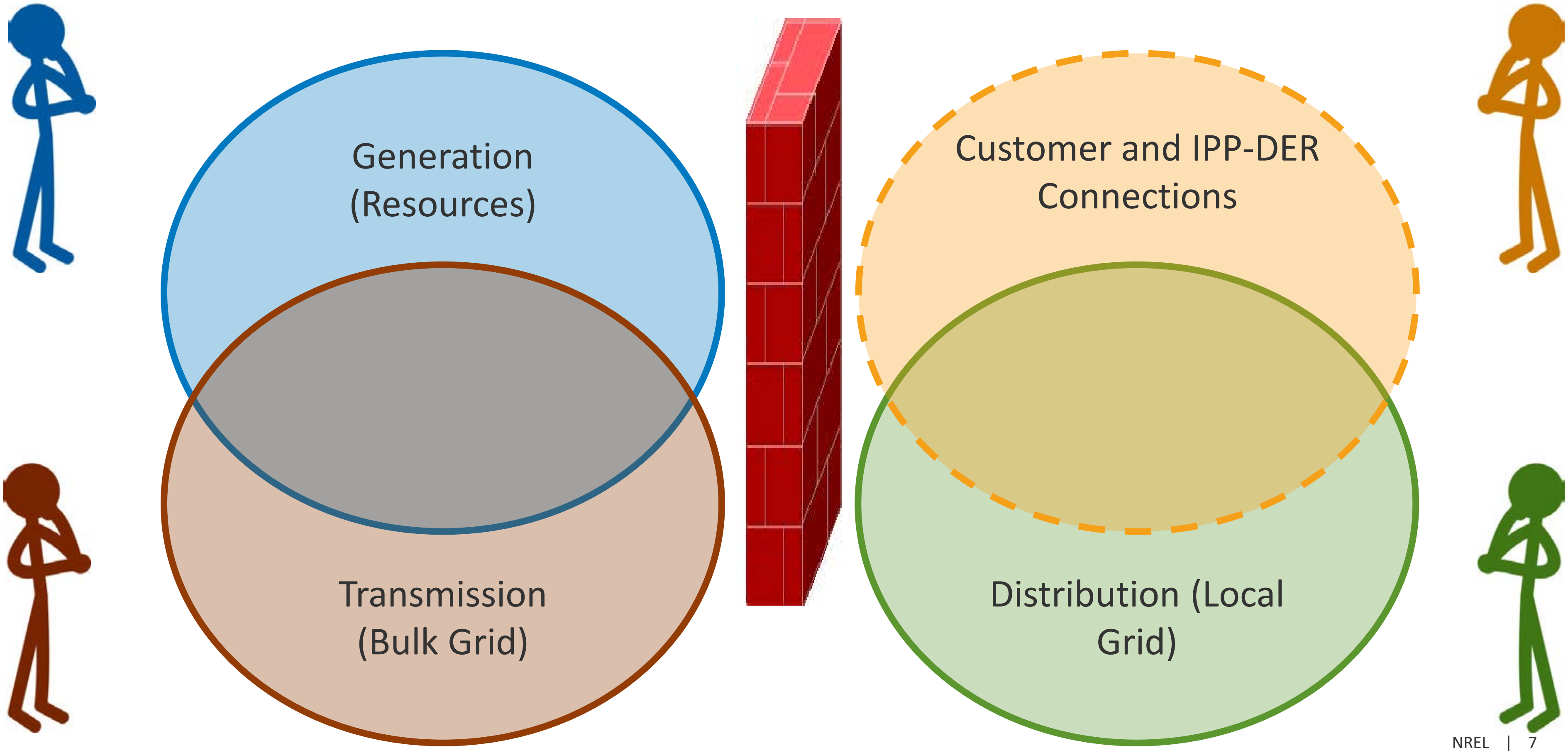
Silos of Excellence



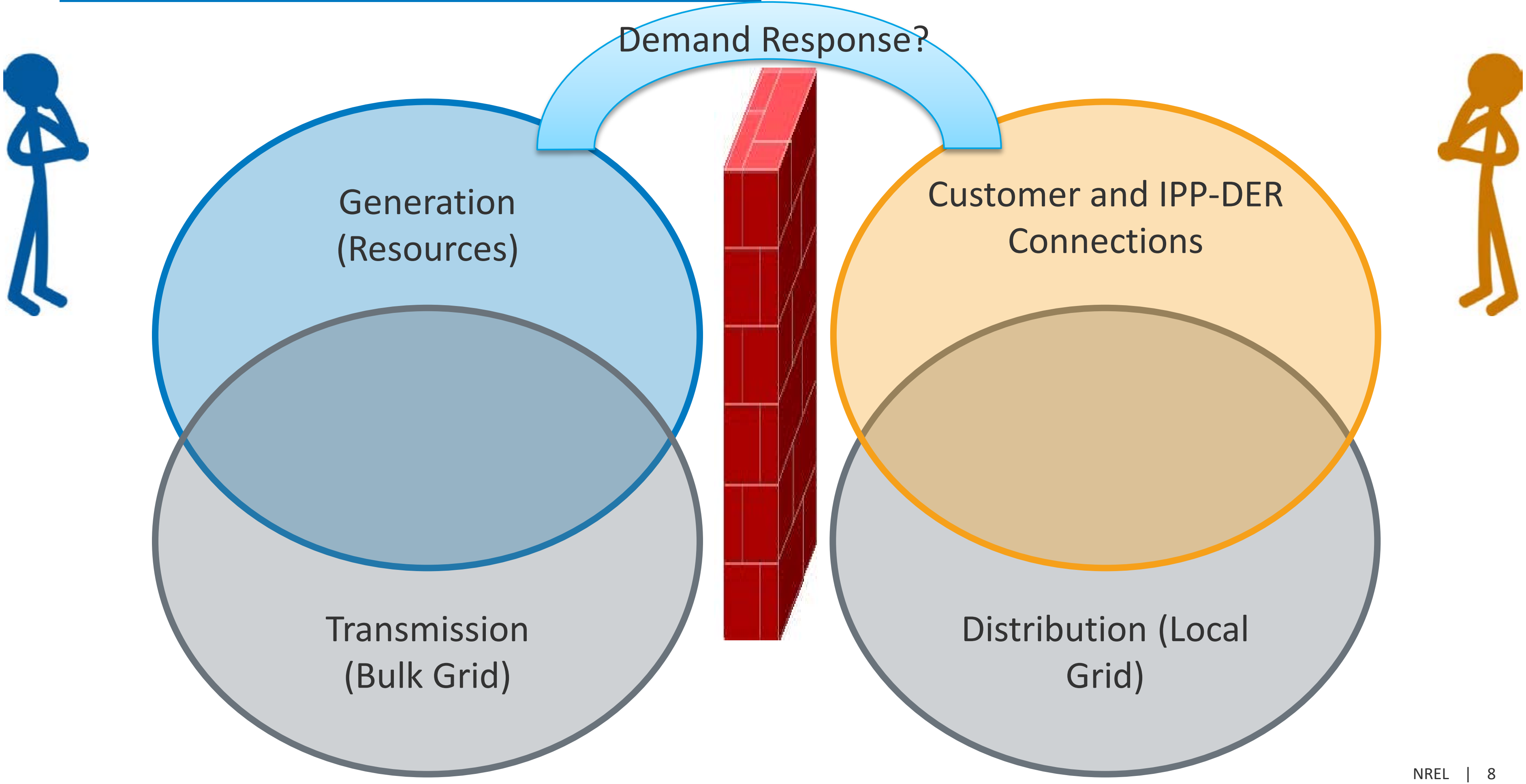
(Partly) Integrated Planning Within Spatial Scales



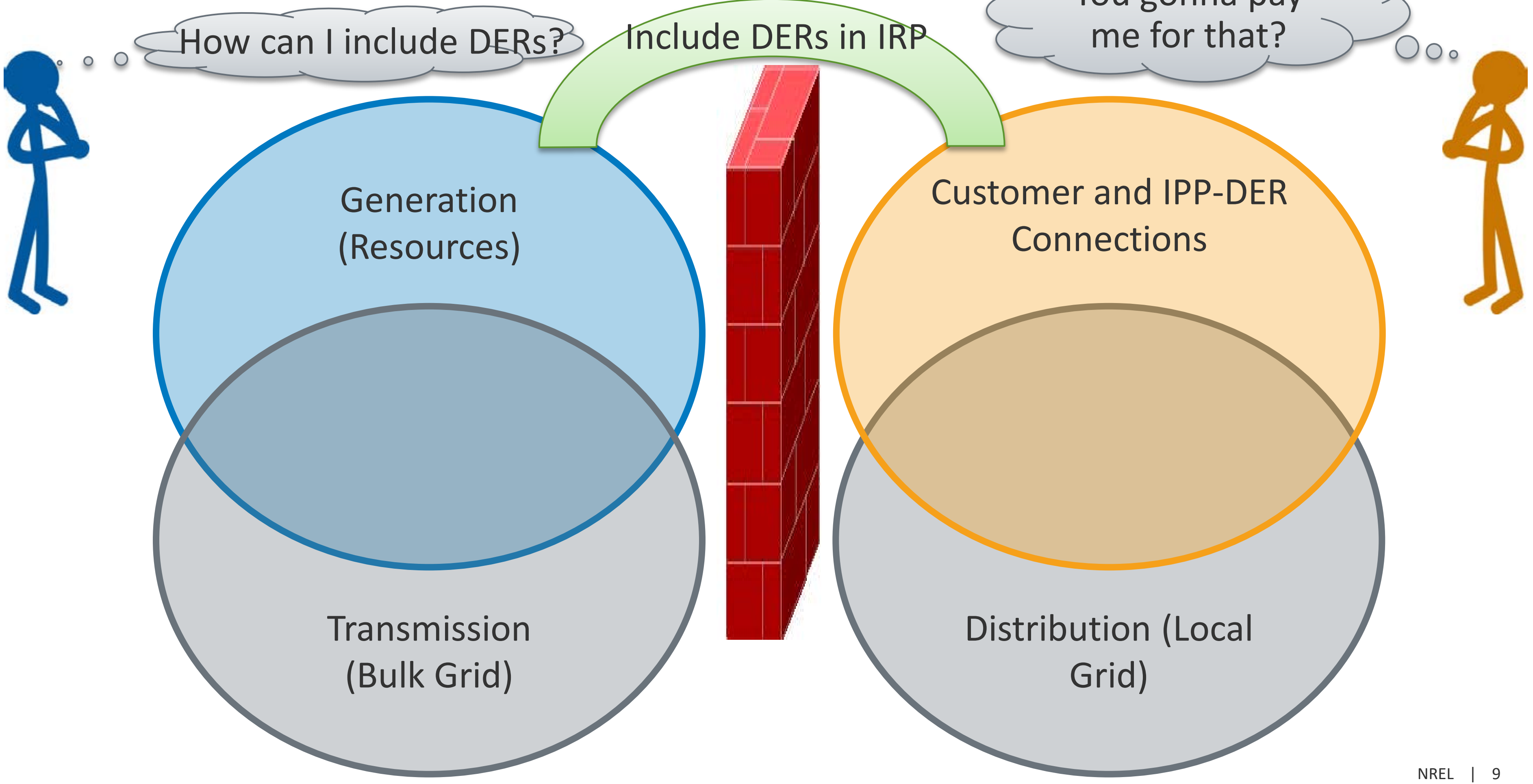
The T-D wall


Generation (Resources)
Transmission (Bulk Grid)
Customer and IPP-DER Connections
Distribution (Local Grid)

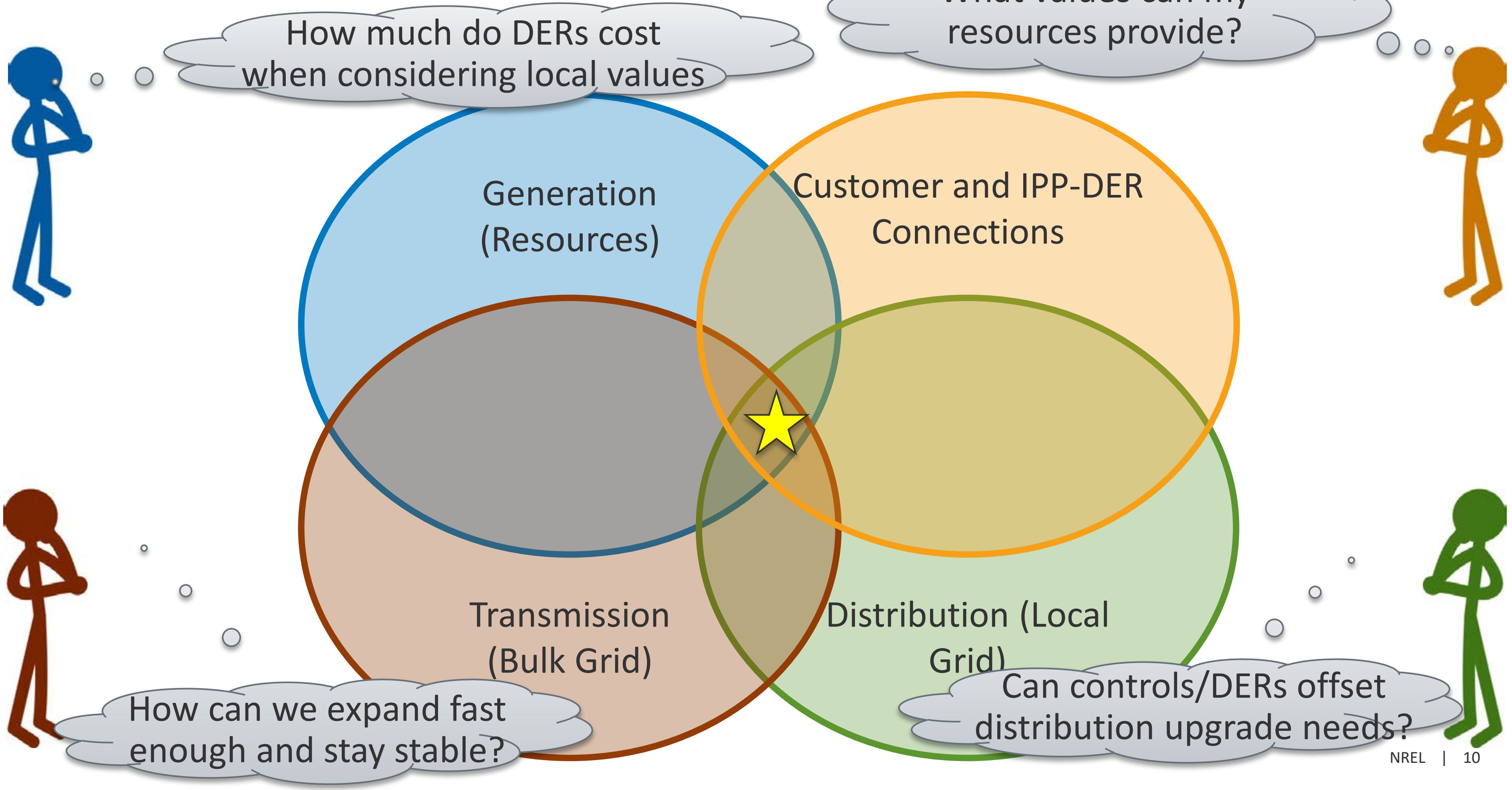
The T-D wall


Demand Response?
Generation (Resources)
Customer and IPP-DER Connections
Transmission (Bulk Grid)
Distribution (Local Grid)

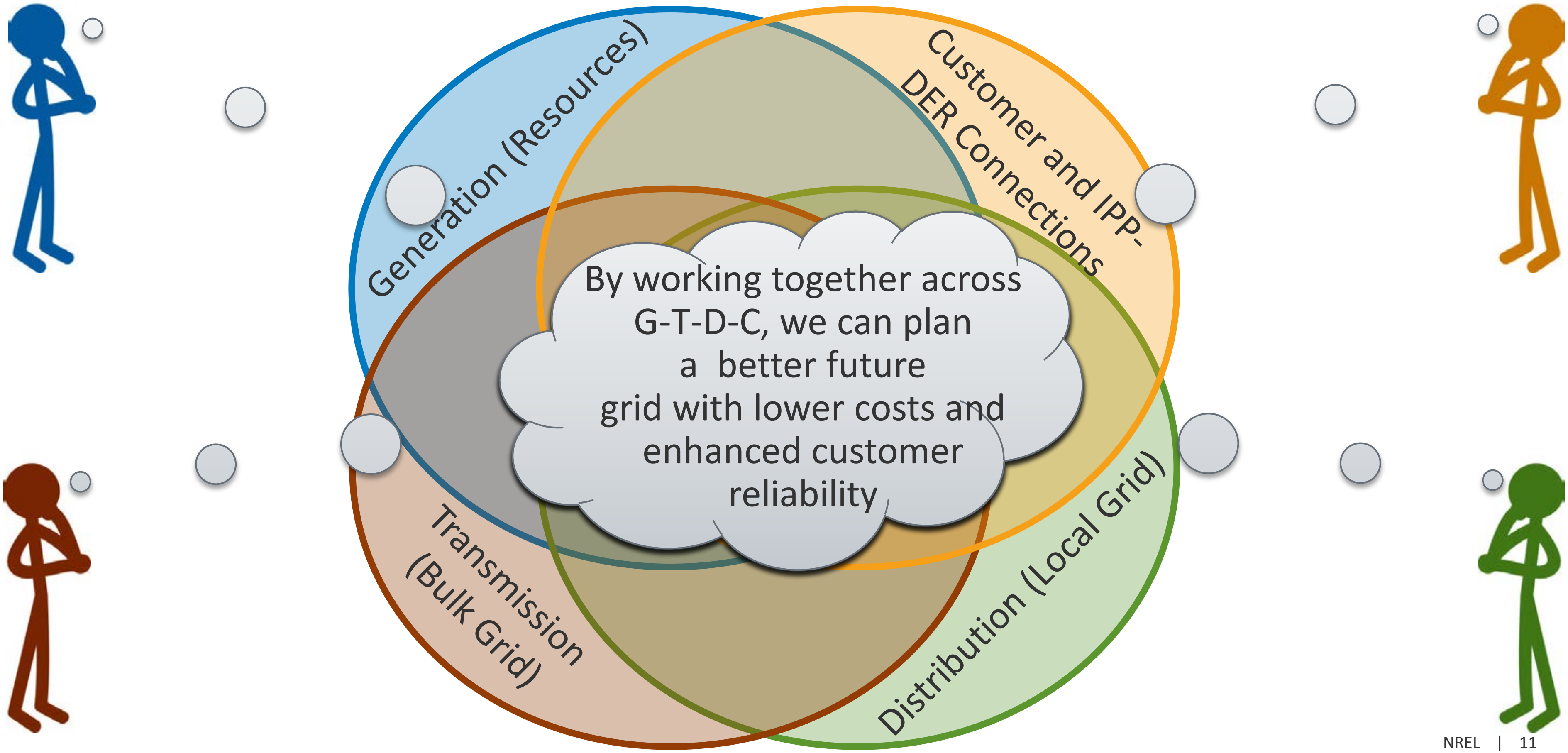
The T-D wall


How can I include DERs?
Include DERs in IRP
You gonna pay me for that?
Generation (Resources)
Transmission (Bulk Grid)
Customer and IPP-DER Connections
Distribution (Local Grid)

G-T-D-C Planning

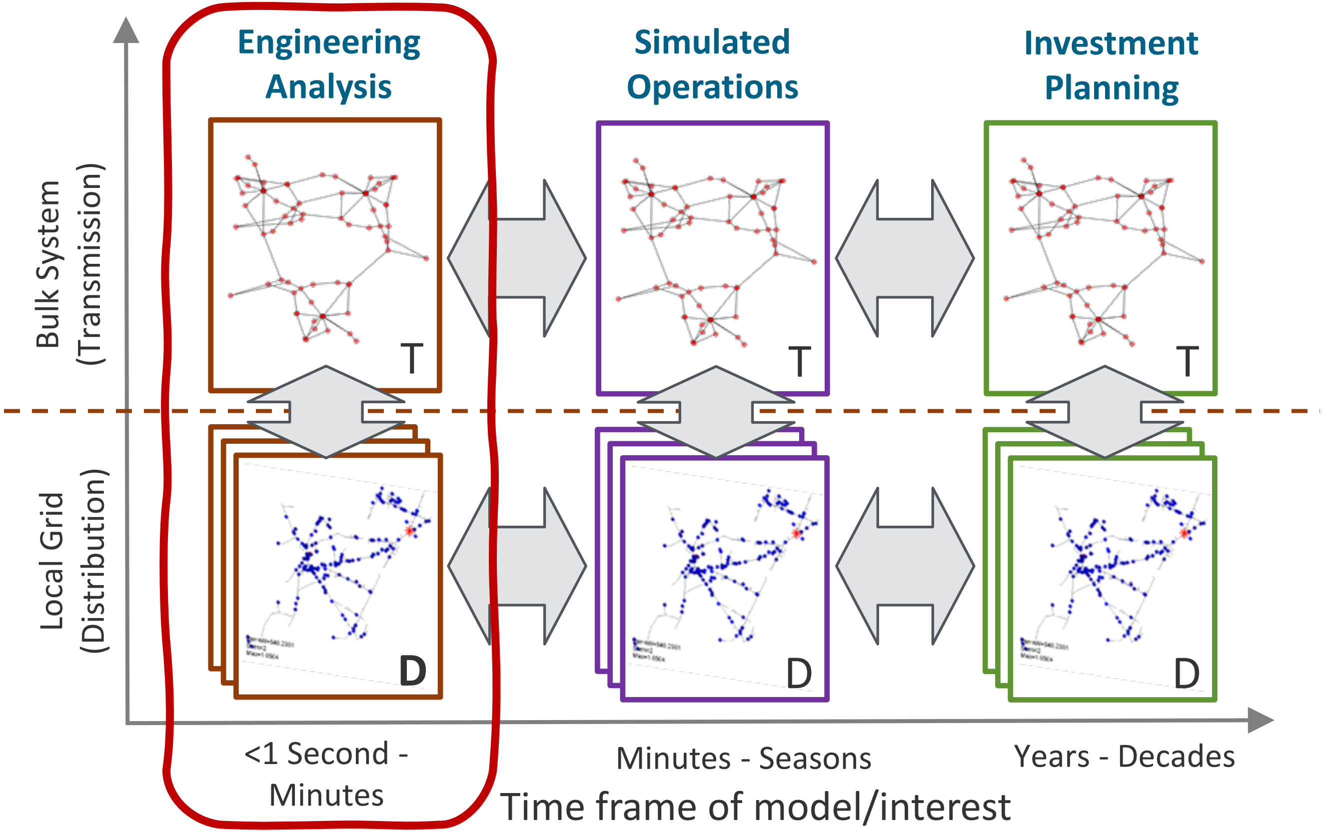


G-T-D-C Planning



Considerations for T&D (scale) Interactions in Planning

T&D interactions cross a range of time scales, with different tools and considerations



Considerations for fast (<1sec) dynamics

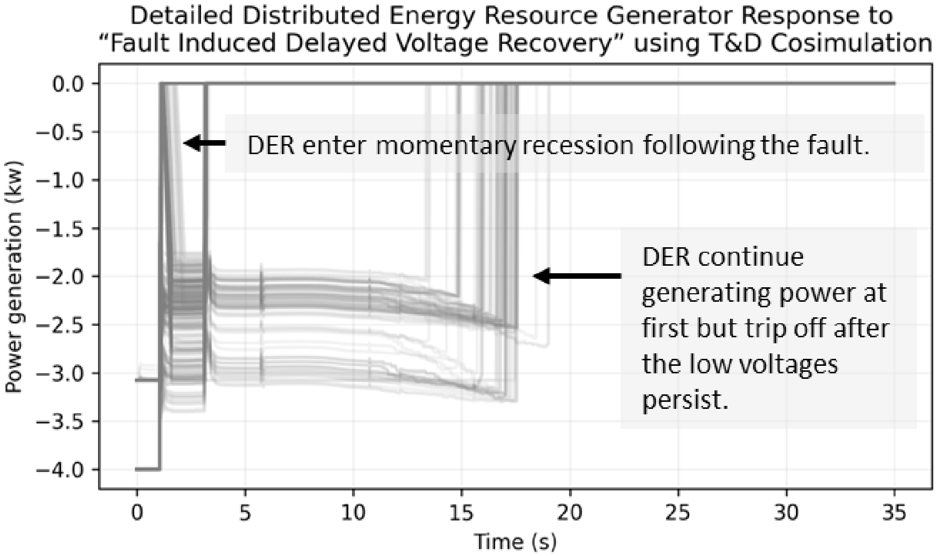
- Dynamic DER models (e.g., DER_A) and composite load models
  - How many, what parameters
- DER impacts on stability
- Reactive Power Support (both directions)
  - EPRI study shows much lower Grid-Forming (GFM) capacity required if also located on distribution
- Contingencies
- Intentional Islanding

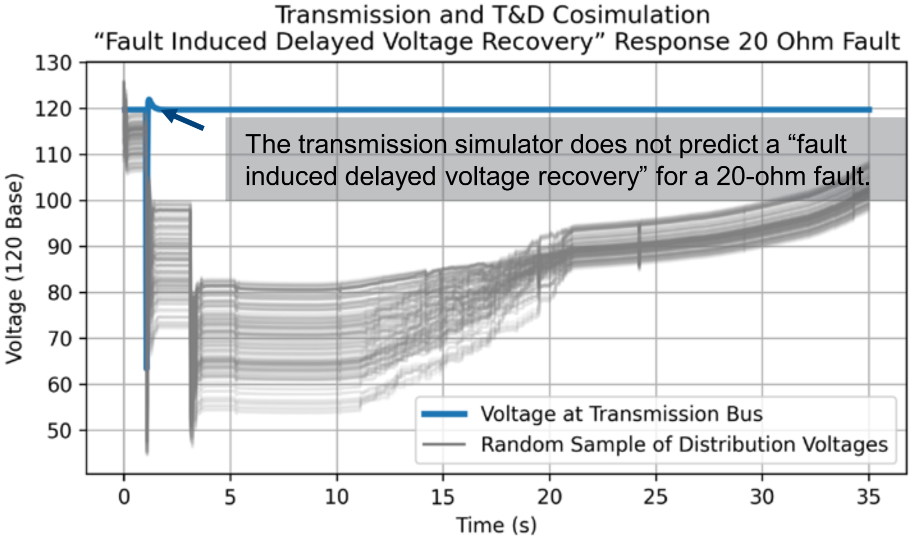
North American Electric Reliability Corporation (NERC). "Reliability Guideline – Parameterization of the DER_A Model." September 2019. URL: *https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_DER_A_Parameterization.pdf*

Venkataramanan, Ashwin, Wenzong Wang, Deepak Ramasubramanian, Aminul Huque, and Ali Mehrizi-Sani. 2025. "Stability Analysis of Distribution Networks With High Penetration of Distributed Energy Resources." IEEE Access 13:83867–80. *https://doi.org/10.1109/ACCESS.2025.3566476.*

Puerto Rico example: Important to model high DER well for transmission stability

- PSS/e with multiple feeders in OpenDSS using HELICS
- Real System Data from Puerto Rico





Elizondo, Marcelo, et al. 2024. "Section 10: Bulk System Power Flow, Dynamic, and Resilience Impact Analysis." In Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100): Final Report. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy24osti/88384.pdf.

HELICS™: Hierarchical Engine for Large-scale Infrastructure Co-Simulation

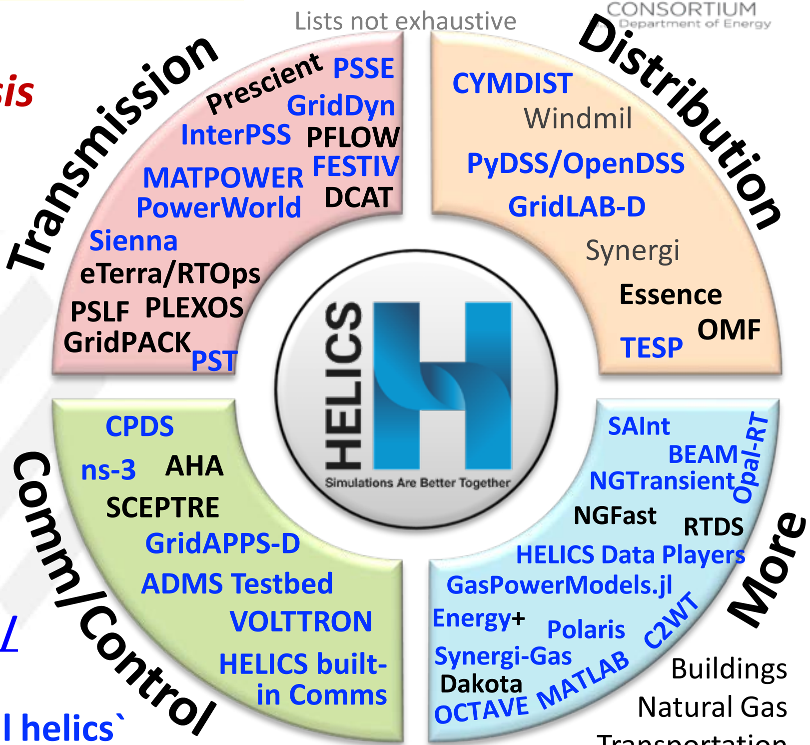
High-performance co-simulation to combine best-in-class tools for breakthrough integrated energy analysis

Capabilities:

- **Scalable:** 2-10,000,000+ Federates
- **Cross-platform:** HPC (Linux), Cloud, Workstations, Laptops (Windows/OSX)
- **Modular:** mix and match tools
- **Minimally invasive:** easy to use lab/commercial/open tools
- **APIs:** Python, C++, C, Julia, C#, MATLAB, Java, FMI, etc.
- **Open Source:** BSD 3-clause
- **Many Simulation Types:** Timeseries, Dynamics, Events
- (Some) **Other Features:**
  - Co-iteration enabled: “tight coupling”
  - Web-based simulation monitoring
  - Built-in Units Management
  - RegEx name matching
  - Real-time mode
  - Dynamic Federations

v3.5.x and details at https://helics.org/introduction/ https://github.com/GMLC-TDC/HELICS/releases or via `pip install helics`

Lists not exhaustive



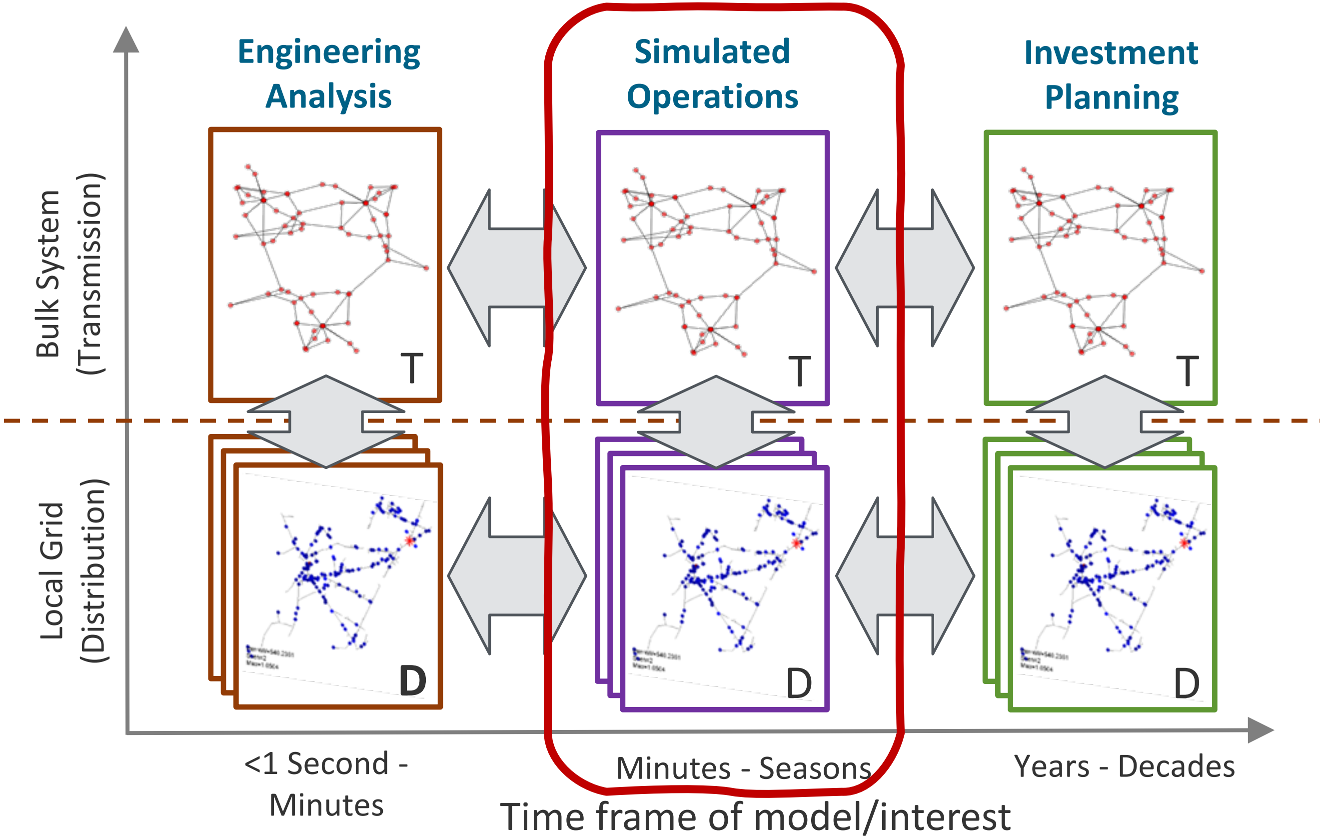
Buildings
Natural Gas
Transportation
Optimization / Solvers

Existing **Ongoing** Waiting

Hardy, Trevor, Bryan Palmintier, Phillip Top, Dheepak Krishnamurthy, and Jason Fuller. 2024. “HELICS: A Co-Simulation Framework for Scalable Multi-Domain Modeling and Analysis.” IEEE Access 12: 24325–24347. DOI: 10.1109/ACCESS.2024.3363615.

Pacific Northwest National Laboratory · Lawrence Livermore National Laboratory · NREL · Argonne National Laboratory · INL Idaho National Laboratory · Sandia National Laboratories · Oak Ridge National Laboratory

T&D interactions cross a range of time scales, with different tools and considerations

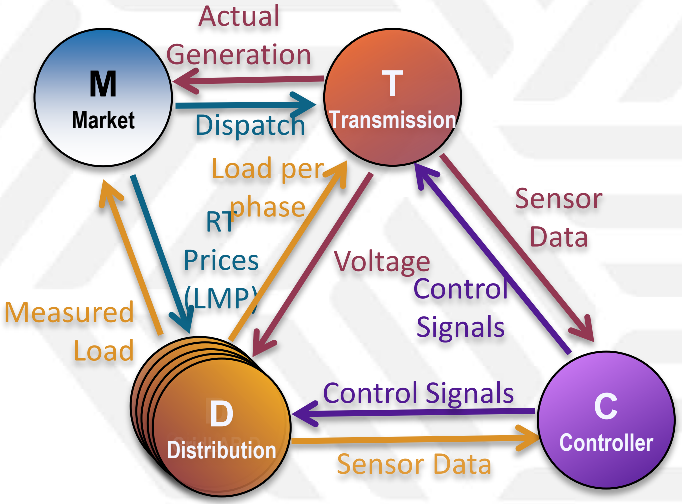


Types of questions for T&D operational simulations

- System-wide energy impacts from DERs
- Dispatch and visibility for DERs
- Market Interactions?
- Services from DER
- Distribution limits on DER use
- Distributed Energy Resource Management System? Aggregators?
- Resource Adequacy?

Co-simulation enables simulating arbitrary combinations of physical/engineering and control/market tools

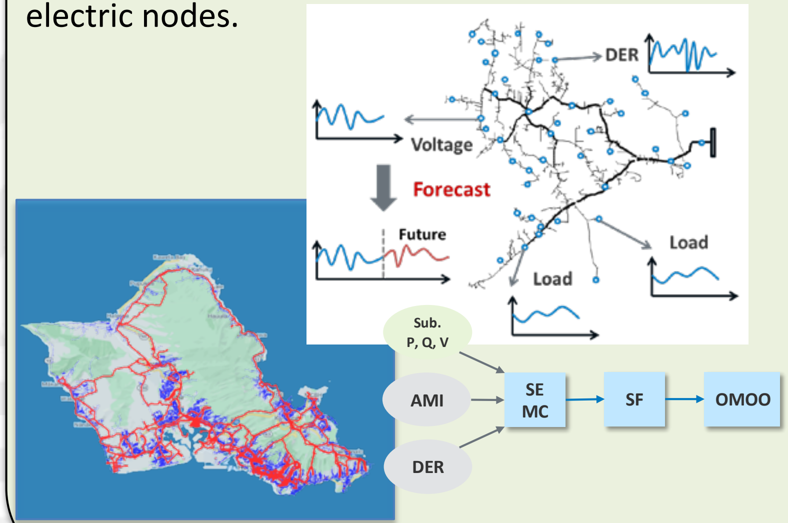
- Physical Data (Values)
  - Voltage, Frequency, Current
- Market Data (Messages)
  - Measured Load, Locational Marginal Prices (LMPs)
- Controller Data (Messages)
  - Sensor Readings, Control Signals



Novel T&D Control Architecture

Design: Predictive State Estimation and Machine Learning Control

Grid Sim: Entire Island of Oahu, Hawaii with >1M electric nodes.



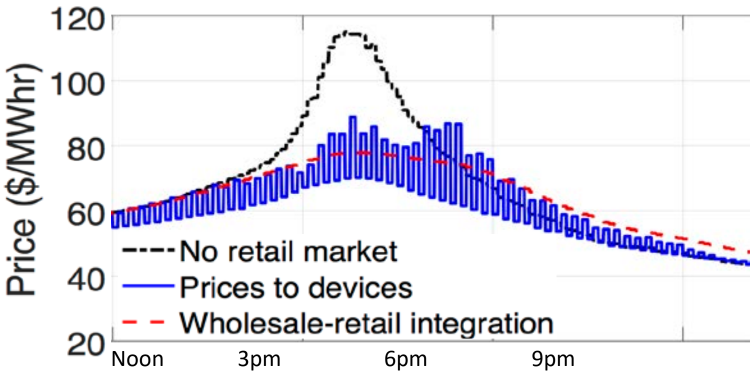
Project: GO-Solar

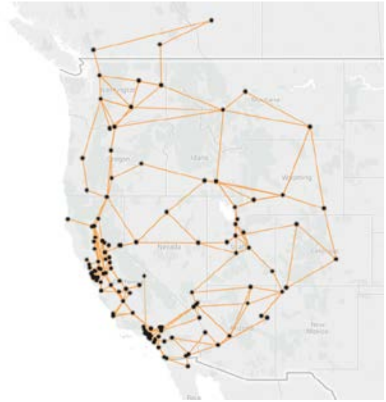
R. Yang *et al.*, "Grid optimization with solar (GO-Solar)," presented at the ADMS Test Bed Webinar, Feb. 16, 2022. https://www.nrel.gov/docs/fy22osti/82026.pdf

Example: Distribution + Market Operations

Large-scale DER-Market Interactions

- Distribution: 35k feeders
  - 25M homes
- Transmission: 240-bus (simplified) WECC
- Simplified California Independent System Operator-style Market.





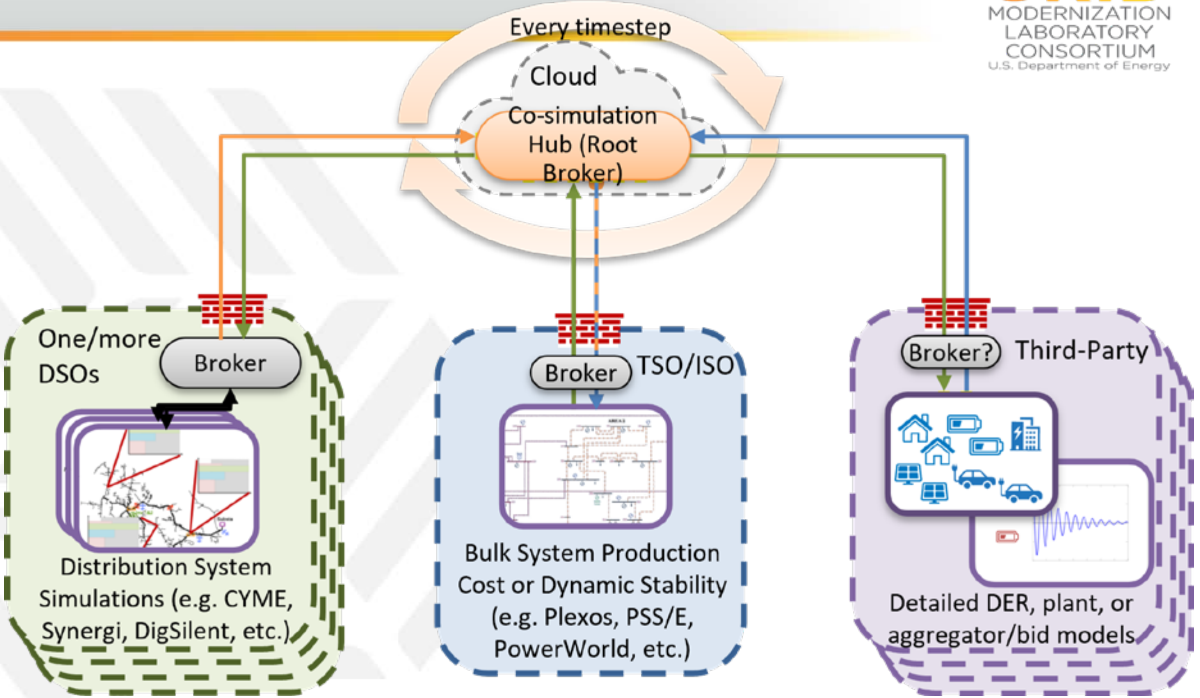
Take aways:

- *Price responsive loads can lower prices, but may introduce oscillations if not done well*
- *T&D co-simulation required to fully capture*

Hansen, Jacob, Trevor Hardy, and Laurentiu Marinovici. 2019. "Transactive Energy: Stabilizing Oscillations in Integrated Wholesale-Retail Energy Markets." Presented at: 2019 IEEE PES Innovative Smart Grid Technologies Conference (ISGT). https://doi.org/10.1109/ISGT.2019.8791658.

Note: multi-model frameworks enable simulation without full data exchange

- Run a combined simulation across multiple sites/organizations
- Only exchange interface data
  - Avoid detailed/sensitive model exchange

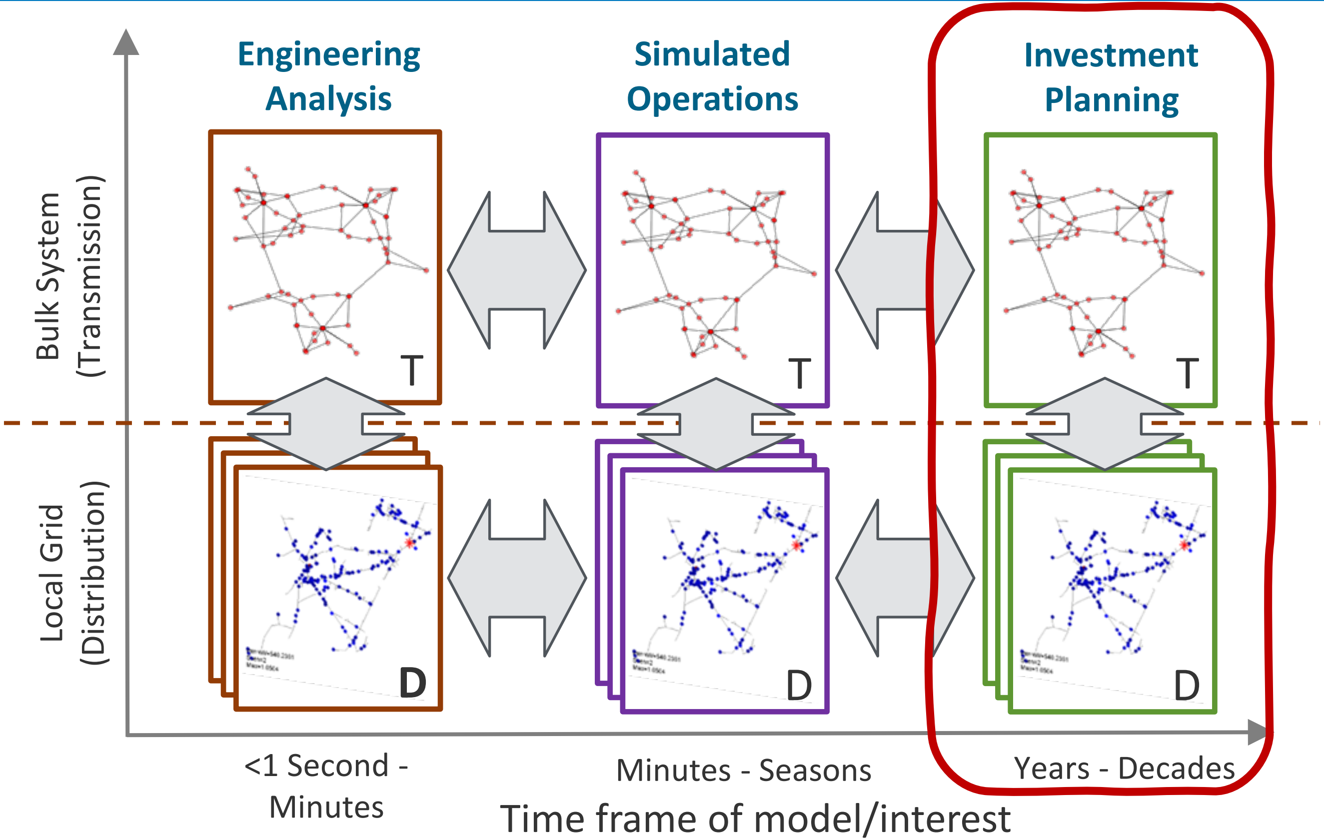


DSO: Distribution System Operator, ISO: Independent System Operator, TSO: Transmission System Operator

Palmintier, Bryan, Trevor Hardy, Phillip Top, Aadil Latif, and Jeremy Keen. 2024. "Keep Your Grid Model to Yourself: Co-simulation for Multi-entity Planning and Simulation Without Needing Detailed Model Exchange." 2024 Grid of the Future Symposium, Raleigh, NC: CIGRE US National Committee.

- Broker hierarchy: simplifies configuration and high local performance
- (optional) message exchange encryption with OpenSSL

T&D interactions cross a range of time scales, with different tools and considerations

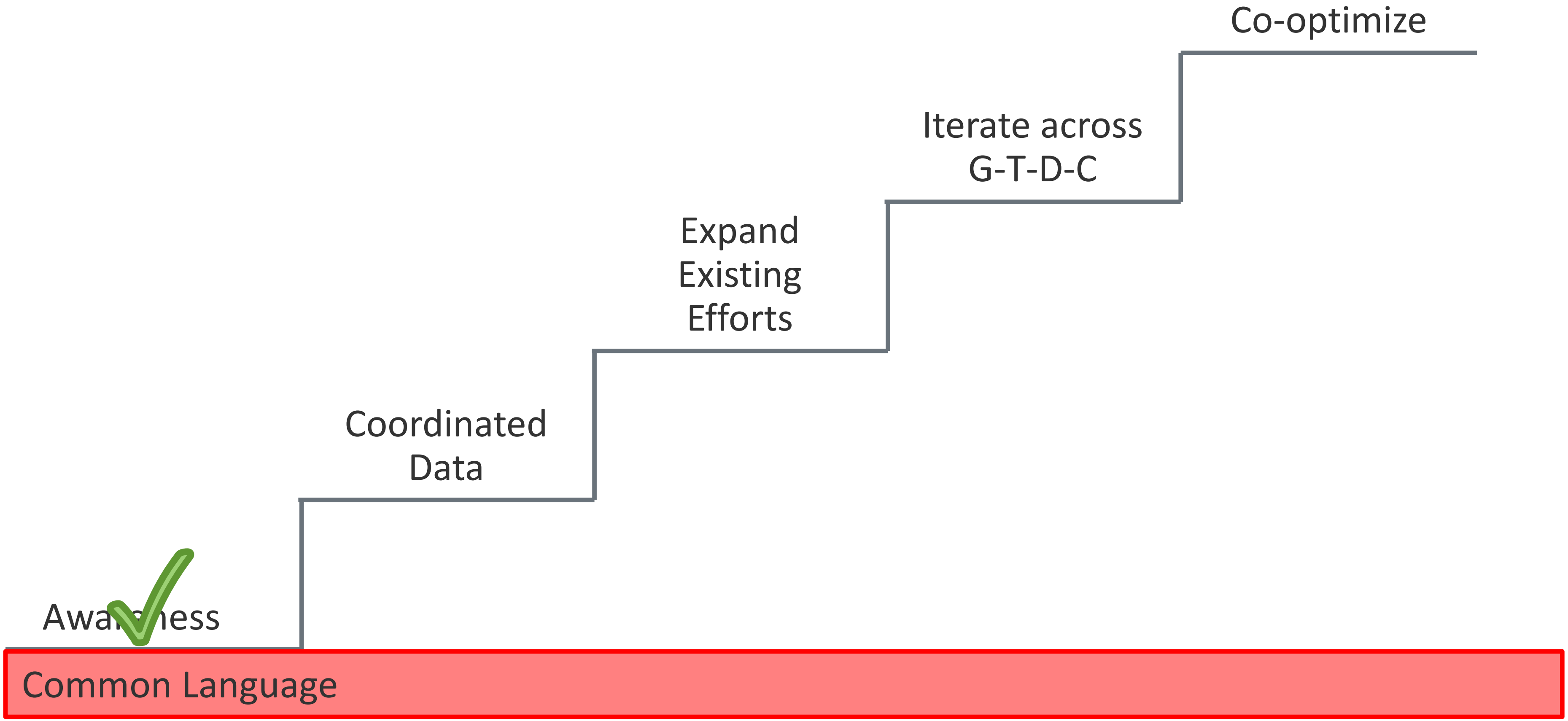


Example integrated planning questions

- To what extent can DER and distribution **offset bulk system investments**? (e.g. generation, transmission)
  - How much **controllability of DERs** is needed?
- Where do **bulk constraints** drive additional front-of-meter (FTM) distribution-sited resources?
  - Are **distribution upgrades** needed? Which?
- **Storage siting:** transmission or distribution?
  - What if resilience is considered?

Evolving Workflows for Integrated T&D Planning

How might we get there? (and challenges/needs)



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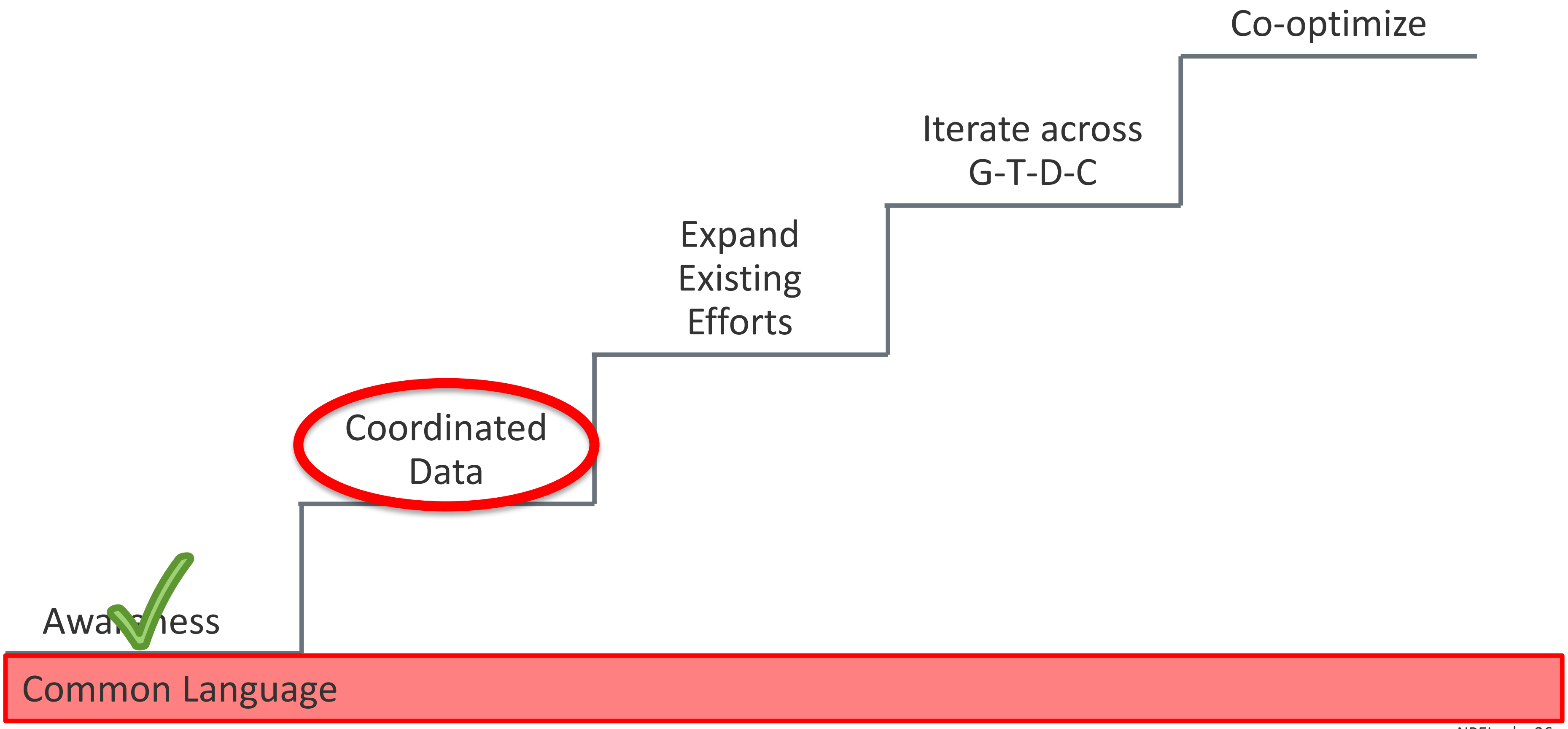


National Transmission Planning Study

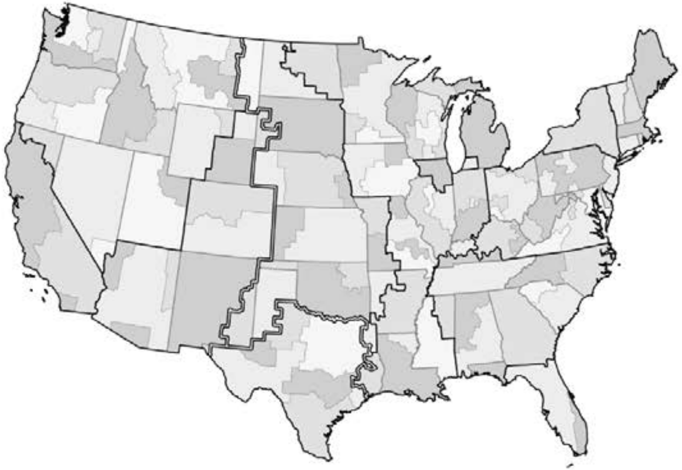
Better understand the role, value, and opportunities for transmission across the United States.

Identify **interregional and national strategies** to accelerate **energy growth** while maintaining system reliability

Inform regional and interregional transmission planning processes, particularly by **engaging stakeholders** in dialogue

Develop **methods for national-scale transmission planning** that are applicable for industry

Multimodel analysis for a low-cost, reliable transmission system of the future



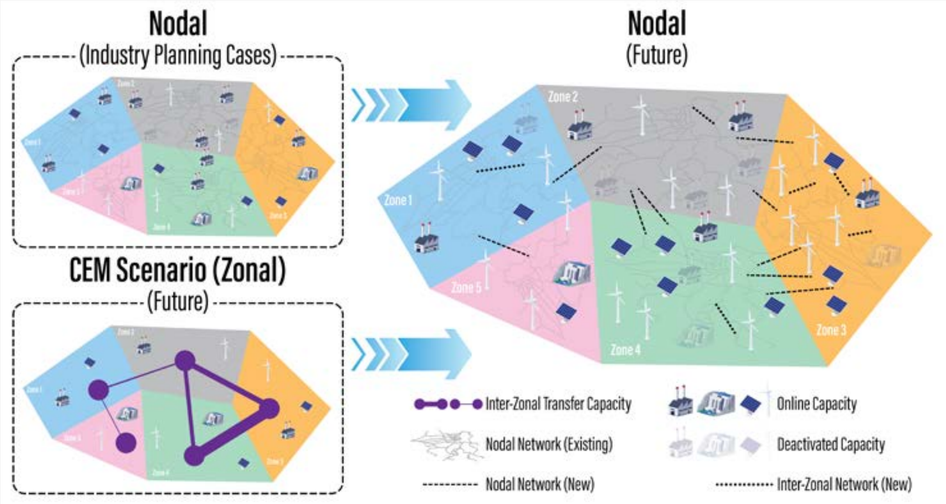
Zonal Resolution
Long-Term Scenarios through 2050

- Capacity Expansion
- Economic Analysis
- Resource Adequacy

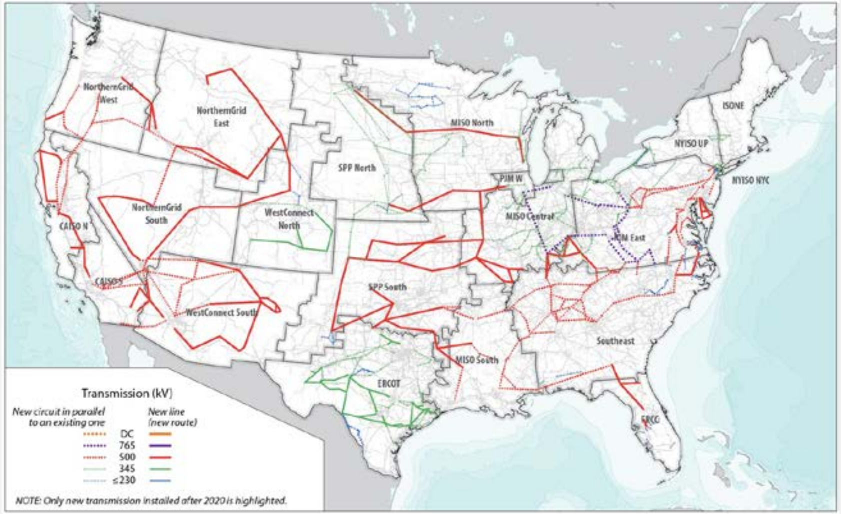
Nodal Resolution
2035 Transmission Portfolios

- Production Cost
- Power Flow
- Stress Analysis

Process for **zonal-to-nodal** translation



Nodal transmission expansion for the AC scenario for the model year 2035



Zonal to nodal translations of future transmission portfolios allows detailed operational analysis

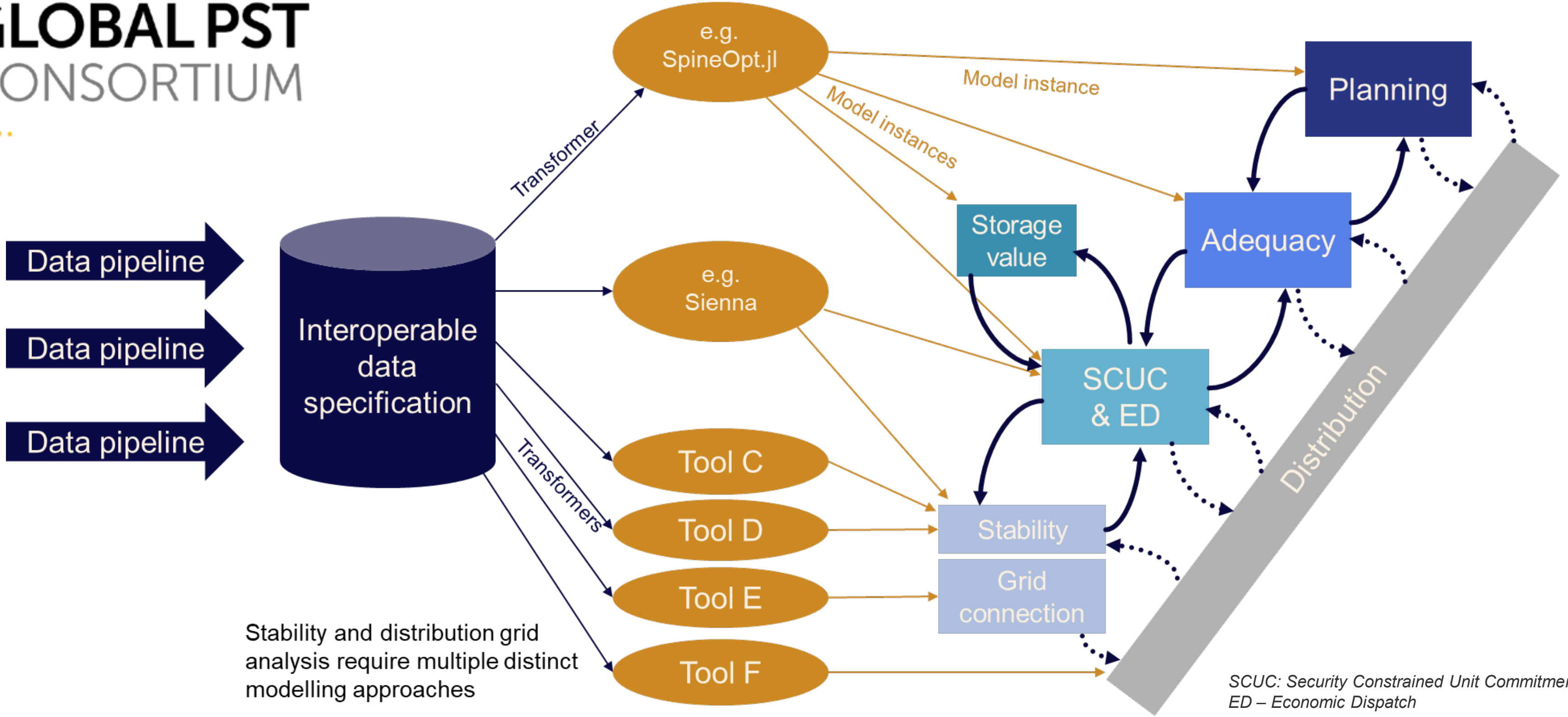
AC – Alternating Current

Advancing integrated distribution planning

Partners: Duquesne Light Company, PEPCO Holdings, Xcel Energy, PGE, Hawaiian Electric

J. Keen et al., “Distribution Capacity Expansion Planning: Current Practice, Opportunities, and Decision Support,” National Renewable Energy Laboratory (NREL), Golden, CO (United States), NREL/TP-6A40-83892, Nov. 2022. https://www.nrel.gov/docs/fy23osti/83892.pdf.

Interoperable data can enable expanded integrated planning workflows

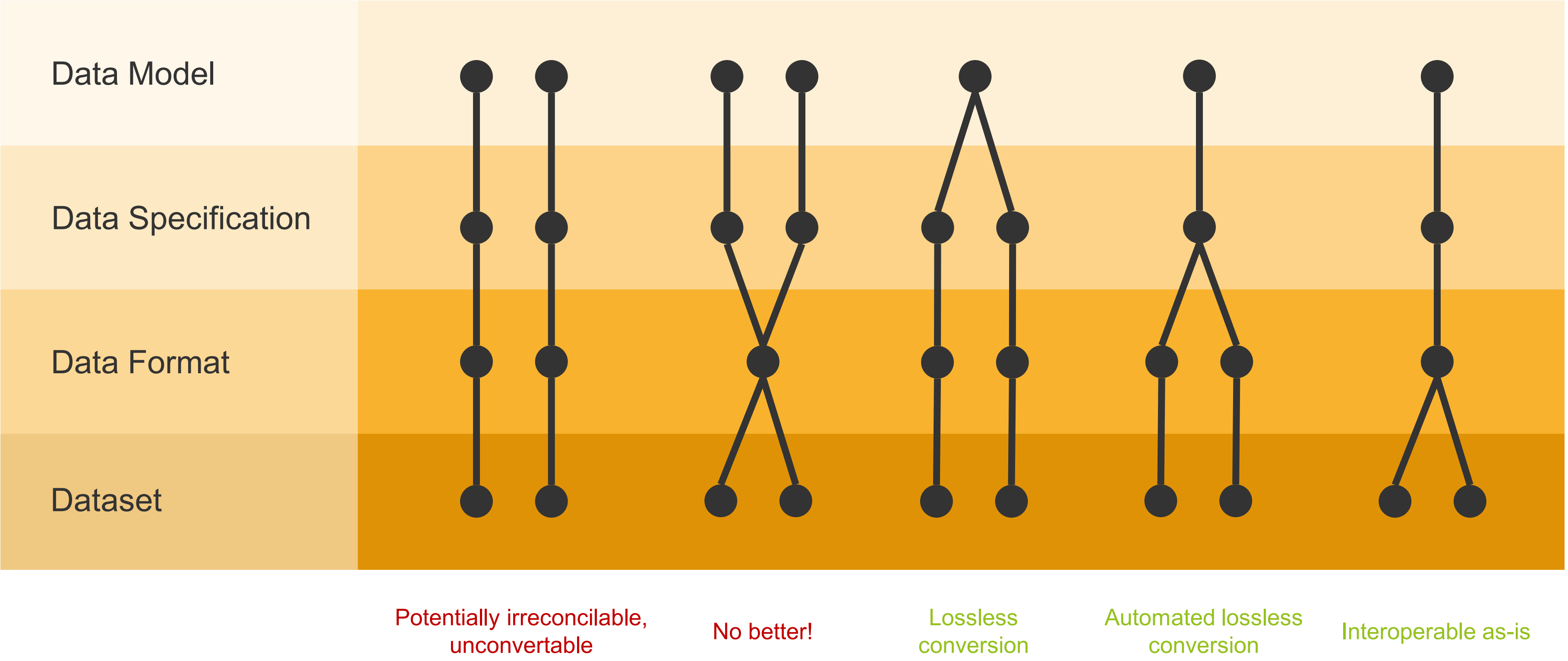


Stability and distribution grid analysis require multiple distinct modelling approaches

SCUC: Security Constrained Unit Commitment
ED – Economic Dispatch

Credit/Contact: Gord Stevens (NREL), Juha Kiviluoma (formerly VTT – Technical Research Center of Finland)

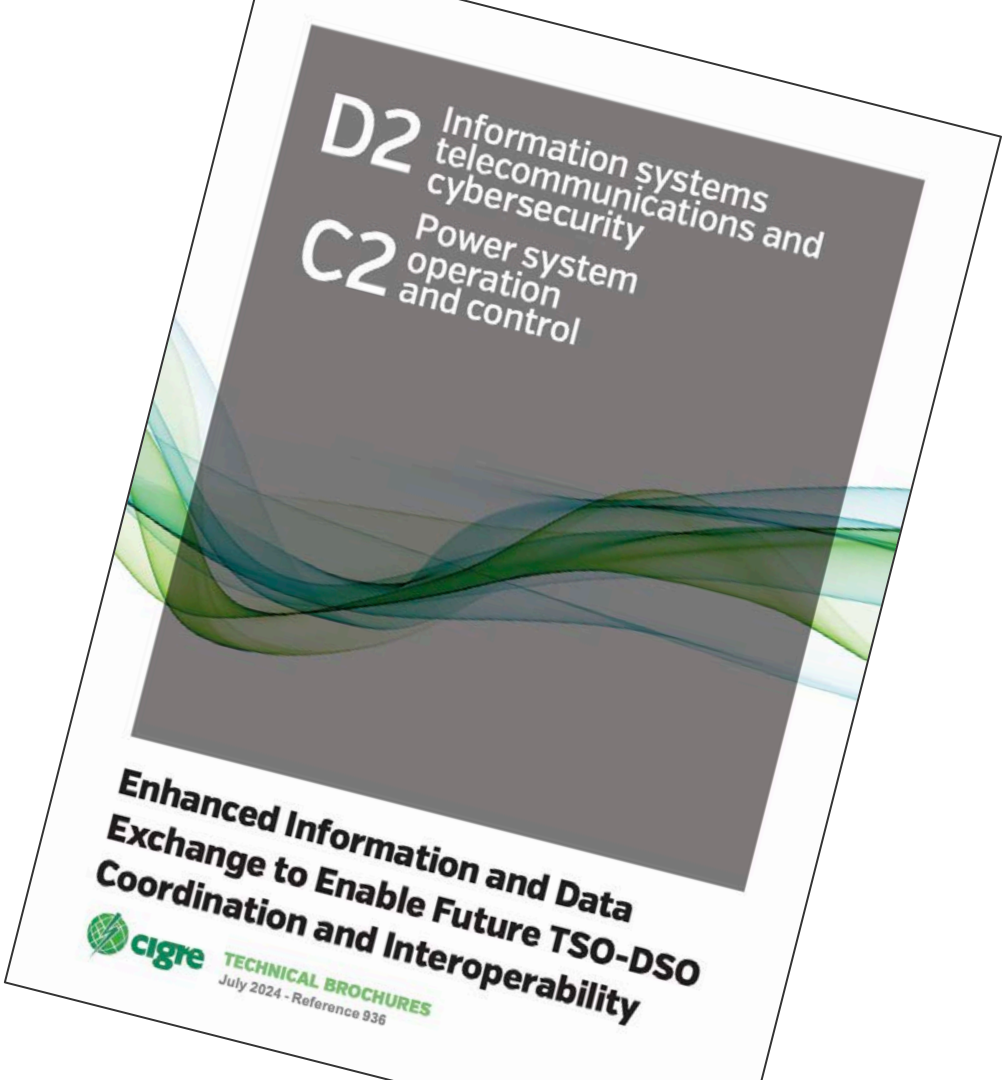
Harmonized data format is a key enabler



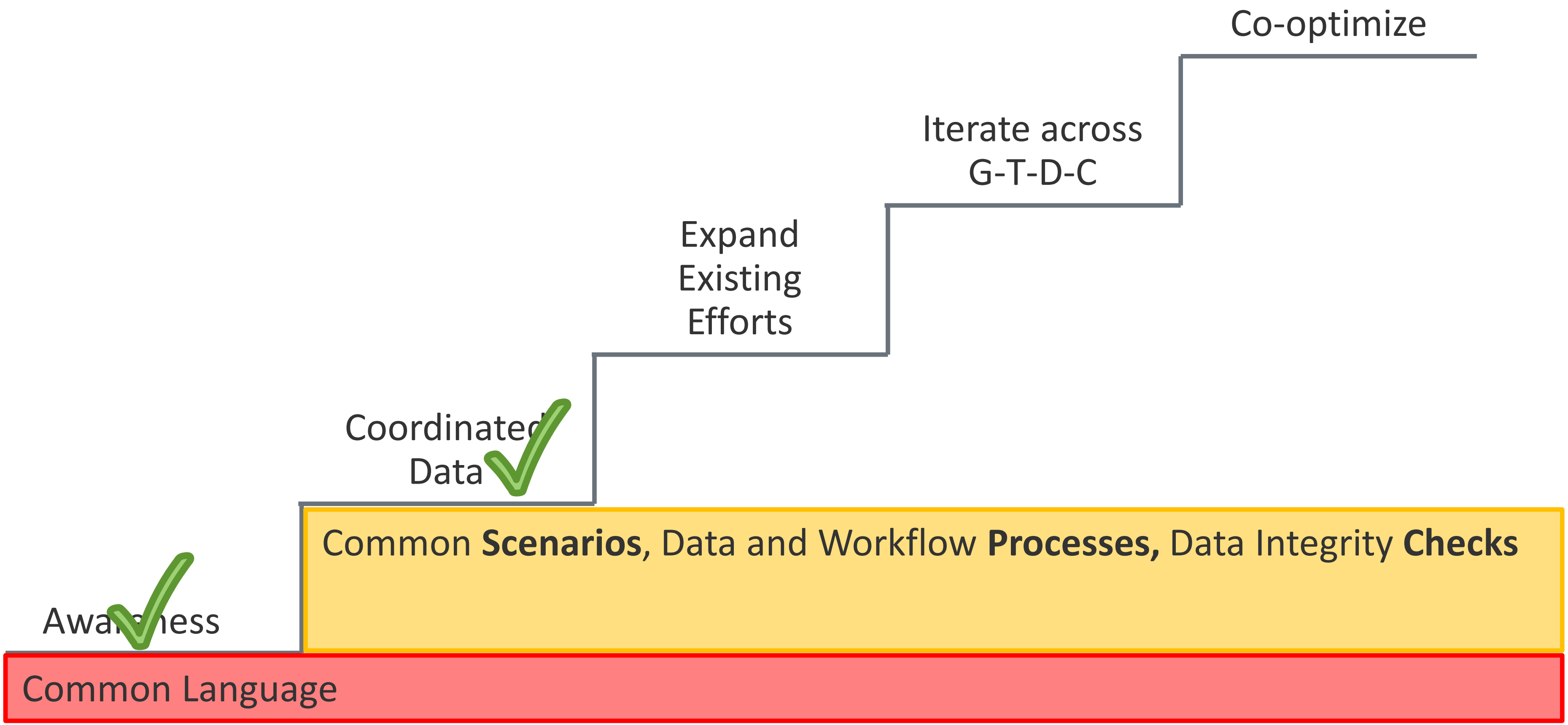
Credit/Contact: Gord Stevens (NREL), Juha Kiviluoma (formerly VTT – Technical Research Center of Finland)

Integrated T&D can require lots of data exchange

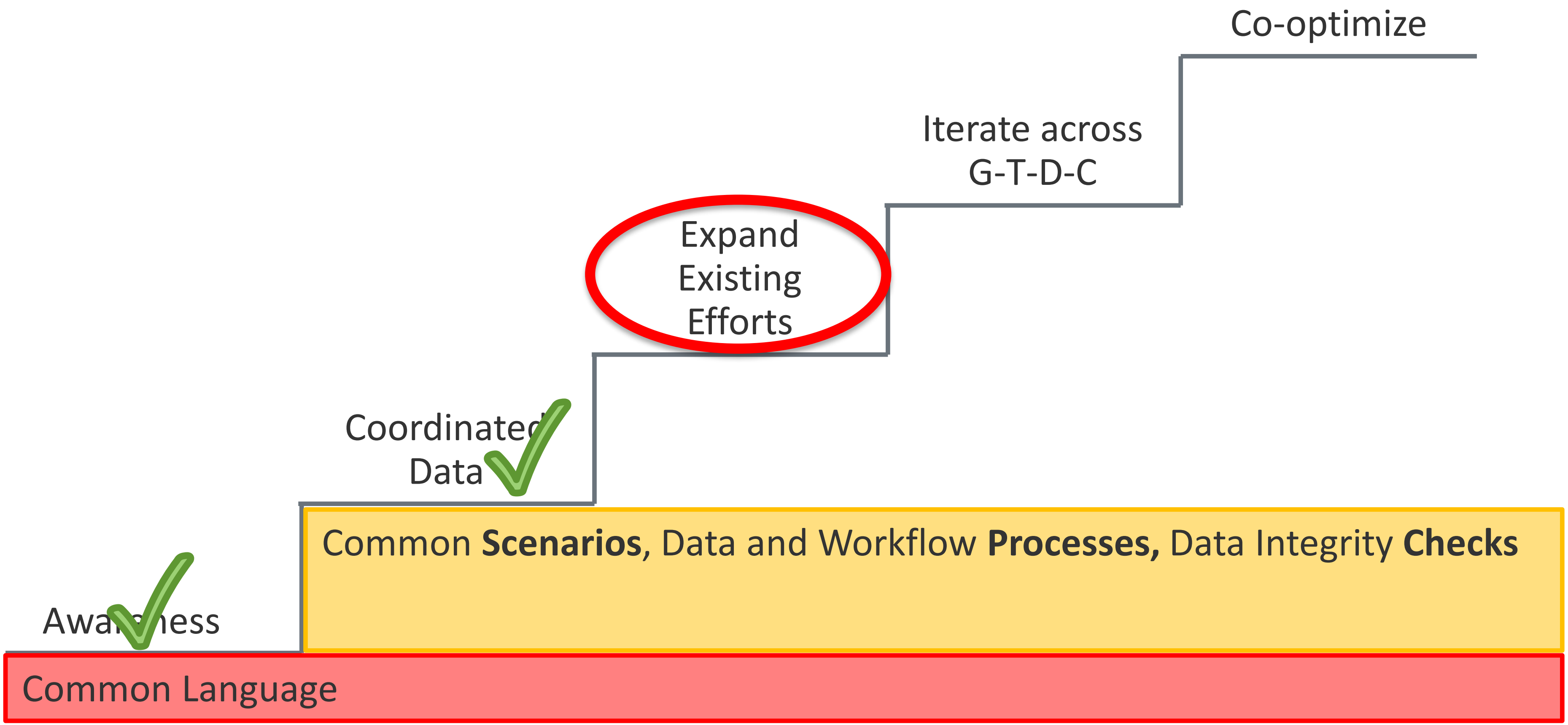
Thankfully, there are efforts to coordinate/ standardize



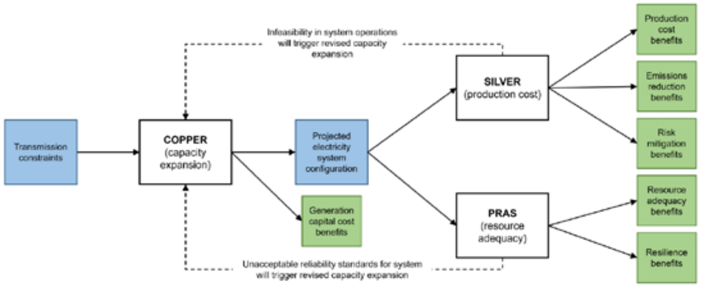
How might we get there? (and challenges/needs)



How might we get there? (and challenges/needs)

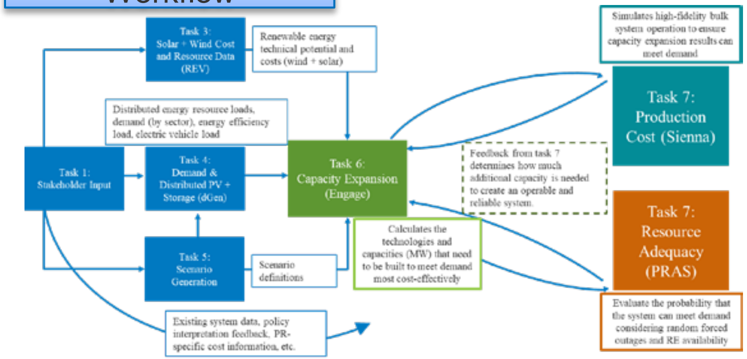


Expanding already complex workflows

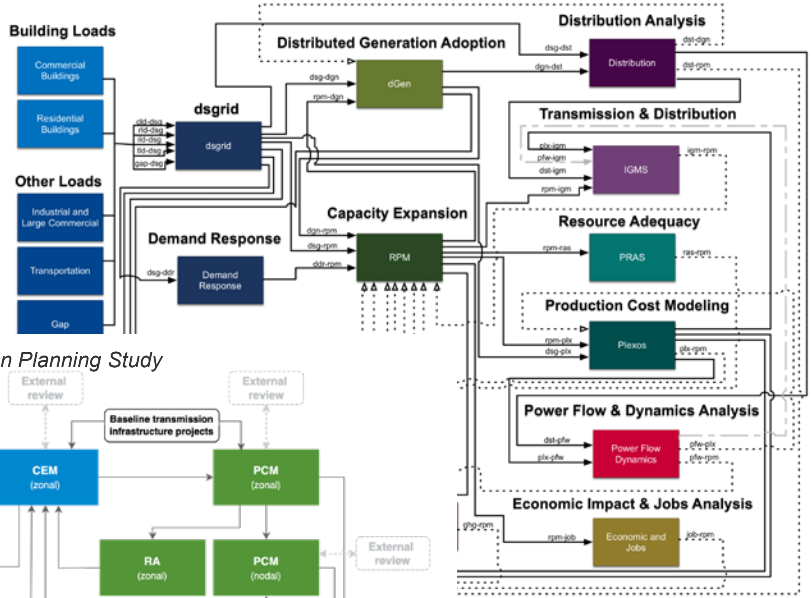


SESIT Group, University of Victoria

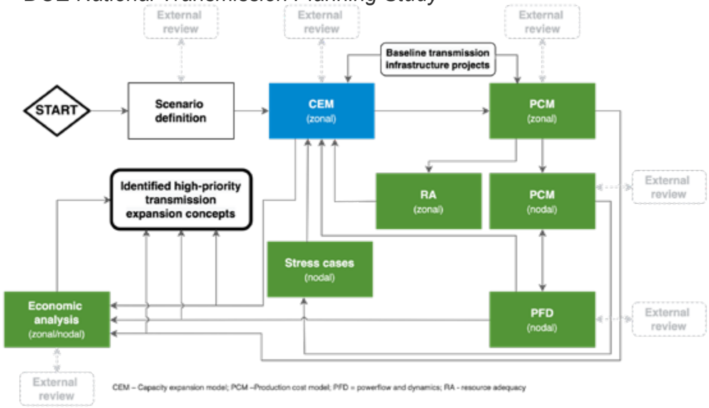
Puerto Rico Study Workflow



Los Angeles Study Workflow



DOE National Transmission Planning Study



And lots of Integrated Resource Planning (IRP) processes

Credit/Contact: Gord Stevens (NREL), Juha Kiviluoma (formerly VTT – Technical Research Center of Finland)

Case study – Comprehensive integrated grid planning modeling and analysis for Los Angeles

Map by Billy Roberts, NREL

LADWP by the Numbers

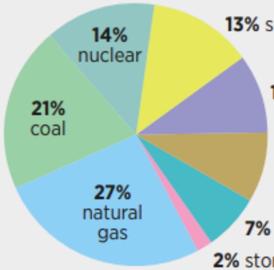
7,880 megawatts (MW) generation capacity

>3,600 miles of transmission lines to move electricity in

>10,400 miles of distribution lines to deliver power to customers

CUSTOMER ENERGY CONSUMPTION

2019 GENERATION MIX

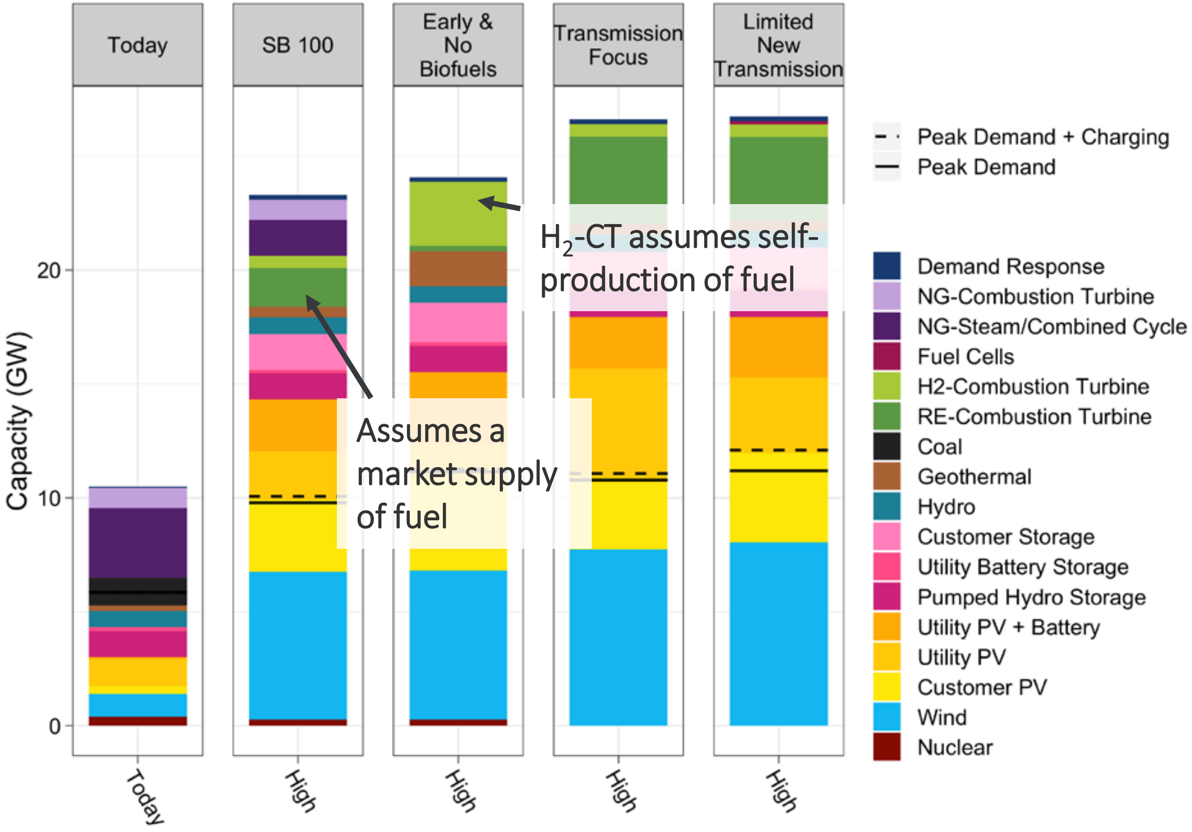


More at https://maps.nrel.gov/la100

LADWP – Los Angeles Department of Water and Power

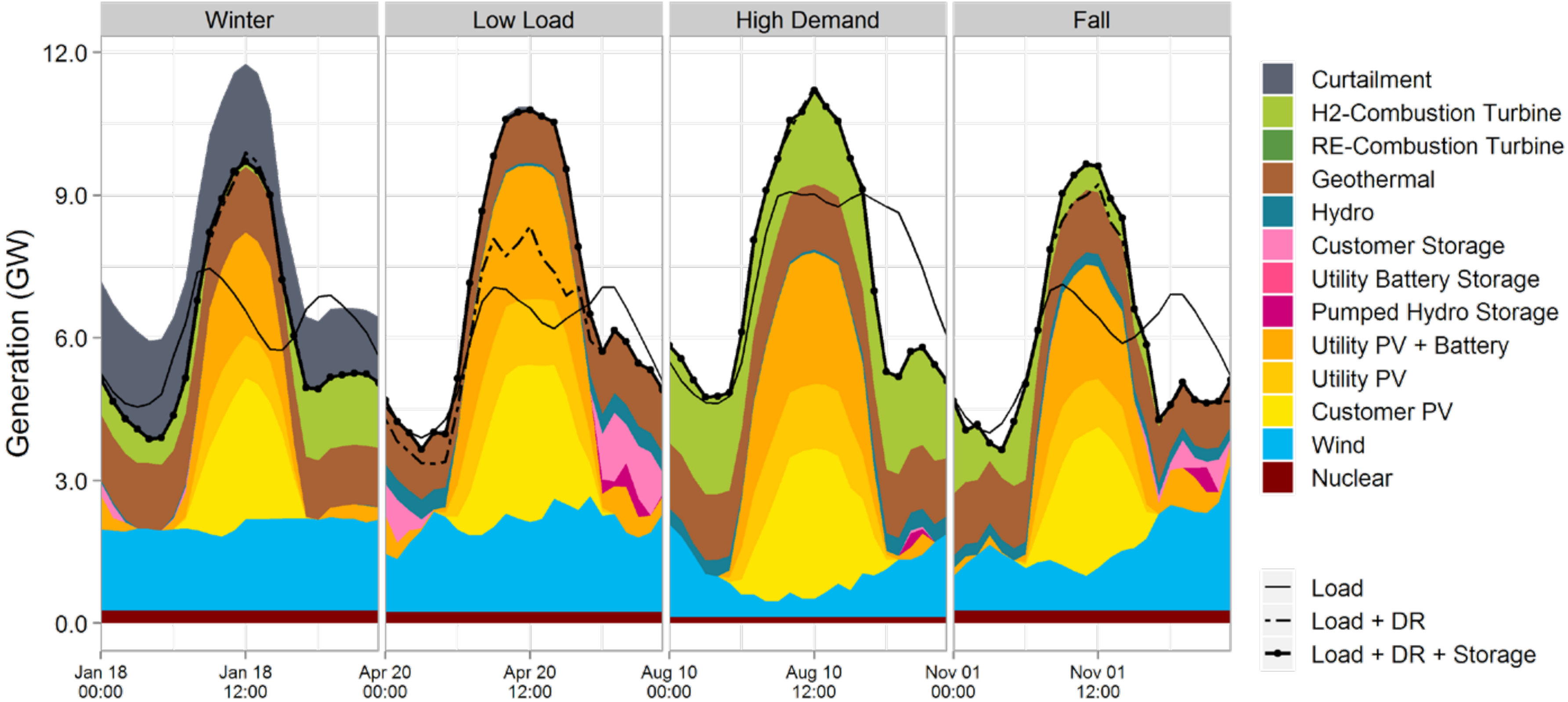
Examining future LA energy scenarios

Significant distribution-connected resources to support in-basin adequacy



Capacity Mix in 2045 — High Load Scenarios, Compared to 2020

System operation: what resources are operating in every hour?



Across all scenarios

Electrification
Efficiency
Flexible Load

Customer Rooftop Solar

Renewable Energy

Solar: + >5,700 MW
Wind: + >4,300 MW

Storage (including coupled with solar)

+ >2,700 MW

Distribution, Transmission

Combustion Turbines

+>2,600 MW (in basin)

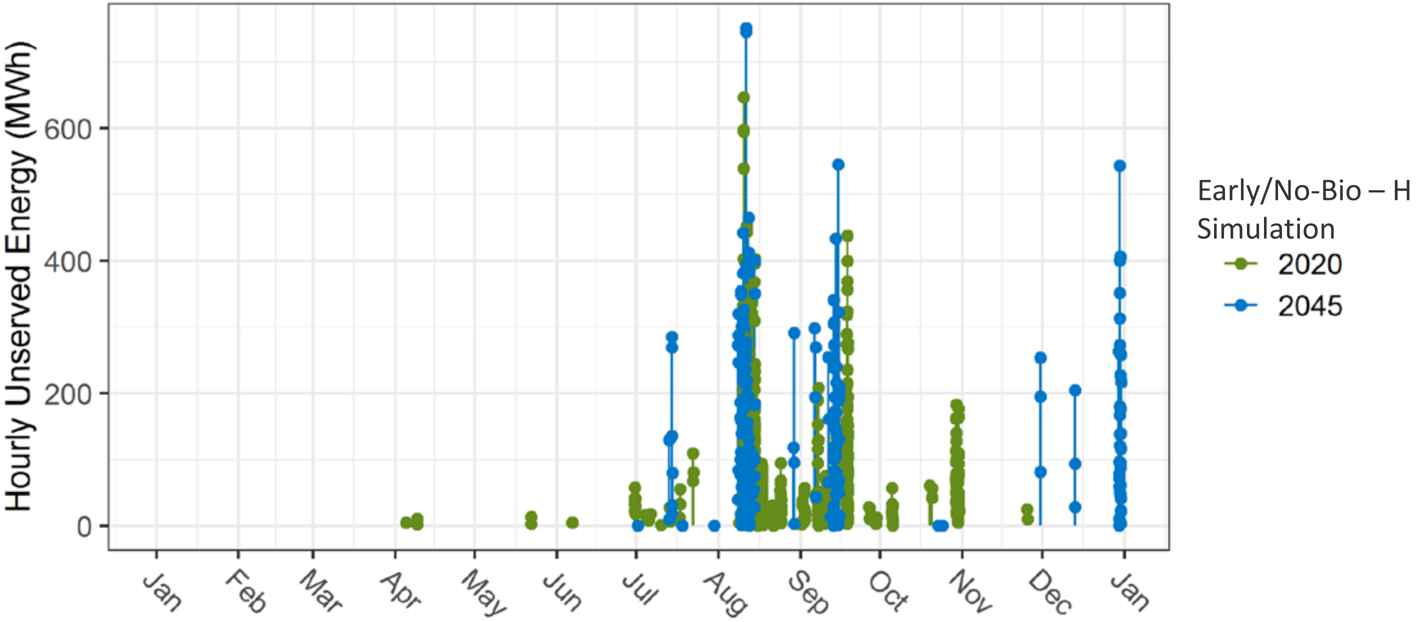
Much More

New

Natural gas	→	Biofuel/hydrogen
Today: Daily		**Future:** Infrequently

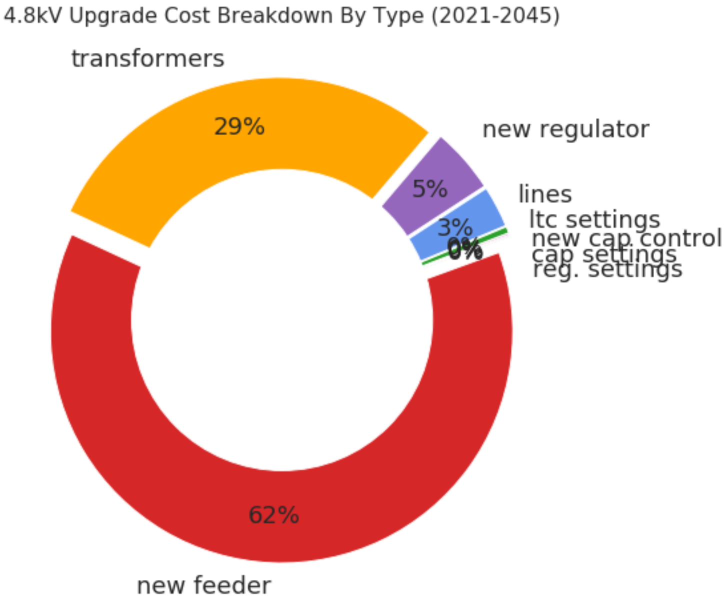
Managing extended transmission outages—Importance in LA of having storable fuel and not just short-duration batteries

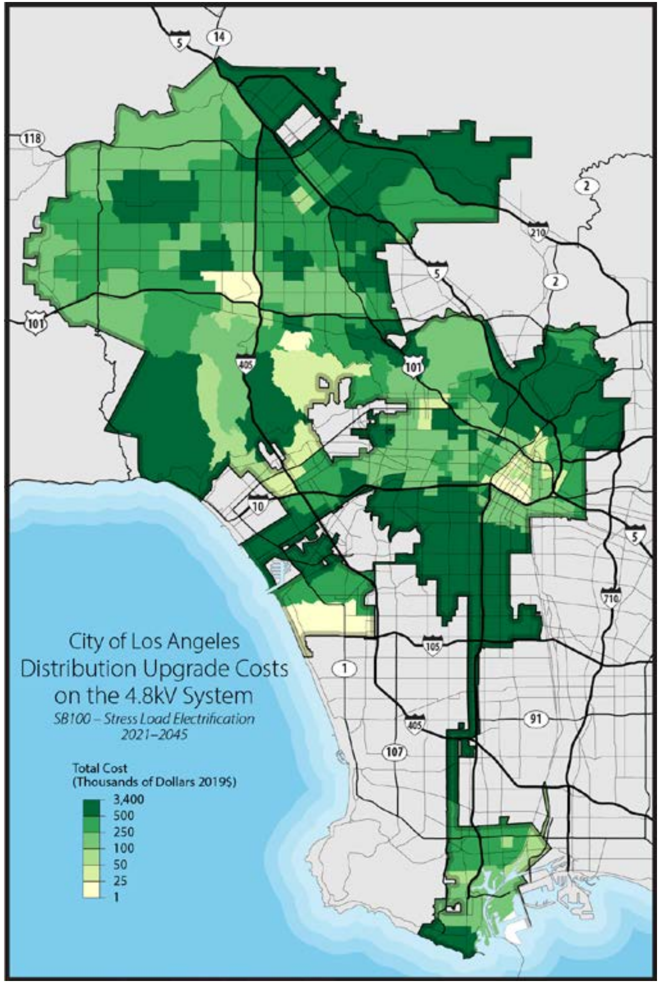
Unserved energy at each time point for all long-duration transmission outage simulations



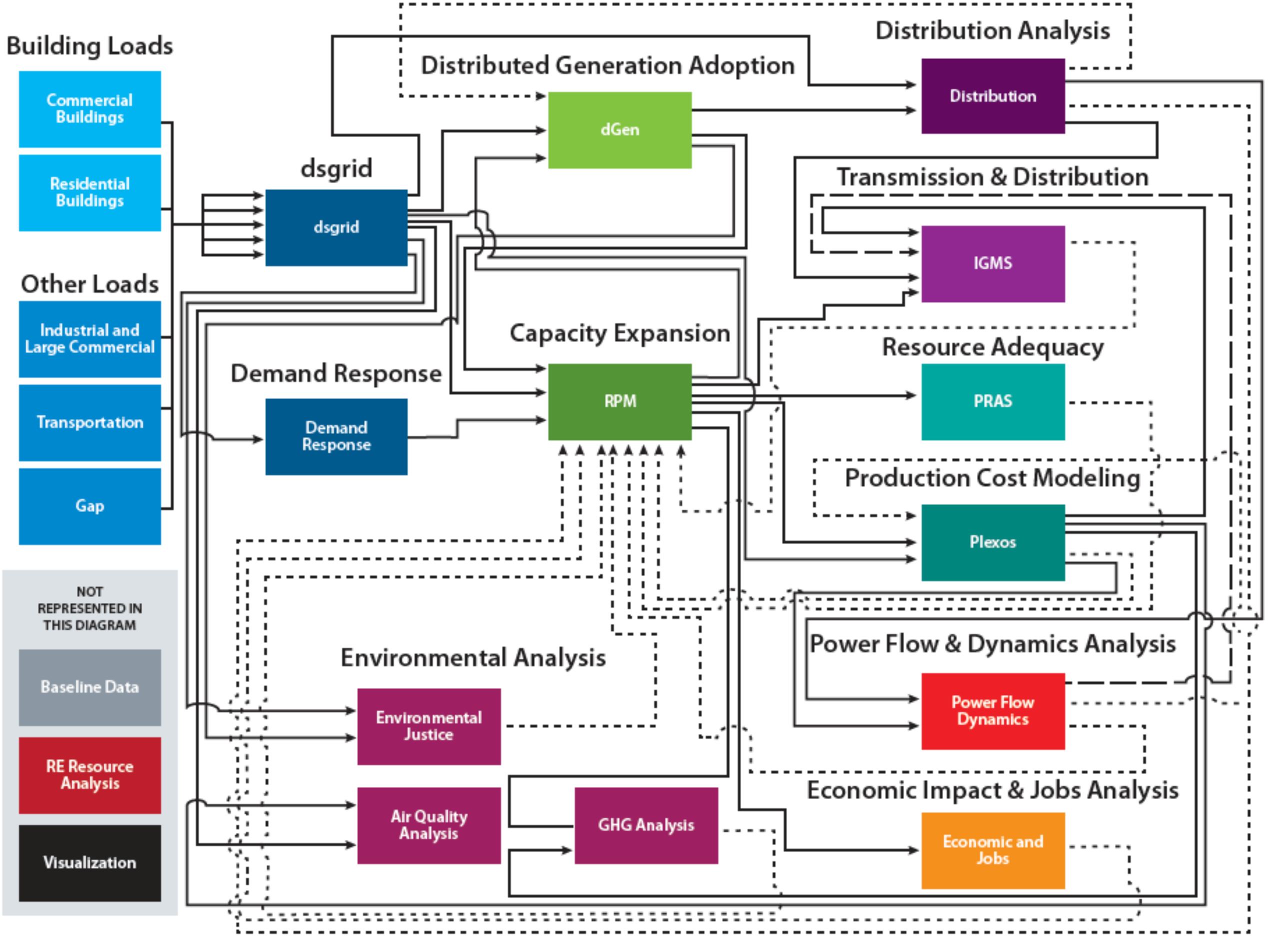
Each dot represents the unserved energy of a specific combination of transmission outages

What type of distribution upgrades are needed and where?





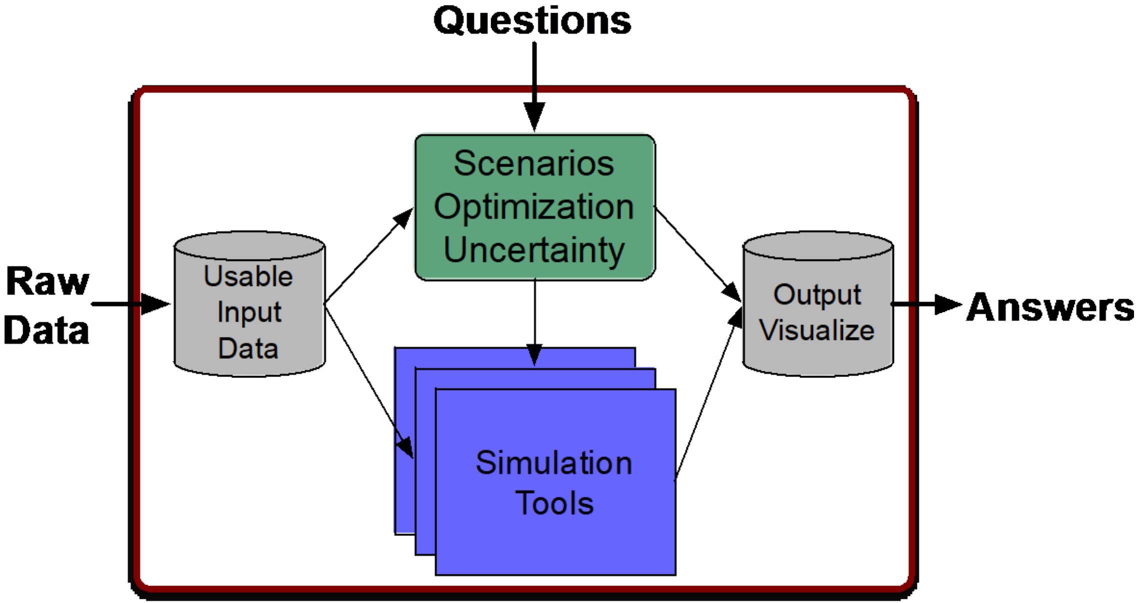
Integrated planning data and simulation workflow



Over 100 million simulations for Los Angeles

Scenario and data management

Often the simulation itself is the "easy" part, compared with set-up, output processing, and analysis.



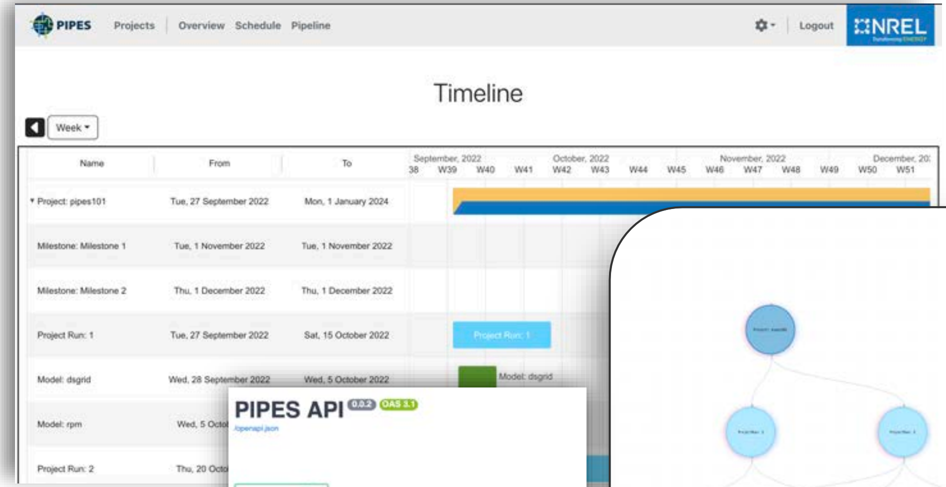
Pipeline for Integrated Projects in Energy Systems

PIPES is a
project management +
data management +
workflow management
layer for integrated modeling teams

Backend: DocumentDB, GraphDB (Amazon Neptune), and REST API
Front End: Web User Interface (UI) and Command Line Interface (CLI)

[PIPES Documentation]

[pipes.nrel.gov]

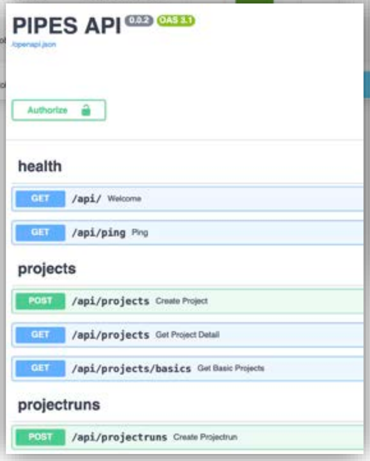


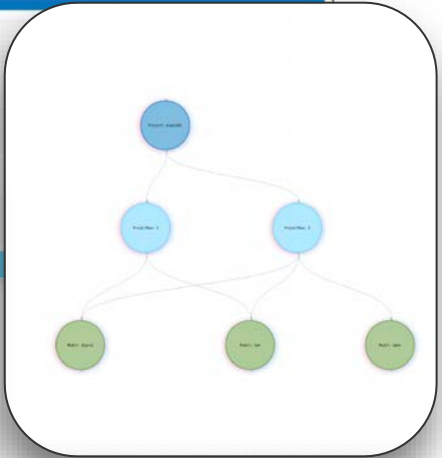

```
❯ pipes --help
Usage: pipes [OPTIONS] COMMAND [ARGS]...

  PIPES CLI client

Options:
  --help  Show this message and exit.

Commands:
  config    config CLI client
  dataset   dataset operation commands
  handoff   task operation commands
  login     login to PIPES
  model     model operation commands
  project   project operation commands
  service   system operation commands
```





```
from pipes import PIPES
pipes = PIPES()
```

How might we get there? (and challenges/needs)

Co-optimize

Iterate across G-T-D-C

Expand Existing Efforts

Coordinated Data

Awareness

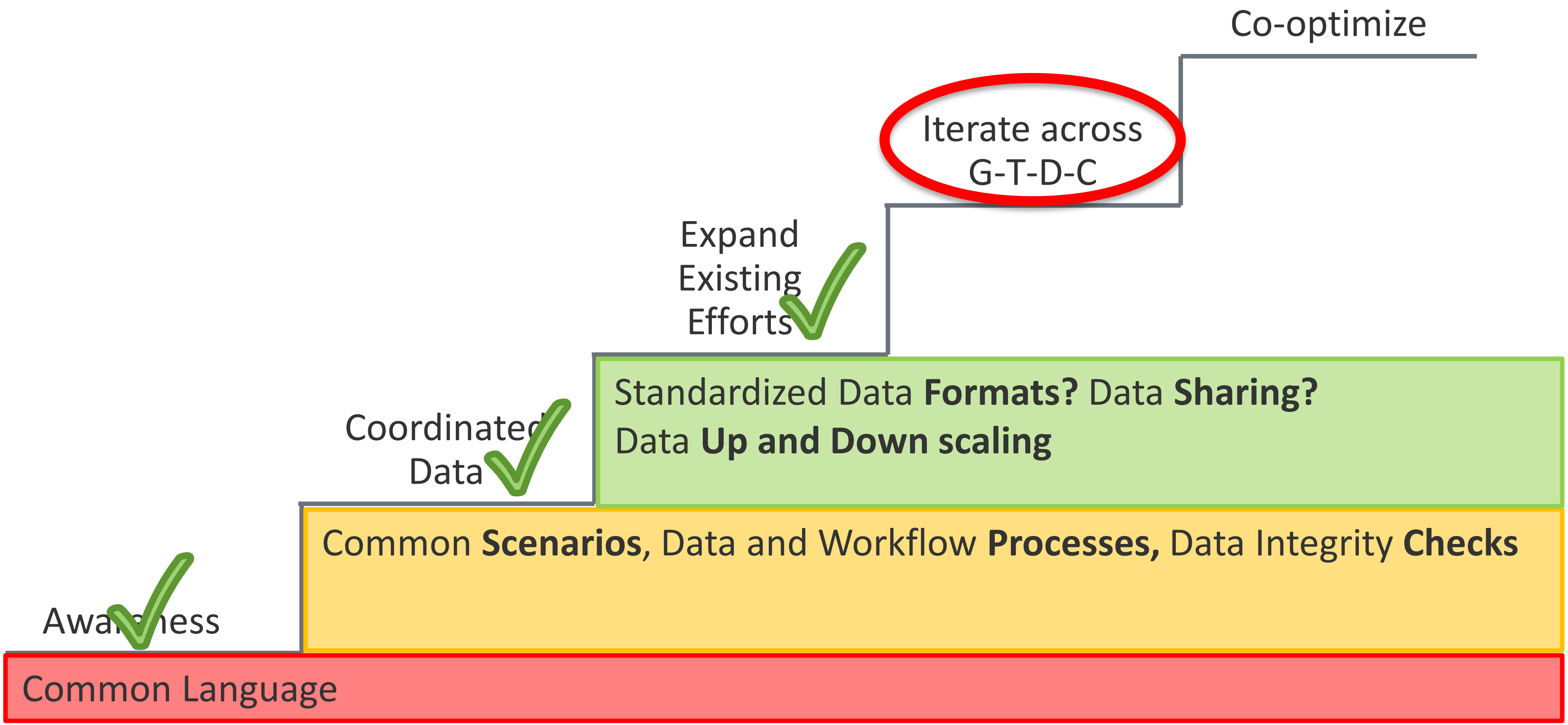
Standardized Data **Formats?** Data **Sharing?**

Data **Up and Down scaling**

Common **Scenarios**, Data and Workflow **Processes,** Data Integrity **Checks**

Common Language

How might we get there? (and challenges/needs)



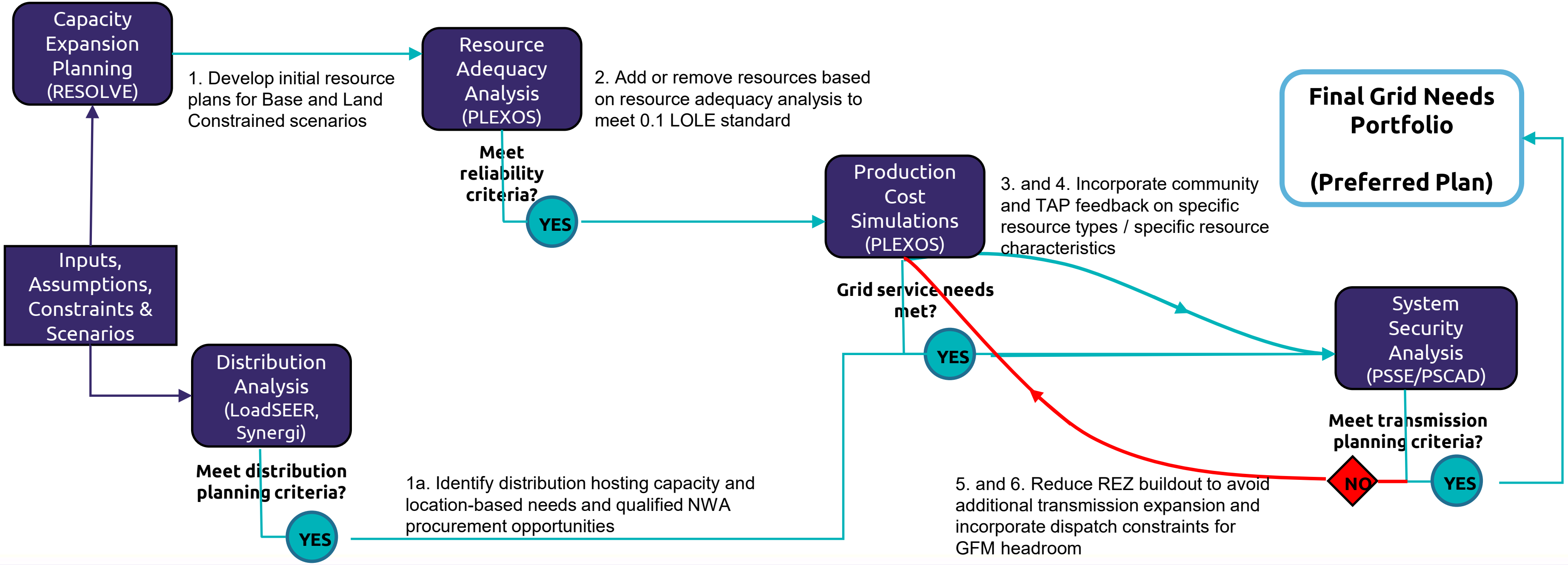
The Integrated Grid Planning Process

Credit/Thanks: Marc Asano and Ken Aramaki, Hawaiian Electric Company

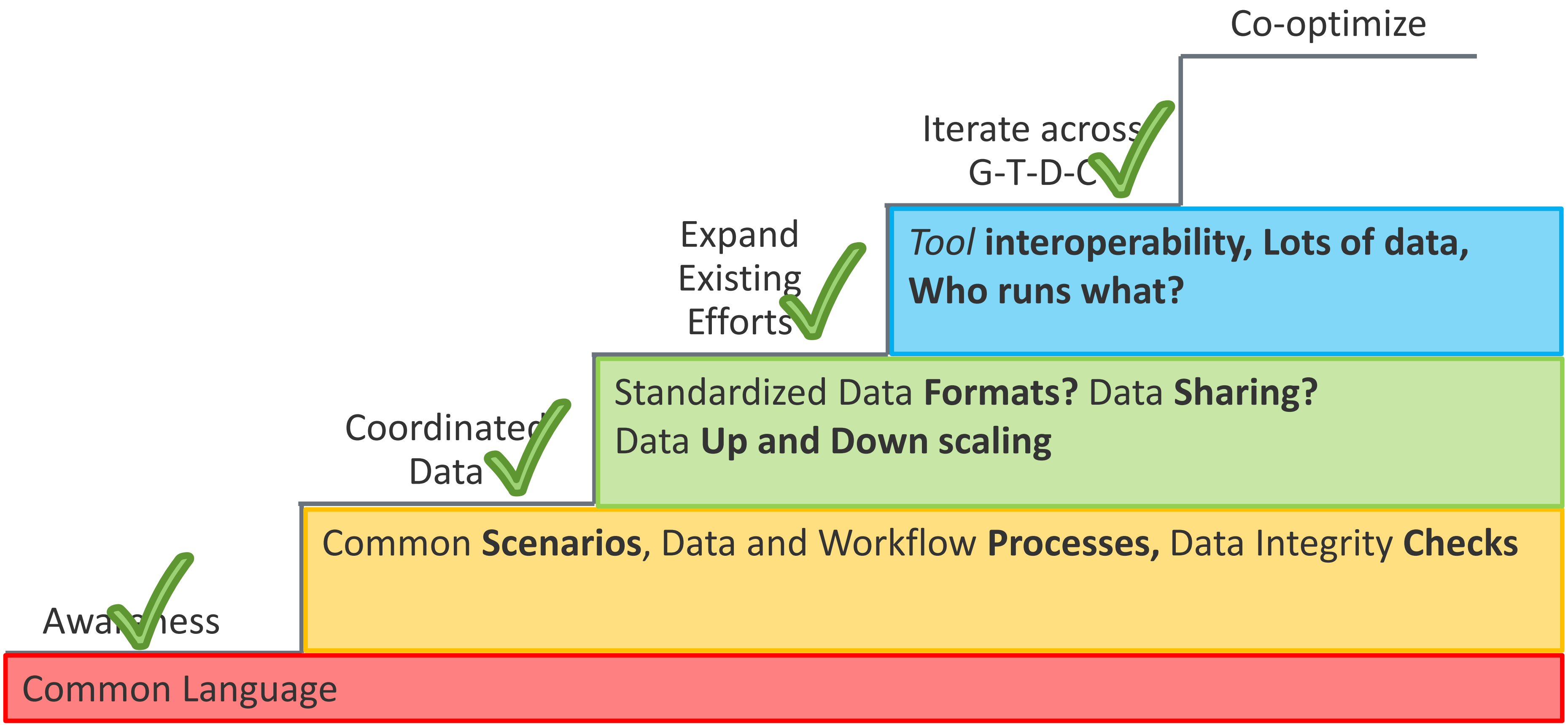
Modeling to Determine Grid Needs

Credit/Thanks: Marc Asano and Ken Aramaki, HECO

The Preferred Plans for each island were developed as a result of the resource, transmission, and distribution analyses.



How might we get there? (and challenges/needs)



How might we get there? (and challenges/needs)

Co-optimize

Iterate across G-T-D-C ✓

Expand Existing Efforts ✓

Coordinated Data ✓

Awareness ✓

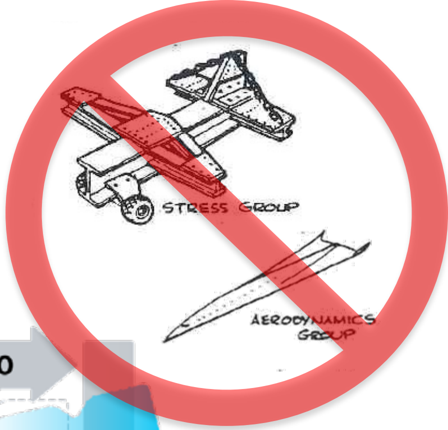
Tool **interoperability, Lots of data, Who runs what?**

Standardized Data **Formats?** Data **Sharing?**
Data **Up and Down scaling**

Common **Scenarios**, Data and Workflow **Processes,** Data Integrity **Checks**

Common Language

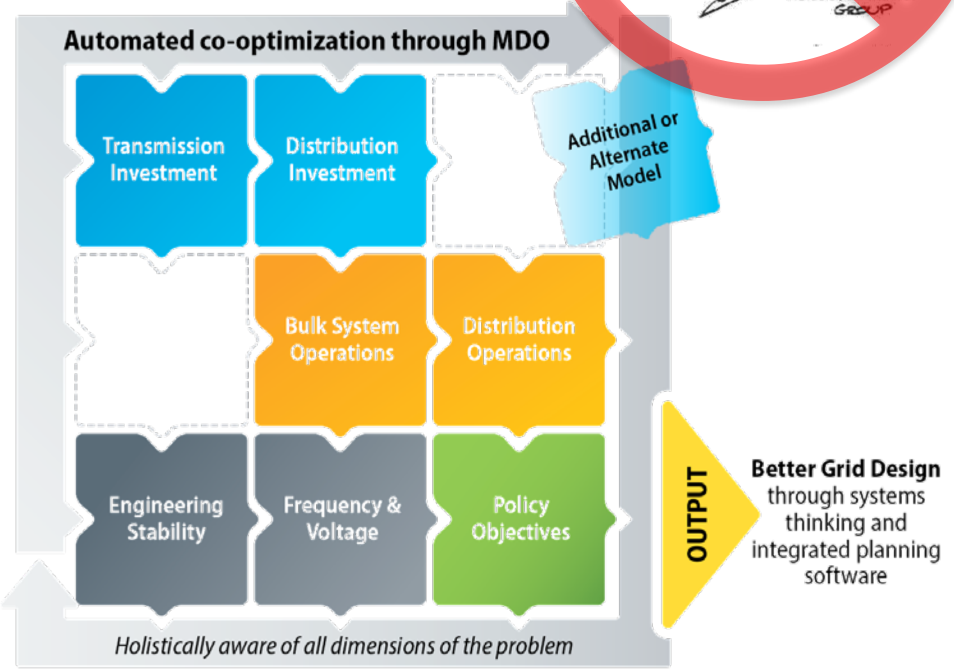
Imagine if you could integrate existing tools into a co-optimization



This is exactly what NREL is doing in collaboration with the New York State Energy Research and Development Authority

MDO4Grid

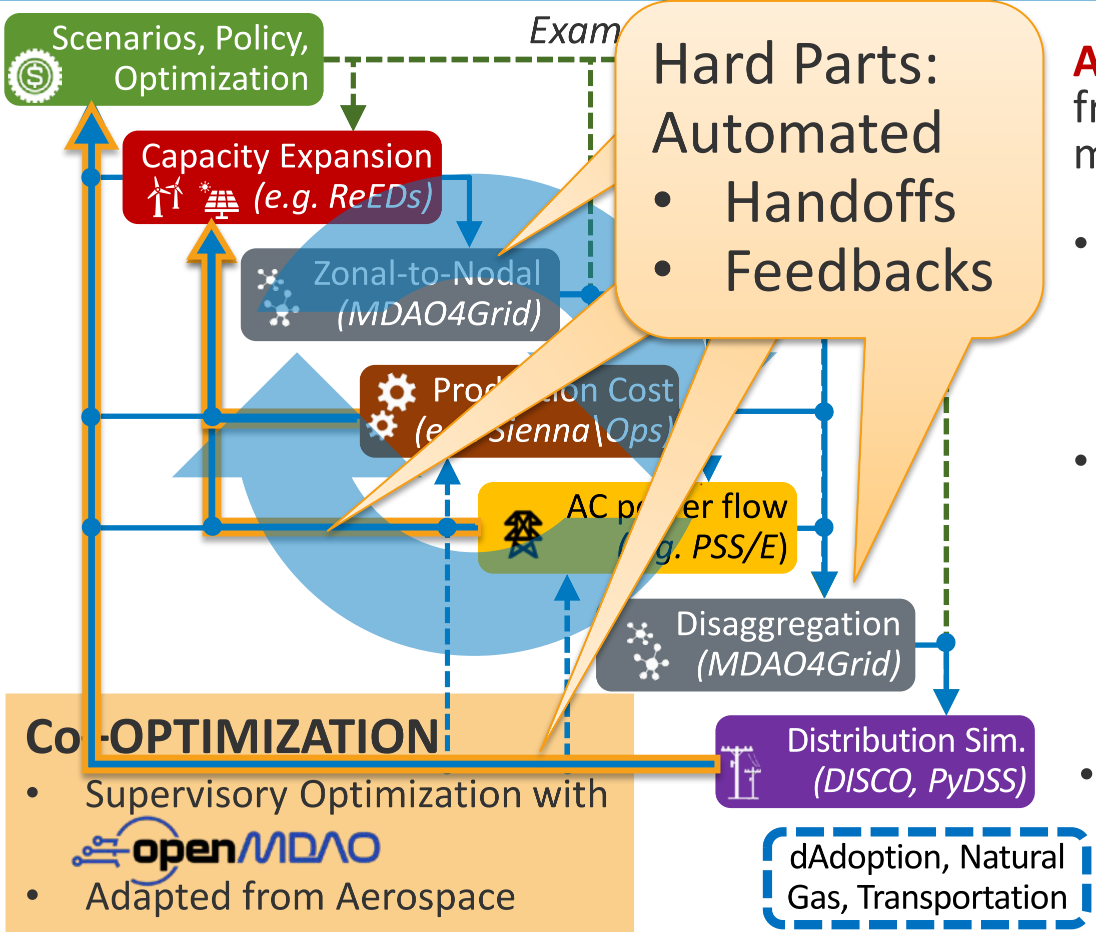
- Adapt aerospace-developed multi-disciplinary design and analysis optimization (MDO/MDAO) for the grid
  - Integration at Conceptual Design Phase
  - Automated supervisory optimization
  - Modular: mix-and-match existing trusted analysis tools
  - Technical, economic, and social considerations in one framework



MDO: Multidisciplinary Design Optimization, MDAO: Multidisciplinary Design Analysis and Optimization

MDO4Grid

Expansion Planning++



Automated conceptual design phase framework to endogenously capture multi-domain interactions and *feedbacks*

- Combine existing design tools
  - Investment, Policy
  - Operations, Markets
  - Engineering Assessments
- Reconfigure for different analyses:
  - Transmission-Distribution
    - Investment, markets, services
    - DER Adoption
  - High-IBR investment
  - Grid+X (transport, buildings, gas)
- Mix and match tools & Flow

Palmintier, Bryan, Rodrigo Henriquez-Auba, Nadia Panossian, Patrick Brown, Jose Daniel Lara, and Aadil Latif. 2025. "Toward Multidisciplinary Design, Analysis, and Optimization (MDO) for Co-Designed Transmission & Distribution Electric Grid Planning." (In Review)

How might we get there? (and challenges/needs)

Co-optimize

Tool **Interfaces, Automation Computation,**

Iterate across G-T-D-C

Tool **interoperability, Lots of data, Who runs what?**

Expand Existing Efforts

Standardized Data **Formats?** Data **Sharing?**
Data **Up and Down scaling**

Coordinated Data

Common **Scenarios**, Data and Workflow **Processes,** Data Integrity **Checks**

Awareness

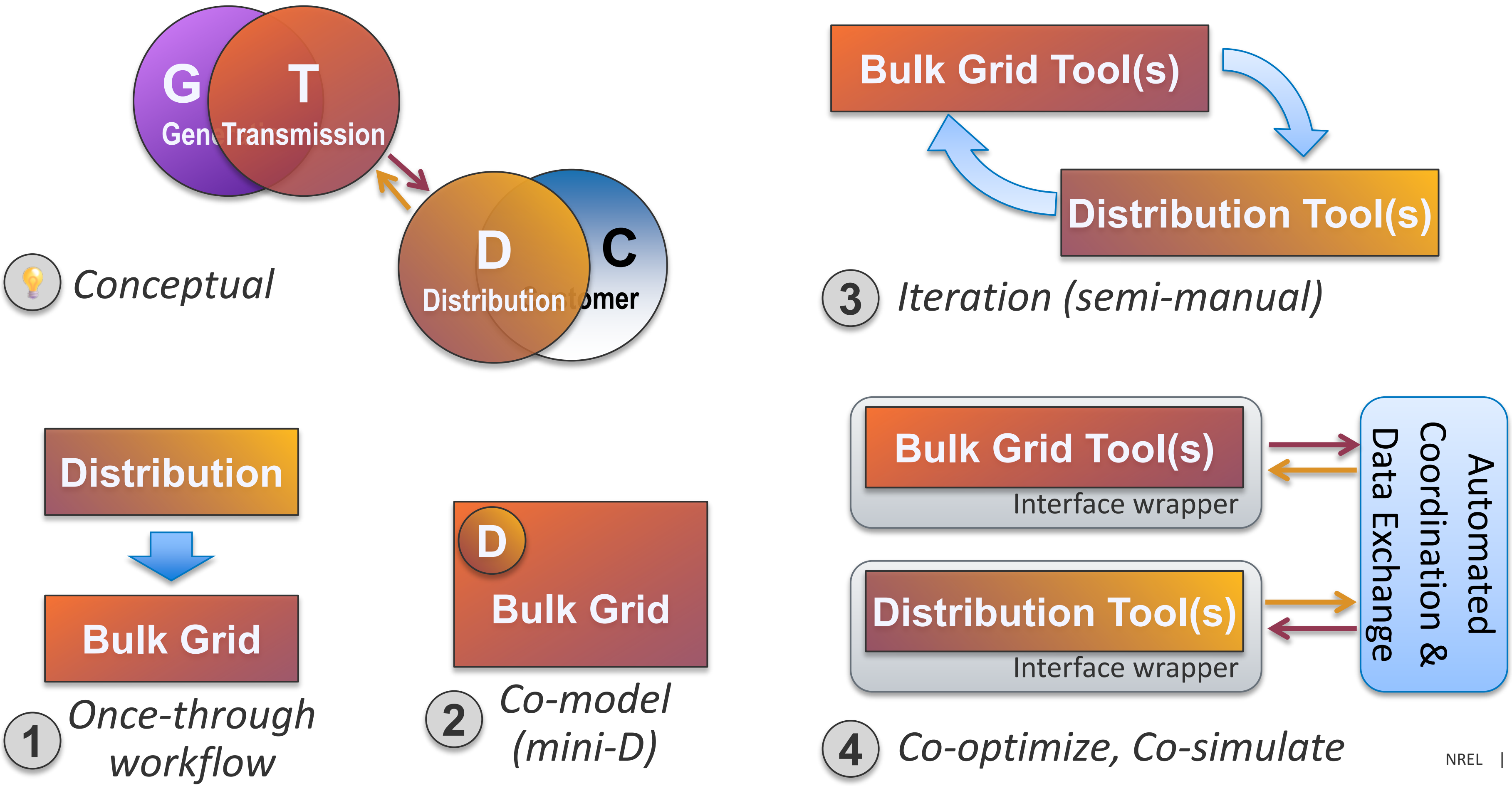
Common Language

Putting It All Together

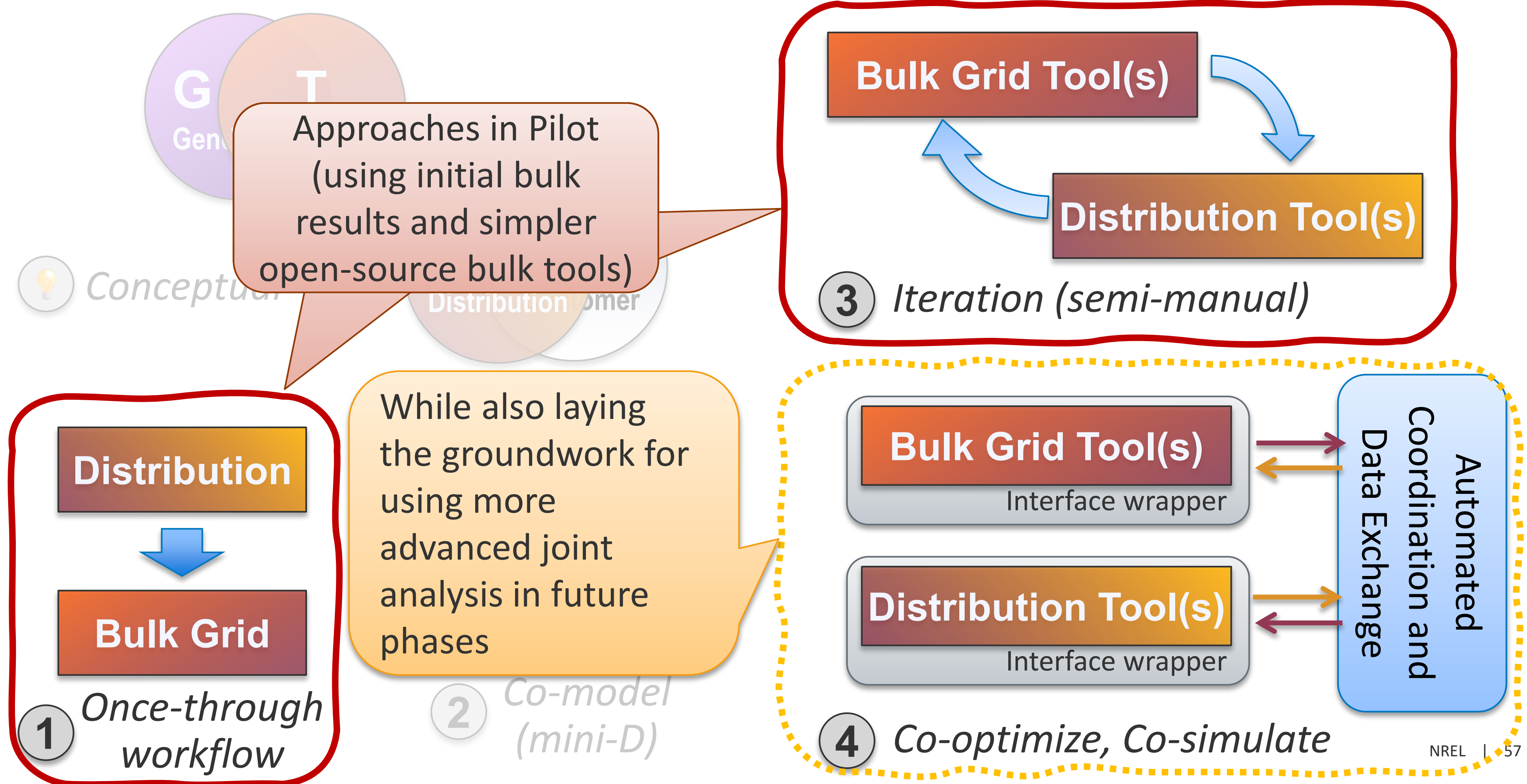
Using an example from the on-going Pacific Northwest Regional Energy Planning Project's Distribution/T&D effort at NREL.

Showcases all levels of the "stair steps" just described

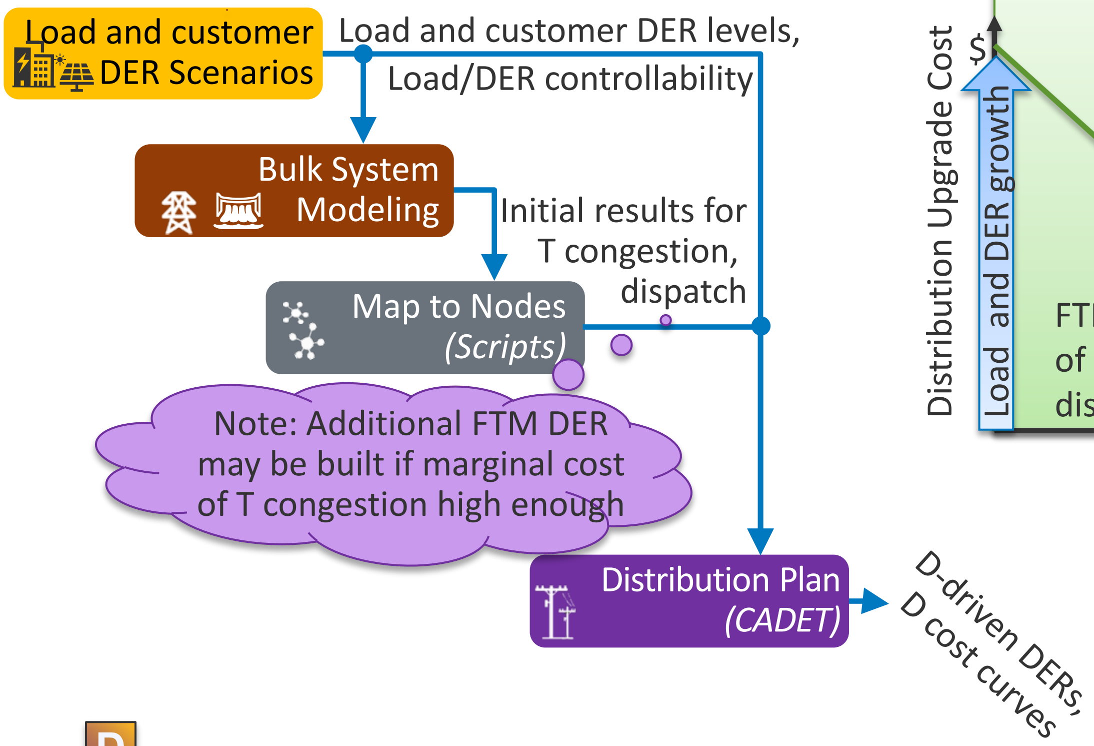
Options for modeling T&D (scales) together

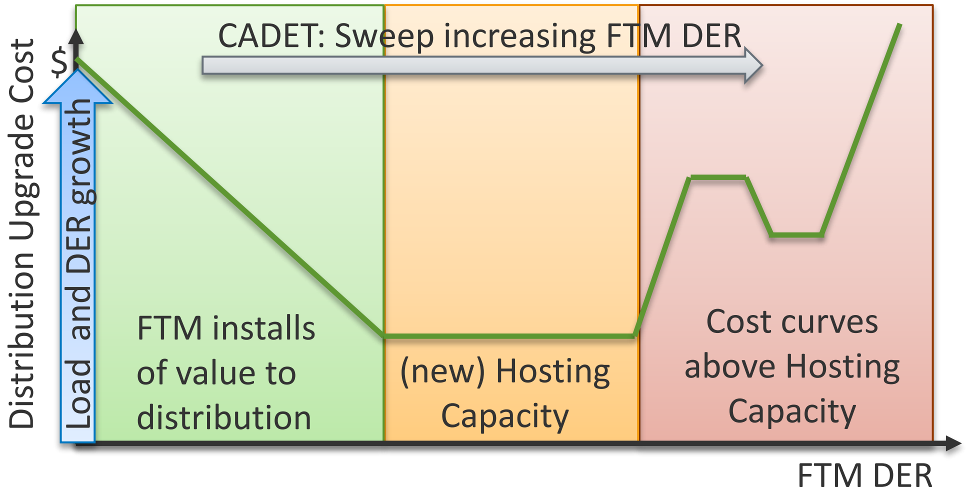


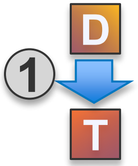
The Pacific Northwest Regional Energy Planning Project (PREPP) T&D example



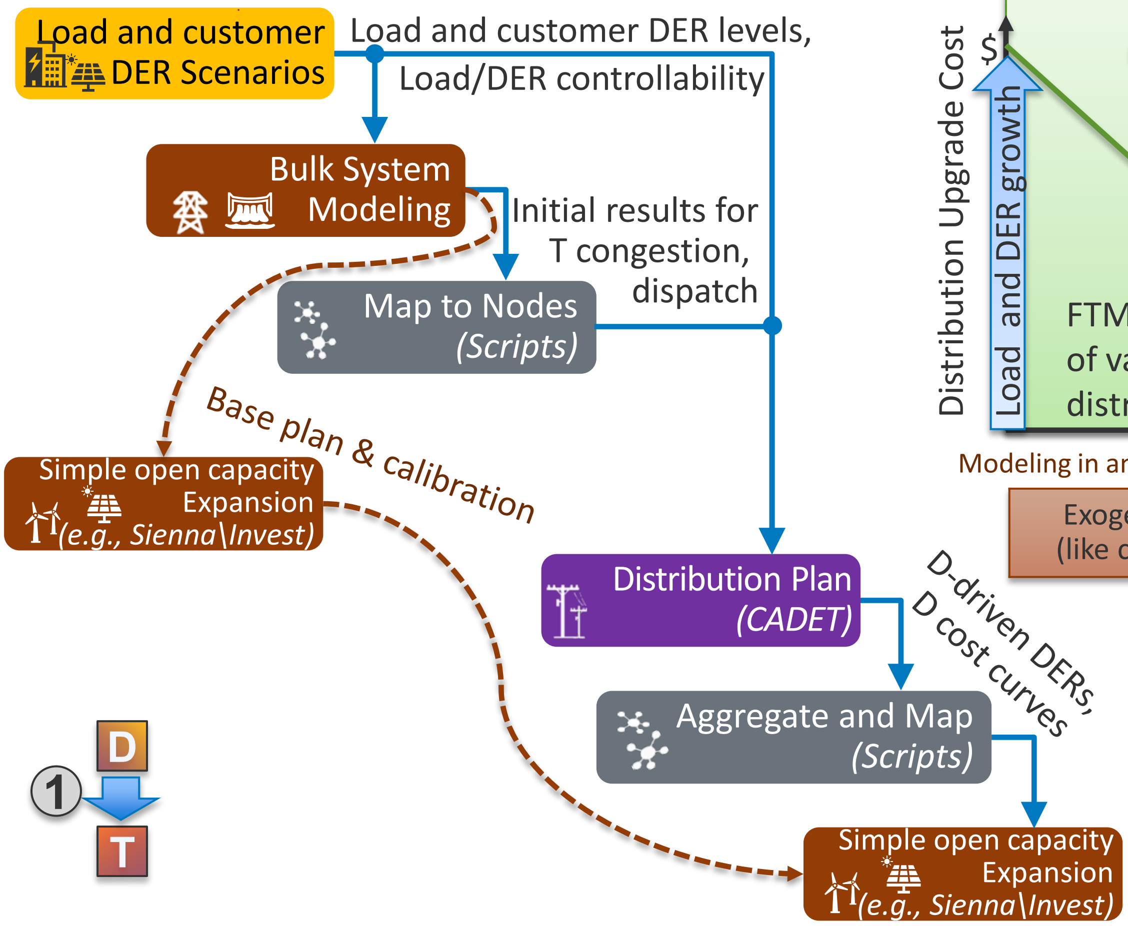
An example for T&D integrated planning

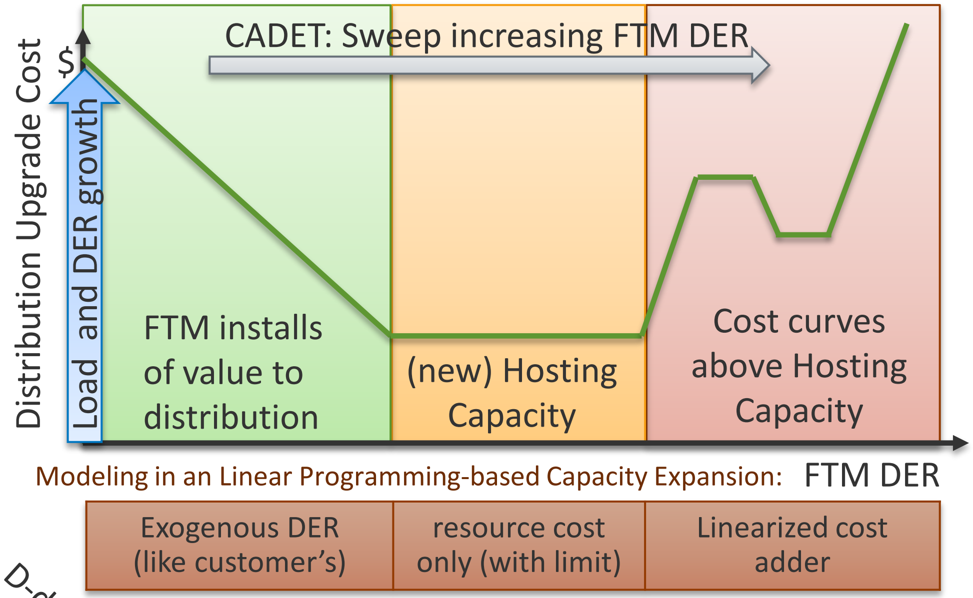






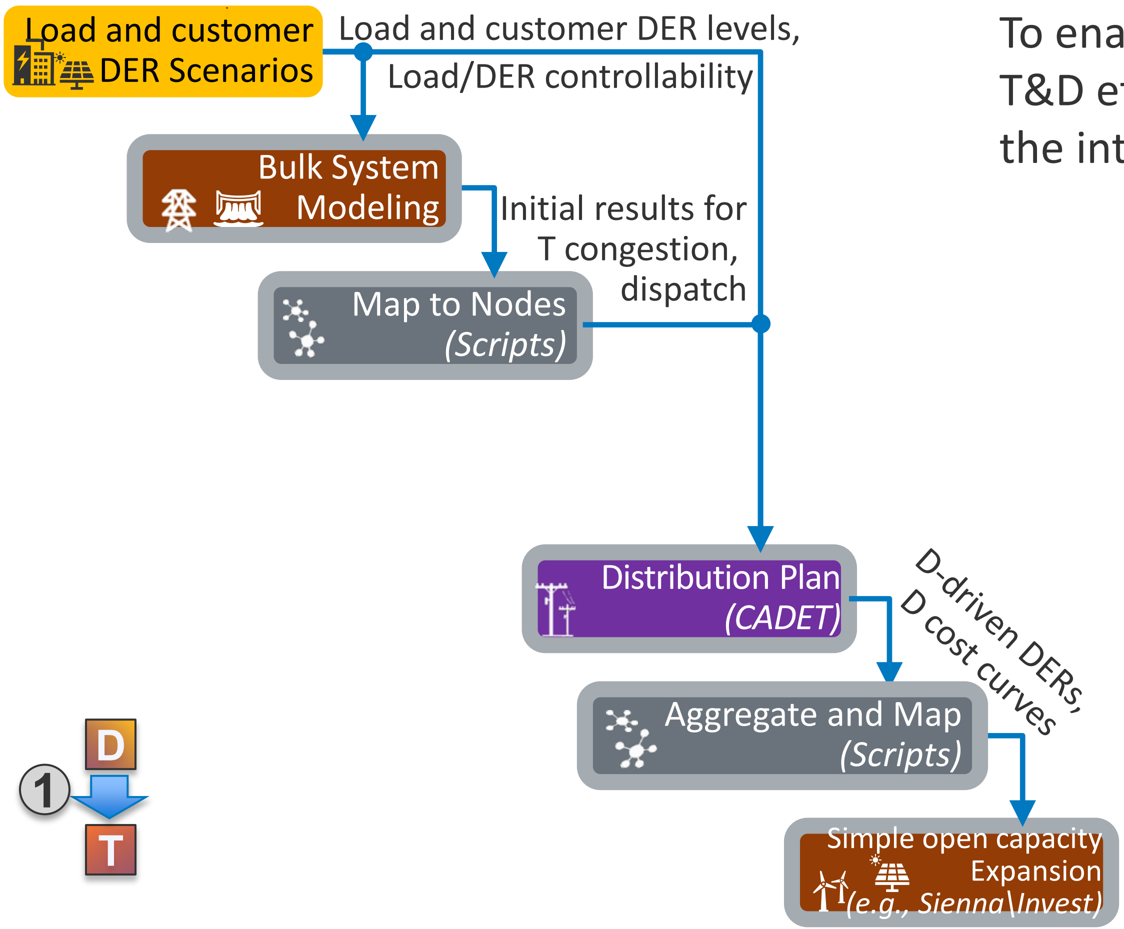
How might the T&D pilot work? (Part 1)



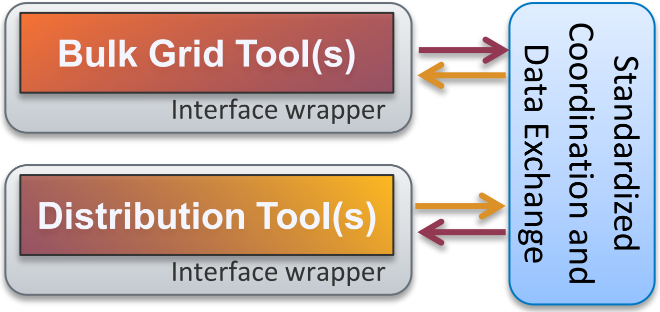


Outcome: Identify changes to bulk capacity plan as result of including distribution

We'll also lay future analysis foundations (Framework)

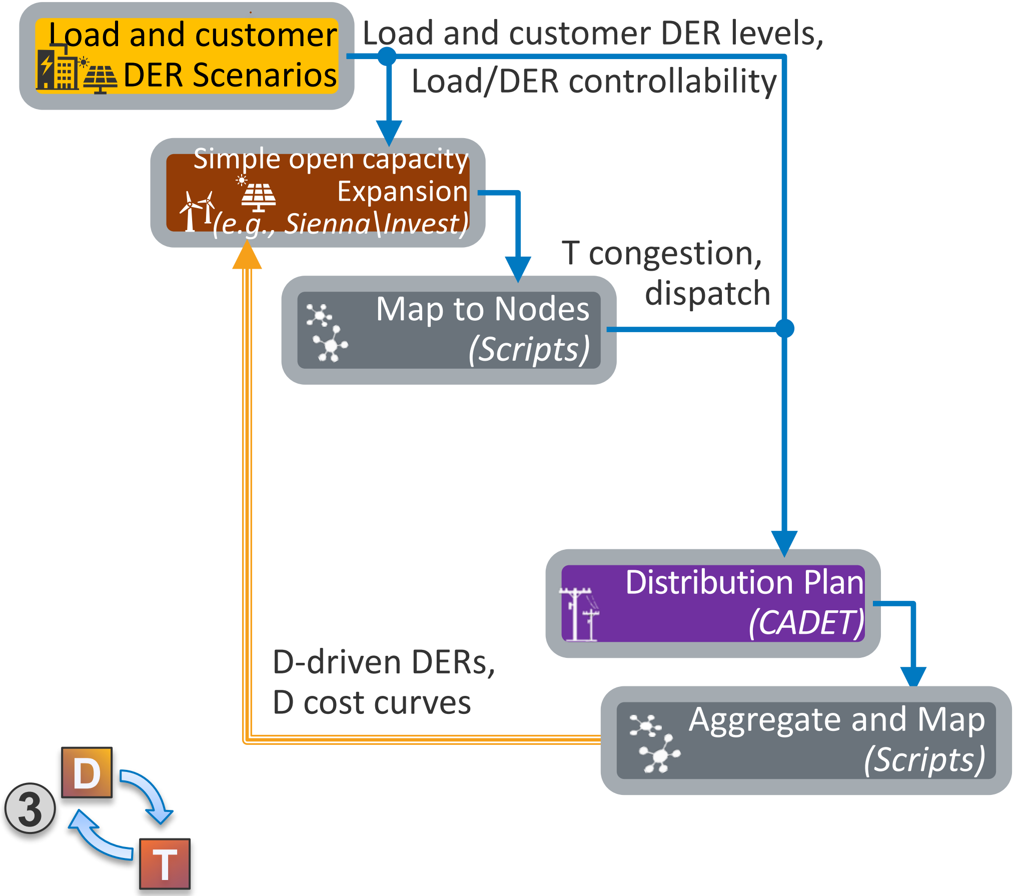


To enable more advanced workflows, the T&D effort will work toward standardizing the interfaces for the various domains.



This allows the use of standardized coordination and data exchange frameworks like **PIPES.**

And (if time allows) try to close the iteration loop



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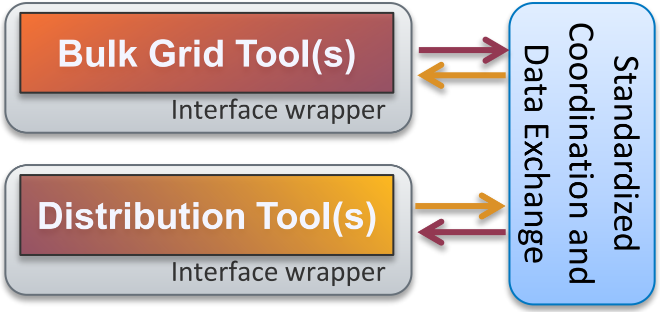
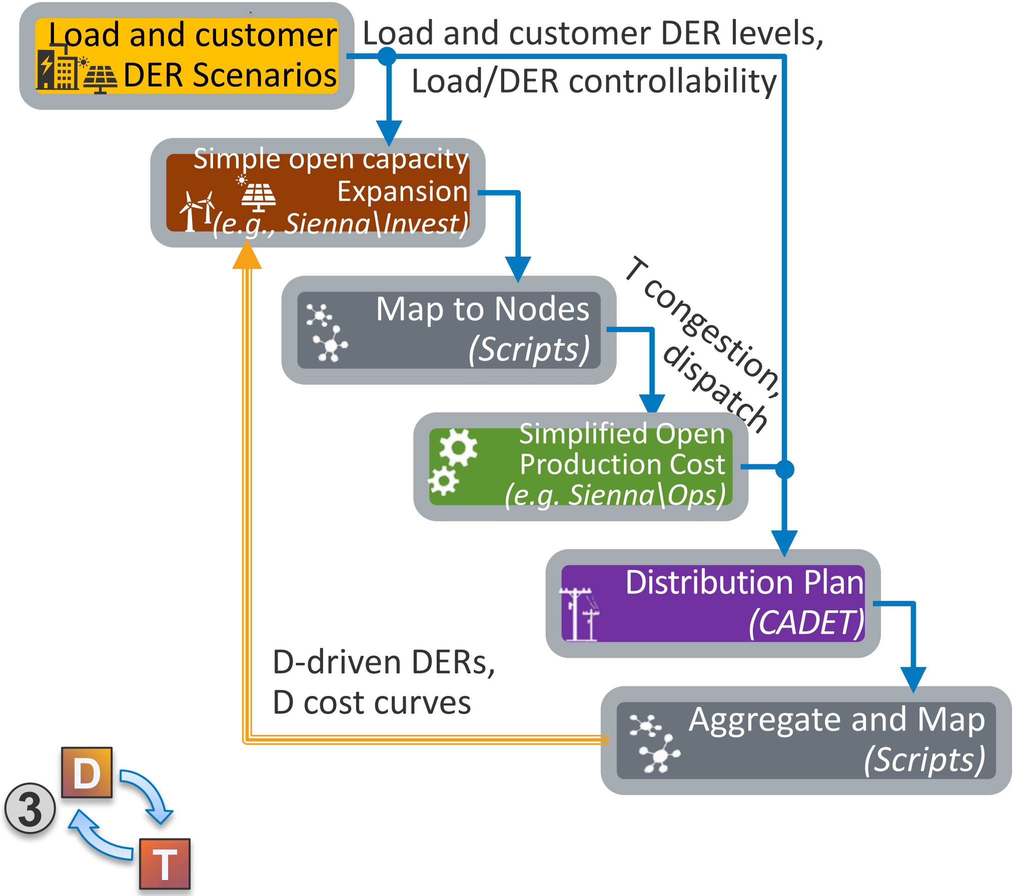


This allows the use of standardized coordination and data exchange frameworks like **PIPES** or **MDO4Grid** for iteration. And it simplifies changing out tools.

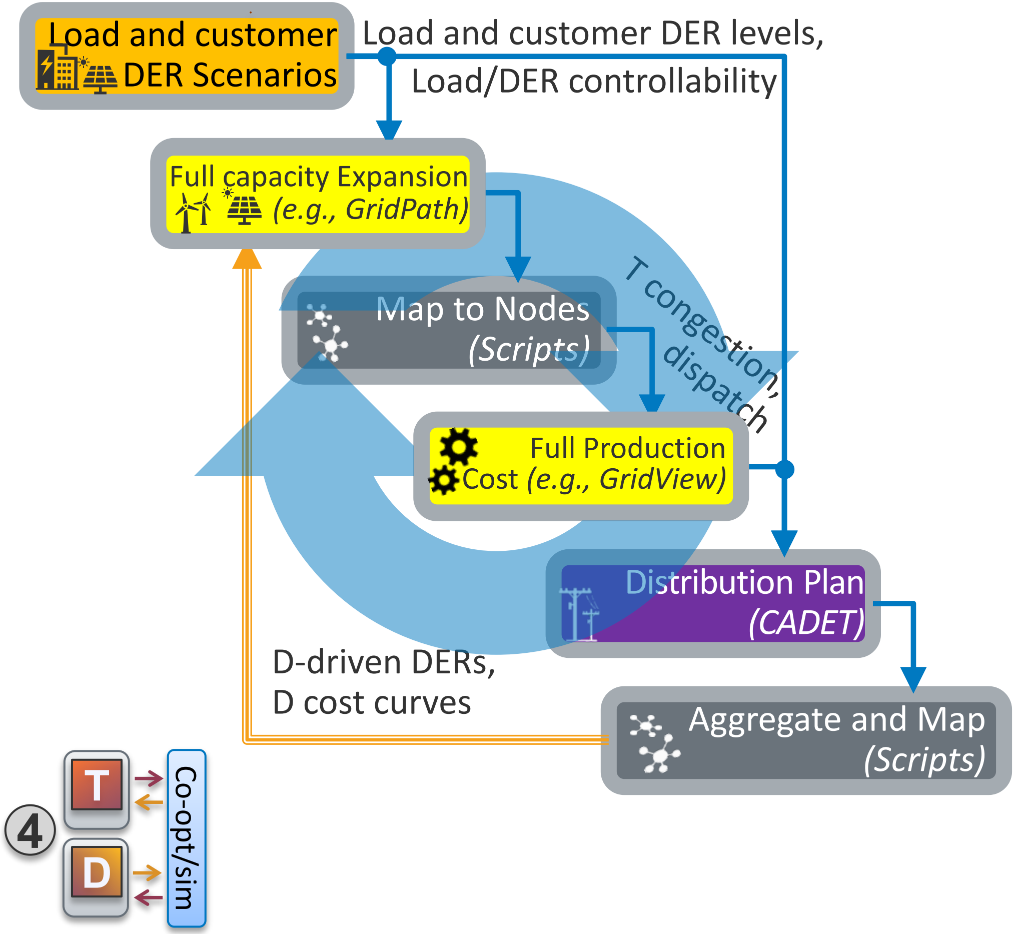
And (if time allows) try to close the iteration loop



Outcome: Semi-automated iteration. Experiments to consider additional value streams, manage convergence, and optimize data exchange

This allows the use of standardized coordination and data exchange frameworks like **PIPES** or **MDO4Grid** for iteration. And simplifies changing out tools

This also enables more integrated analysis for Phase 2+



Phase 2 possibilities:

- Integrating bulk PREPP tools
- Expanding analysis (without changing other pieces):
  - Adequacy
  - Multi-Energy
  - Endogenous Adoption
- Co-simulation for T&D ops & engineering with HELICS

This allows the use of standardized coordination and data exchange frameworks like **PIPES** or **MDO4Grid** for iteration. And simplifies changing out tools

Recap, benefits, and looking ahead

- Increasingly important to combine bulk and local scales for the grid
  - Reduce overall costs, e.g. by avoiding over/double building
  - Increase system reliability/resilience, e.g. DERs can support local power during storms, etc.
- Across multiple time-scales: Engineering, Operations, Planning
- Range of increasingly sophisticated approaches (examples in slides):
  - Walk: awareness, Harmonize data and scenarios
  - Jog: Expand existing approaches, e.g. data exchange
  - Run: Iteration, automation, co-optimization
- Multi-model frameworks can support Jog & especially Run levels

Thank You

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