SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Final Project Review

Optimization Framework for Solar Energy Integrated Resilient Distribution Grid

Argonne National Laboratory
CPS# 34228 – Final Project Review
May 22nd 2020

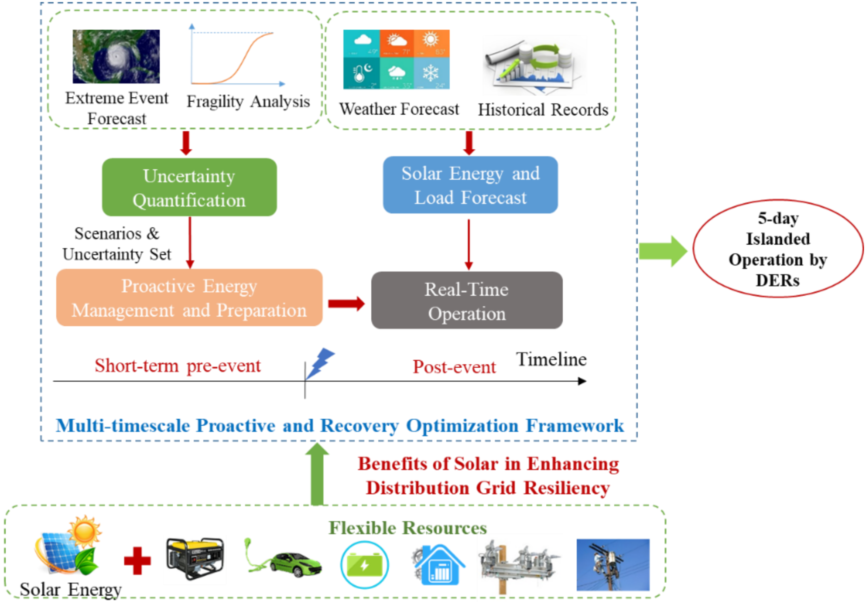
Principal Investigator: Bo Chen
Other Contributors: Iowa State University, Southern Methodist University

Project Objectives

- Develop an optimization framework to facilitate the benefits of distributed solar energy in resilience improvement of distribution grid against disastrous events and ensure a 5-day islanded operation supported by DERs after the events.

Key innovation:

- Solar energy in coordination with other flexible resources to ensure supply continuity
- Cover pre-event preparation and post-event operation
- Uncertainties caused by external factors and grid characteristics
- Verification using extensive simulation case studies: small-scale and large-scale test cases



Task/Deliverable Summary

- Task Summary

Task 1: Set up an industrial advisory board (IAB) and deliver webinars

Task 2: Development of pre-event proactive management optimization models and solution algorithms.

Task 3: Development of Post-event operation and restoration optimization models and solution algorithms

Task 4: Setting up test cases used for pre-event preparation and post-event operation optimization solution algorithms

Task 5: Extensive case studies to evaluate the benefits of solar energy in resilience improvement

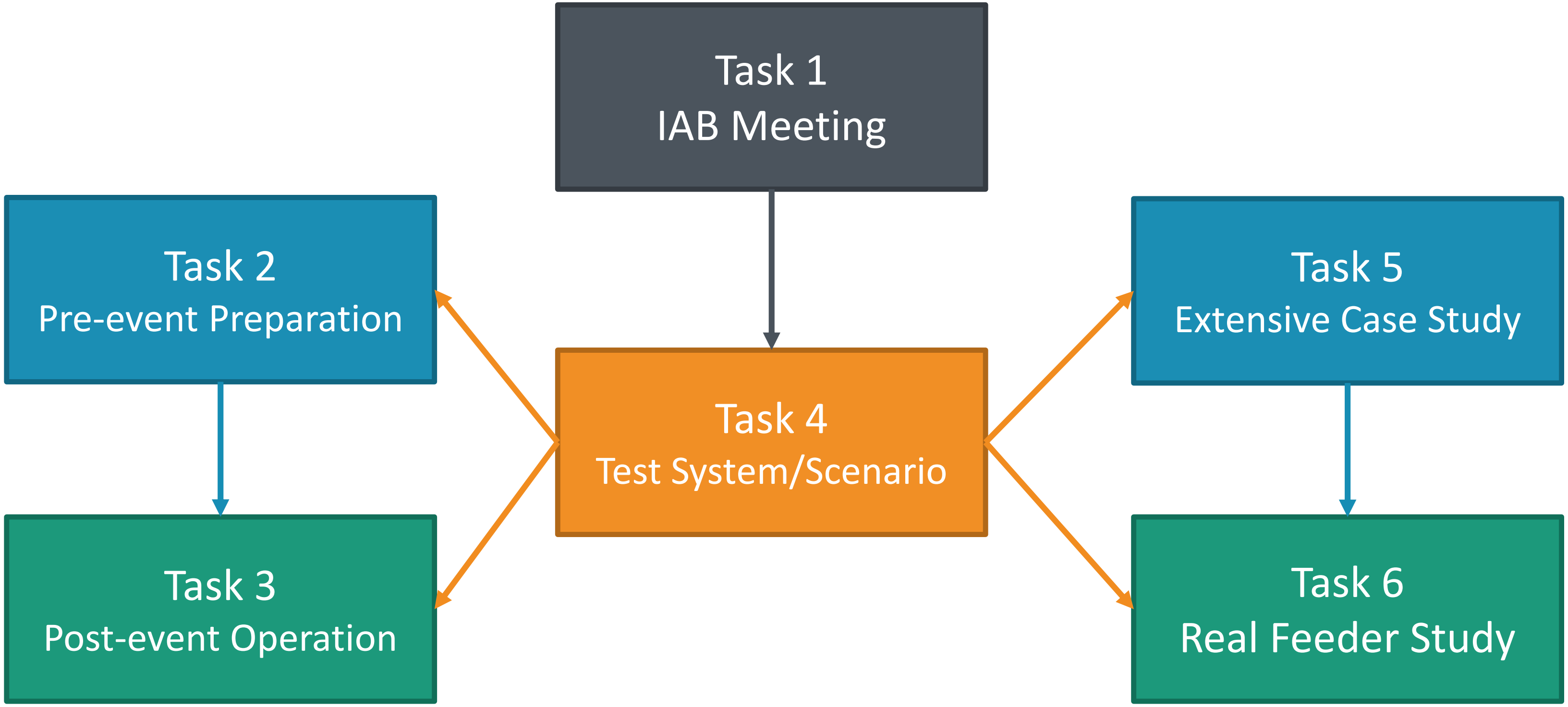
Task 6: Testing of the pre-event and post-event optimization via simulation using real feeder data

- All milestones achieved
- Deliverables
    - Optimization models and solution algorithms
    - 4 journal papers, 1 conference papers, 7 conference presentations
    - Quarterly reports (Q1 – Q5)
    - Final Technical Report (Q6)
    - 3 IAB webinars (Q1, Q3, Q6)

Project Management

- Assign task lead for each task
- Bi-weekly team meeting scheduled
  - Technical progress
  - Budget and subcontracts
- Additional meetings
  - Real-feeder data collection
  - Model development
  - Solution alignment
  - Code sharing and discussion

Task Summary



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Task 1

- Task 1: Set up an industrial advisory board (IAB) and deliver webinars
    - Subtask 1.1: (Completion in Q1-FY19) Set up IAB
    - Subtask 1.2: (Completion in Q3-FY19) Webinar for the pre-event preparation and post-event energy management optimization
    - Subtask 1.3: (Completion in Q3-FY19) Webinar for post-event restoration optimization model development, and intermediate results of pre-event preparation and post-event energy management optimization

- Deliverables:
    - Delivered 3 webinars with IAB members on 01/03/2019, 7/12/2019 and 04/08/2020
    - Report of detailed comments from IAB and corresponding response

Task 1: IAB Setup and Deliver Webinars

- The project team invited experts from 7 companies to form Industrial Advisory Board (IAB)

Company	Name
Electric Power Research Institute (EPRI)	Tomas Tinoco Rubira, Aidan Tuohy
S&C Electric Company	Yoav Sharon
Oncor Electric Delivery	Bill Muston
Maquoketa Valley Electric Cooperative	Jeremy Richert, Nik Schult
Aliant Energy	Joe McGovern, Bekki Watkins
Algona Municipal Utilities	John Bilsten
City of Bloomfield Utility	Chris Ball

Task 1: IAB Setup and Deliver Webinars

- 3 IAB meetings via webinars on 01/03/2019, 7/12/2019 and 04/08/2020
- IAB members gave positive feedback and provided several detailed comments regarding the application and path forward of this project.

Selected Comments from IAB	Response
Official definition and categorization for different types of PVs, and their differences	IEEE1547 provides the categories of different PV types according to their controllability, and Type I, II, and III PVs are defined based on academic reference.
Differences between pre-event crew dispatch and post event crew dispatch	Pre-event dispatch will assign crew to depots. Post-event dispatch will determine the repair sequence.
Difference between stage II pre-event model and the post-event model	The project team provided illustration that differences are in the level of operation details and level of uncertainties
Clarification on the stage I and stage II in pre-event stochastic optimization	The project team introduced the stochastic optimization model and the solution approach

Task 1: IAB Setup and Deliver Webinars

Selected Comments from IAB	Response
Clarification on the test system setup parameters: Definition of PV penetration, DG capacity and grid operation mode, definition of resilience, generation of weather-induced outages	The project team provided illustrations on the PV levels and DG details. We will add power parameters in future presentation to better show the PV impact. The definition of resilience and weather-induced outages are clarified.
Clarification on the test system results: resource allocation patterns; parameters in resilience improvement; resilience changing pattern according to penetration level increase; comparison between the critical and non-critical load	The project team provided detailed illustration of results analysis such as the load profile used, the pre-determined critical / non-critical loads and corresponding different supplied percentage. Specifically, explained the benefit of PV in restoration is not directly proportional to PV penetration levels and provided "turning point" scenario analysis.
Suggestions on the presentation of the approaches and results	The project team will update the future presentations accordingly.

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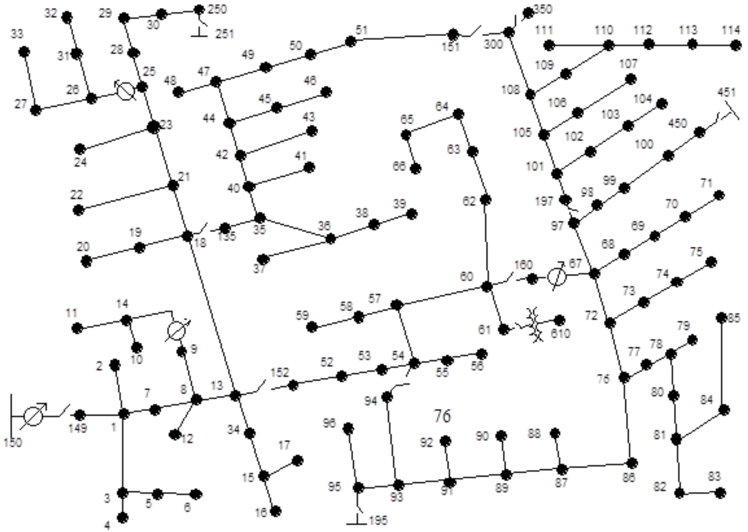
Task 4

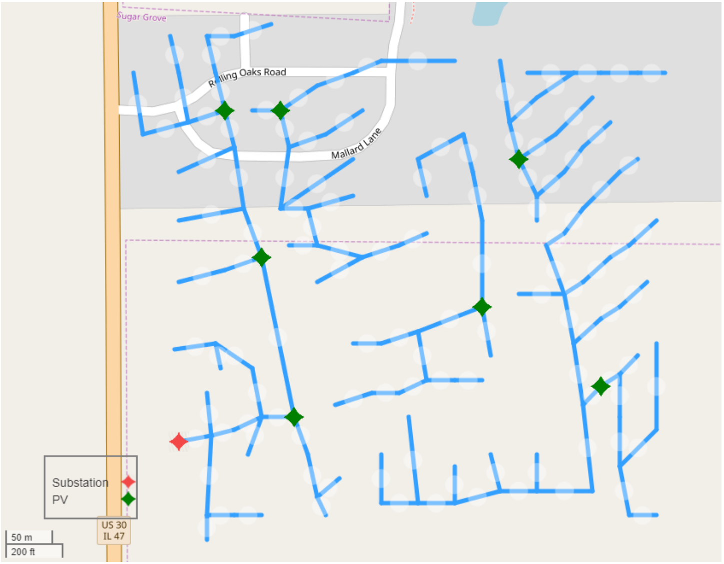
- Task 4: Setting up test cases used for pre-event preparation and post-event operation optimization solution algorithms
  - Subtask 4.1: (Completion in Q1-FY19) Set up small-scale test cases with three-phase single feeder systems
  - Subtask 4.2: (Completion in Q2-FY19) Set up large-scale test cases with three-phase multiple feeder systems
  - Subtask 4.3: (Completion in Q4-FY19) Data preparation of real feeder data

- Deliverables:
  - Small-scale test system adapted from IEEE-123 test system
  - Large-scale test system with 14, 319 nodes
  - Real feeder test system contains 240 nodes, 233 lines and 9 switches
  - Framework of test case generation mechanism

Task 4.1: Small-Scale Test System

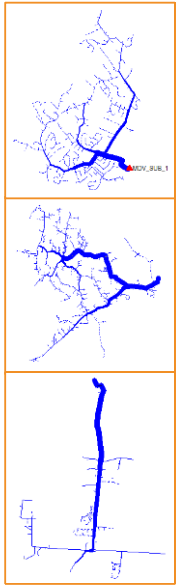
- Small-scale test system: Updated version of IEEE-123 bus test system
- Projected to the map according to its actual size

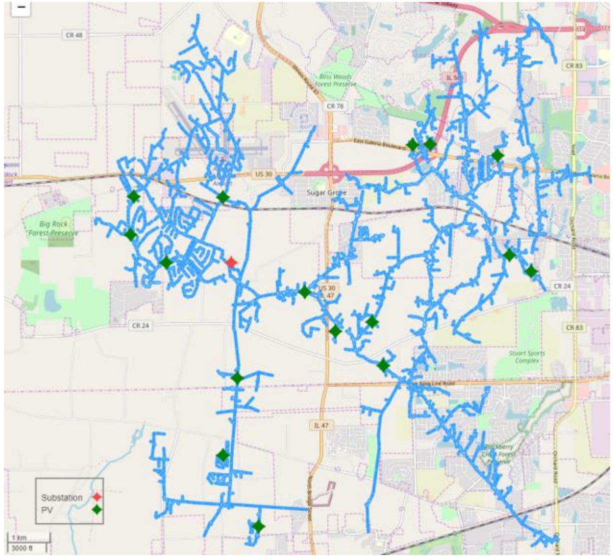




Task 4: Test Systems – Large-scale System

- Large-scale test system — Composite of 3 systems: EPRI Ckt5, EPRI Ckt7, IEEE-8500 bus test system
- 9,057 buses and 14,319 nodes
- A large-scale three-phase unbalanced system with multiple feeders and over 10,000 nodes
- Projected to the map according to its actual size





Test System and Test Scenarios Preparation

- PV Scenarios
  - Type of PV

Type	Model	Capacity	Storage	Mode	Dispatch
III	Large utility PV farm	2,000 kW	16,000 kWh	Grid-forming Grid-following	Dispatch-able
II	Midsize PV system	48 kW	364 kWh	Grid-following	Dispatch-able
I	Residential PV panel	6 kW	N.A	Grid-following	MPPT

  - Penetration of PV
    - 9%, 18%, 27% …. to 99%
    - Added case at 99% penetration to increase percentage of residential PV (Type I)

Test System and Test Scenarios Preparation

- PV Scenarios
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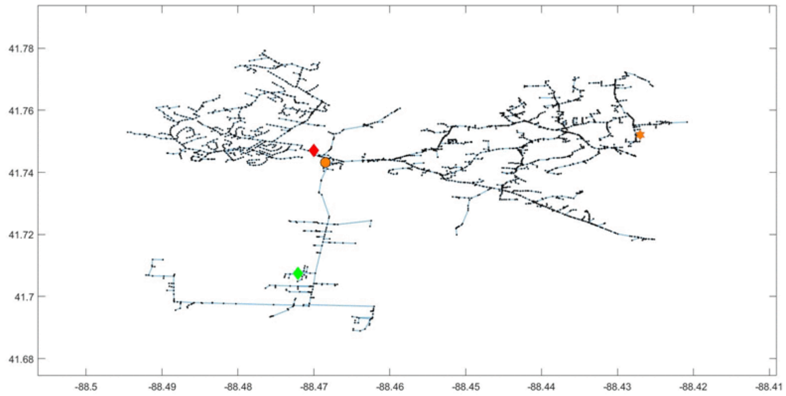
9% PV Penetration



Penetration	Type III PV	Type II PV	Type I PV
9%	1	1	8
18%	2	3	16
27%	3	4	24
36%	4	6	32
45%	5	7	40
54%	6	7	48
63%	7	9	63
72%	8	10	64
81%	9	12	72
90%	10	13	80
99%	11	15	88
99% with more Type I PV	11	0	208

Task 4: Test Case Setup Mechanism

- 3 major steps in test case setup mechanism
  - Following the similar standardized process in HAZUS software developed by FEMA
- 2 slightly different sub-mechanism
  - Due to characteristics and data availability of extreme weather events
  - Evolution: Hurricane — Using simulation-based method
  - Snapshot: Flood / Winter Storm — Using fragility curve-based method

1. Generate weather metric of extreme weather events
2. Prepare fragility model of test systems which describes the behavior of electric components in test system under extreme weather events
3. Acquire damage status of components in test system subject to specific extreme weather events

Evolution

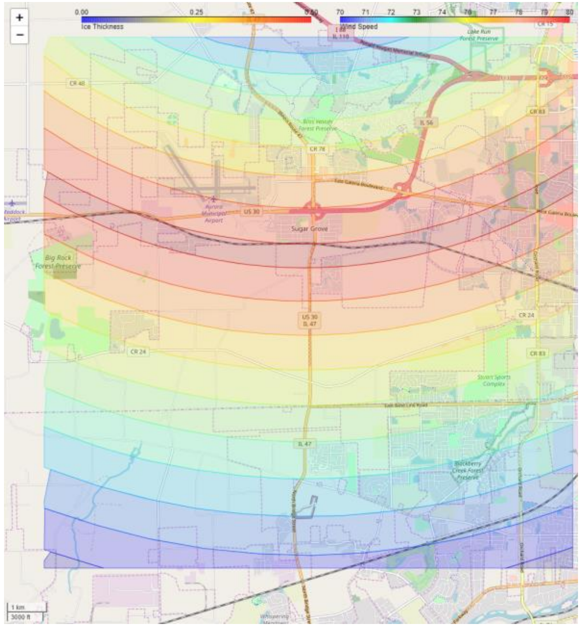
Simulation-based

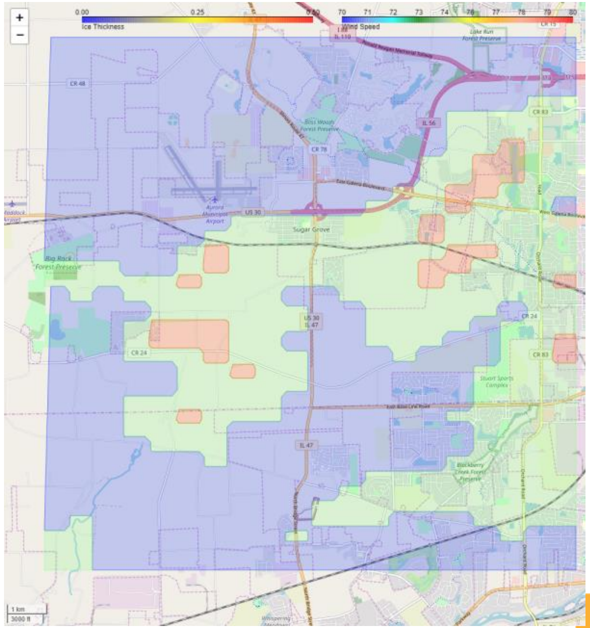
Snapshot

Fragility curve-based

Task 4: Generation of Weather Metric – Winter Storm

- Winter Storm – Snapshot sub-mechanism
  - Characterize winter storm by its impact on power system - Combined impact of wind and ice
  - Wind speed distribution adapted from hurricane extreme weather events
  - Ice thickness distribution determined based on wind speed, elevation and icing duration



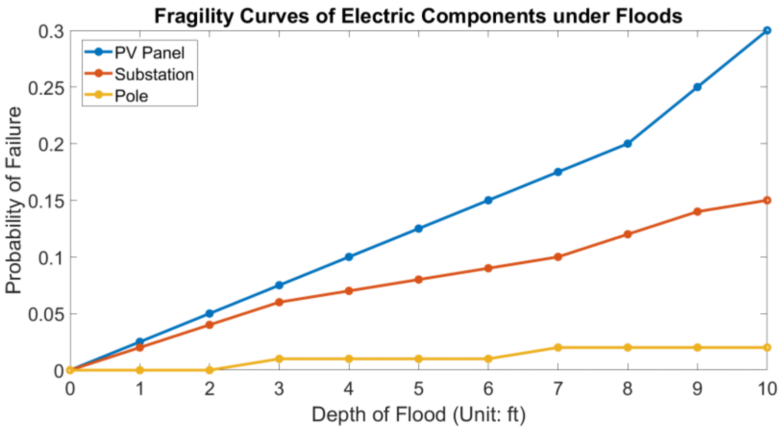


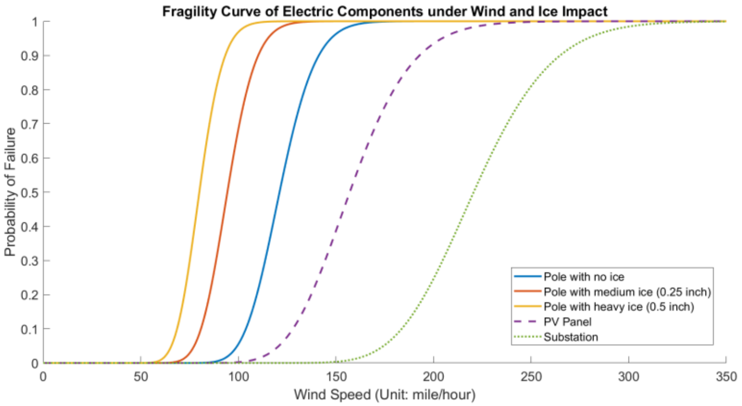
[1] B. E. K. Nygaard, I. A. Seierstad, and A. T. Veal, "A new snow and ice load map for mechanical design of power lines in Great Britain," Cold Regions Science and Technology, vol. 108, pp. 28–35, Dec. 2014.

Task 4: Preparation of Fragility Model and Acquisition of Damage Status

- Fragility Curves of electric components under **flood** and **winter storm** extreme weather events

- 3 electric components considered: poles, substations and PV panels.

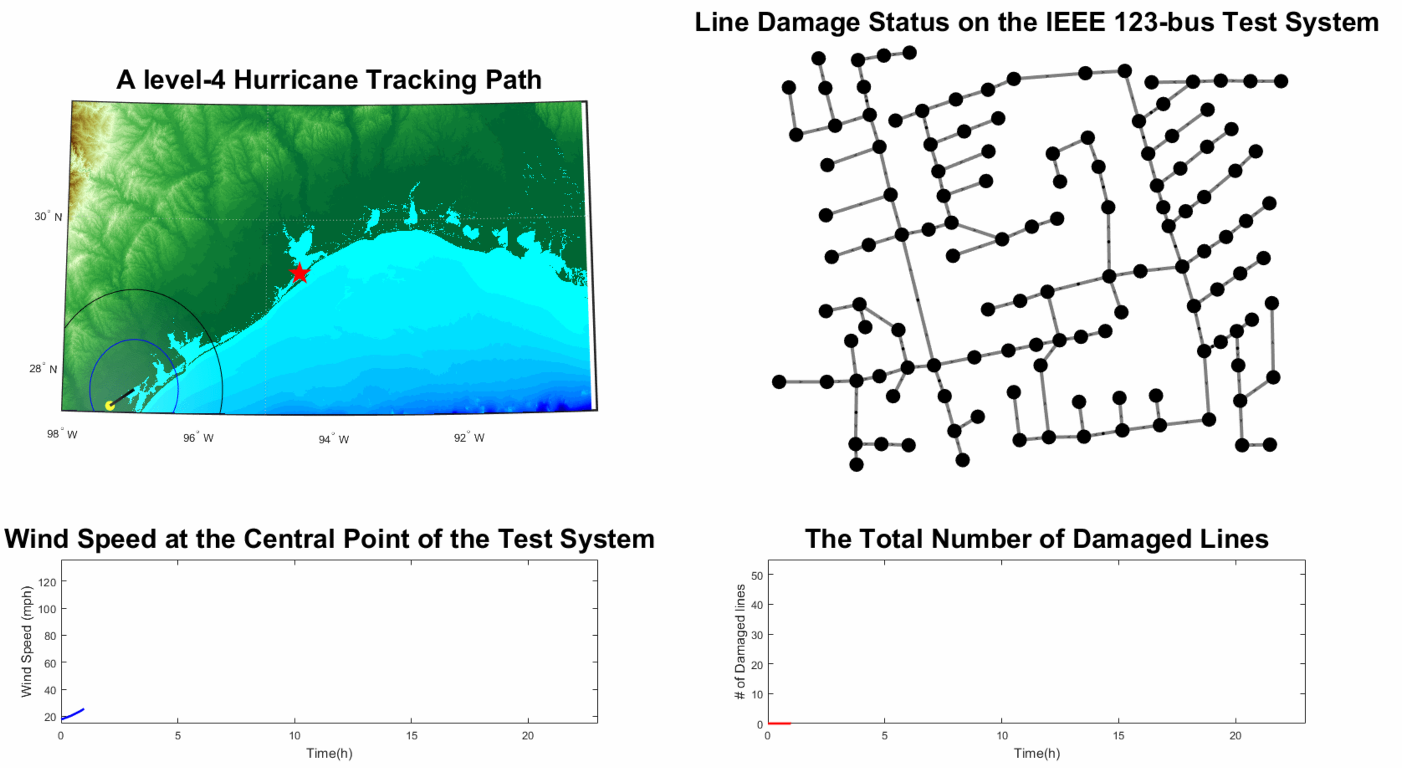




[1] "HAZUS Flood Model Technical Manual," Federal Emergency Management Agency.

Task 4: Results of Test Case Setup and Visualization

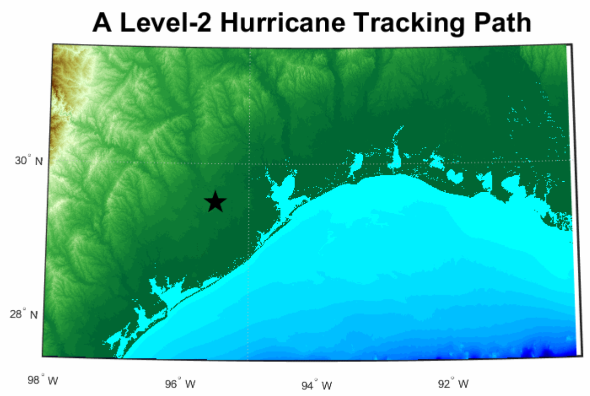
- **Small-scale** test case under **hurricane** extreme weather events **Level-4 Hurricane**

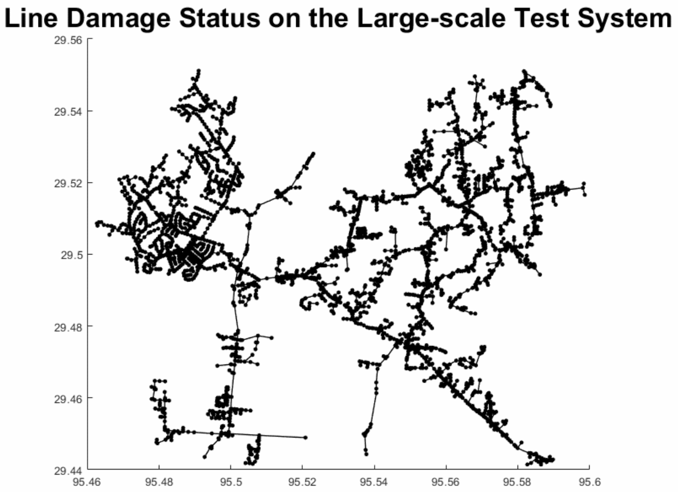


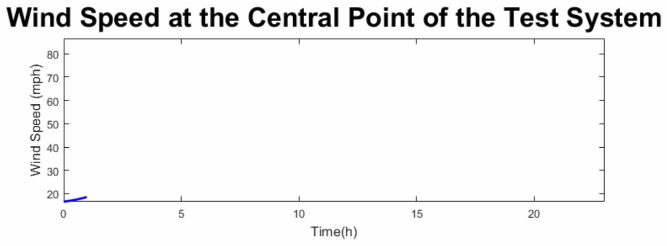
Task 4: Results of Test Case Setup and Visualization

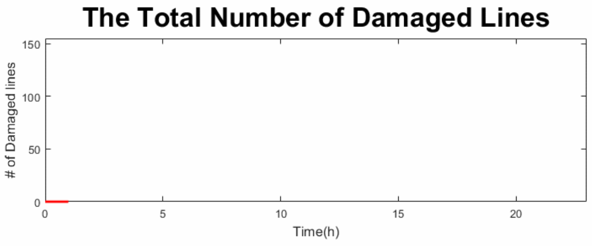
- **Large-scale** test case under **hurricane** extreme weather events

Level-2 Hurricane



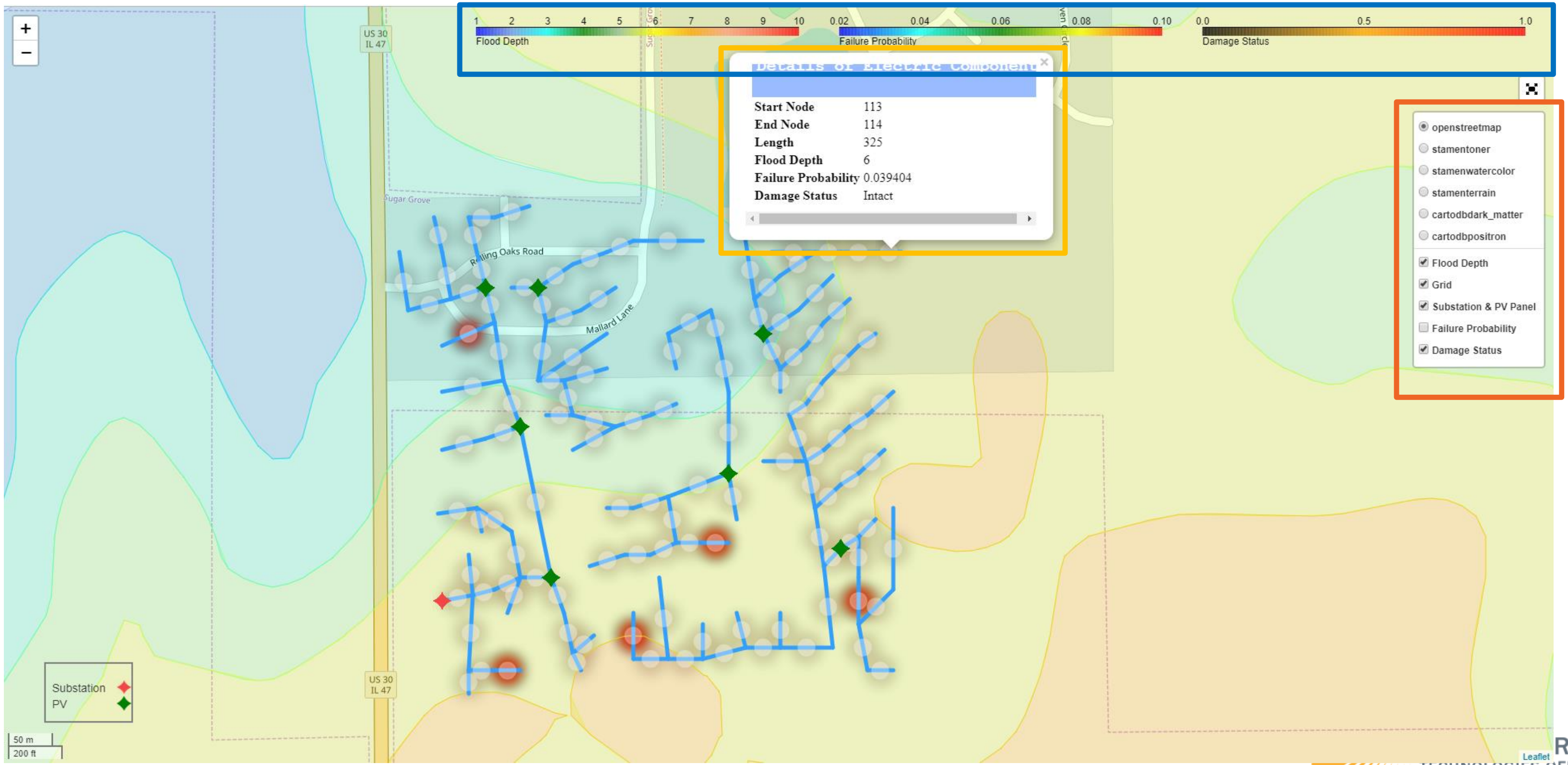






Task 4: Results of Test Case Setup and Visualization

- **Small-scale** test case under **flood** extreme weather events **Demonstrative Example**



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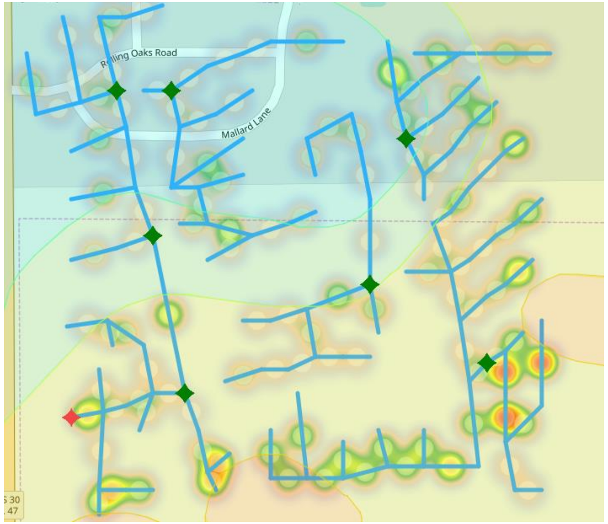
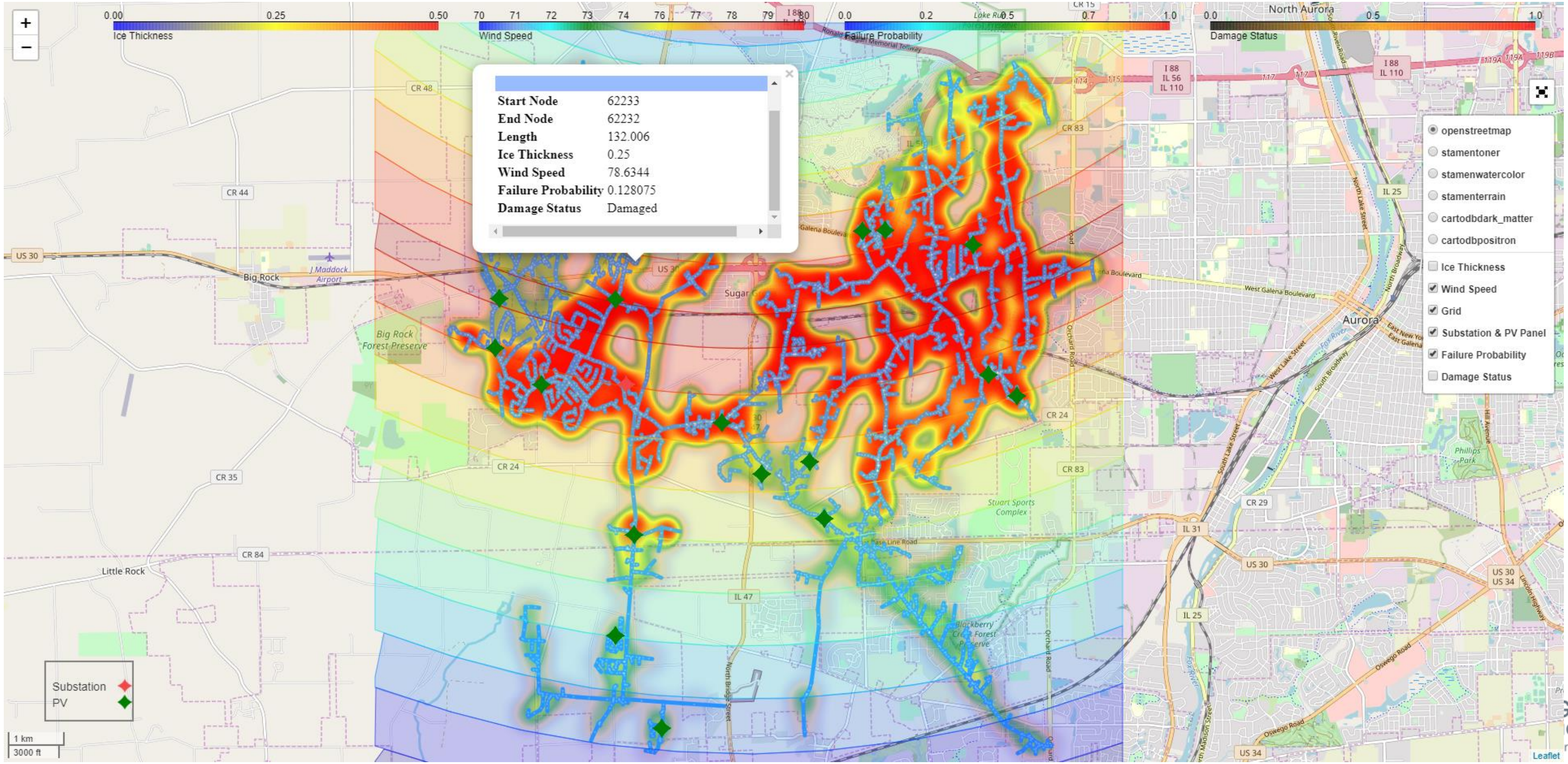
- **Small-scale** test case under **flood** extreme weather events



- 5 out of 118 lines are damaged in this test case
- 7 PVs on average are at 86% of functional capacity

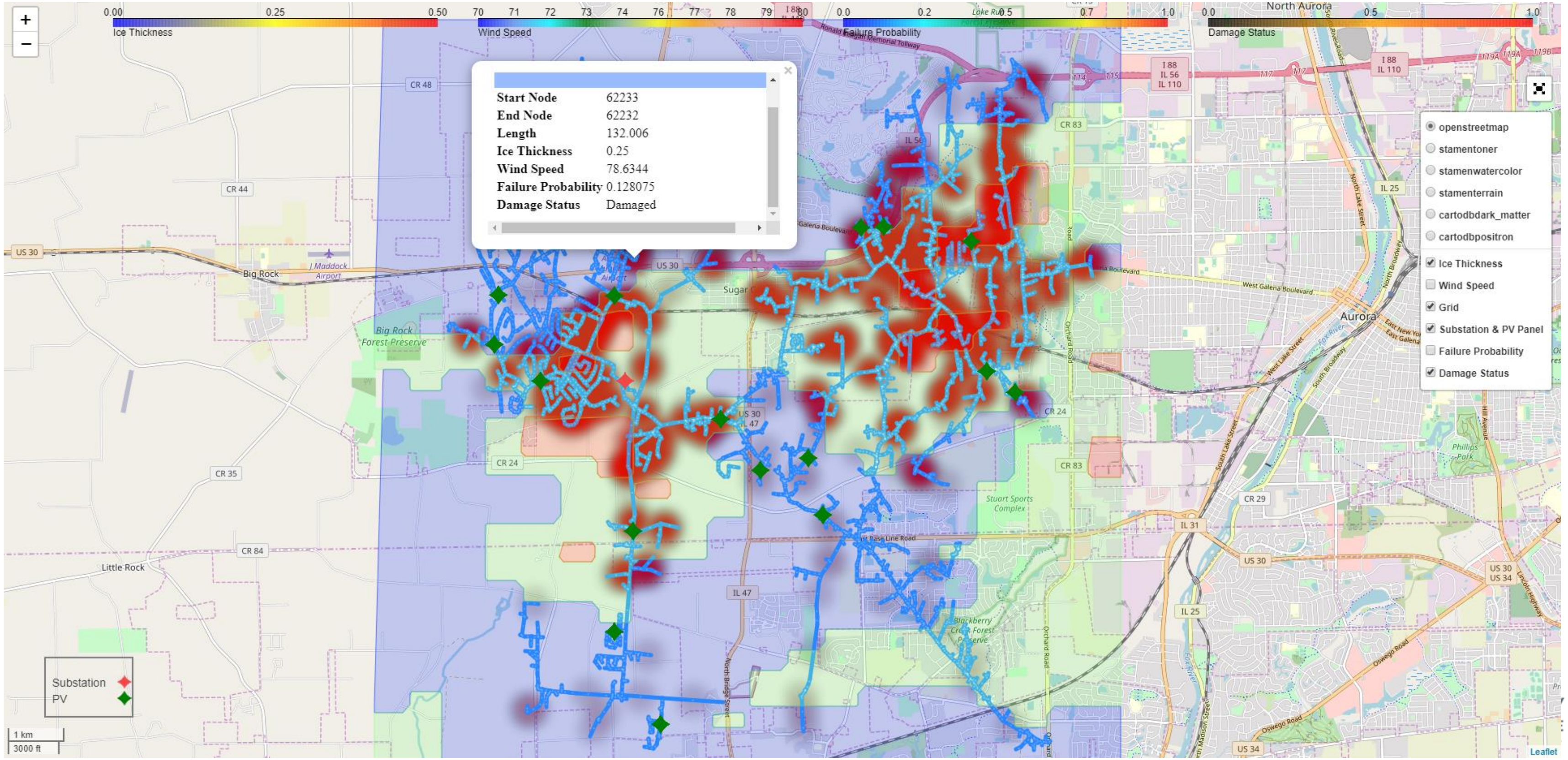
Task 4: Results of Test Case Setup and Visualization

- **Large-scale** test case under **winter storm** extreme weather events **Failure Probability**



Task 4: Results of Test Case Setup and Visualization

- **Large-scale** test case under **winter storm** extreme weather events **Damage Status**



Task 4: Results of Test Case Setup and Visualization

- **Large-scale** test case under **winter storm** extreme weather events

- 556 out of 3673 lines are damaged in this test case
- 16 PVs on average are at 99% of functional capacity

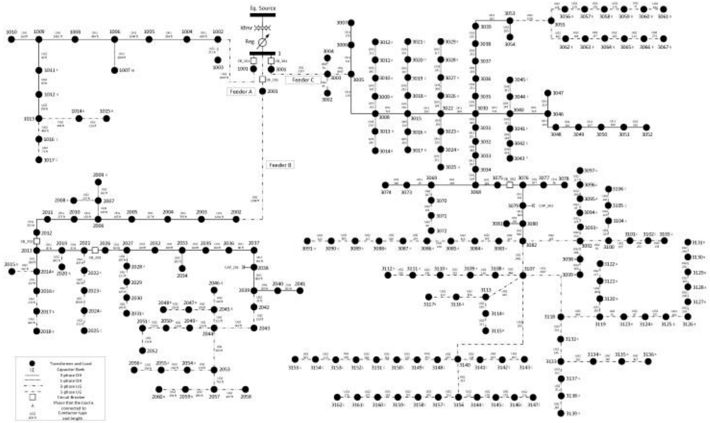
- **Large-scale** test case under **flood** extreme weather events

- 139 out of 3673 lines are damaged in this test case
- 16 PVs on average are at 83% of functional capacity

Task 4: Collecting real data from utility partners

- Real Feeder System
  - Located in Midwest U.S.
  - Consists of 3 feeders and contains 240 nodes, 233 lines and 9 switches
  - The real system topology and component parameters are also included
  - 4 crew depots, properly dispatched in pre-event preparation
    - 18 crews
    - 1 DGs, 4 mobile DGs and 3 mobile energy storage

Item	Number
Substation Transformer with Tap Changer	1
Feeder	3
Conductor Length	23 miles
Distribution Transformer	194
Capacitor Bank	2
Circuit Breaker	6
Customer	>1120
Data Length	1 year



Task 4: Test System and Test Scenarios Preparation

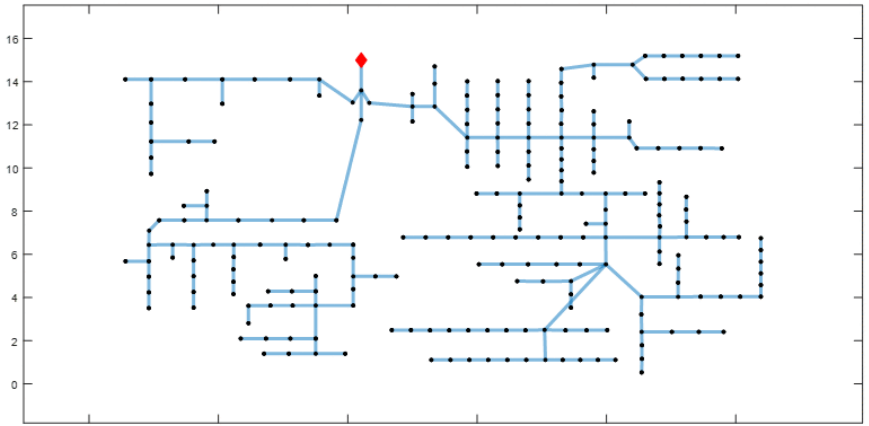
- PV Scenarios
  - Type of PV (I, II, and III)
  - Penetration of PV (0% to 100%)
  - Percentage of residential PV
    - 2 “turning points”

Type	Model	Capacity	Storage	Mode	Dispatch
III	Large utility PV farm	600 kW	4,800 kWh	Grid-forming Grid-following	Dispatch-able
II	Midsize PV system	12 kW	96 kWh	Grid-following	Dispatch-able
I	Residential PV panel	5 kW	N.A	Grid-following	MPPT

Task 4: Test System and Test Scenarios Preparation

- PV Scenarios
  - Penetration of PV
    - 0%, 10%, 20% …. to 100%
    - Percentage of residential PV has 2 “turning points”

0% PV Penetration



PV Penetration Level	Type III Number	Type II Number	Type I Number	Residential PV Percentage (%)
0%	0	0	0	N/A
10%	0	7	6	26.32
20%	0	9	25	53.65
30%	0	9	49	69.41
40%	0	9	72	76.92
50%	1	0	0	0
60%	1	7	6	4.20
70%	1	9	25	15.01
80%	1	9	49	25.71
90%	1	9	72	33.71
100%	1	0	117	49.37

Task 4

- Task 4: Setting up test cases used for pre-event preparation and post-event operation optimization solution algorithms
  - Subtask 4.1: (Completion in Q1-FY19) Set up small-scale test cases with three-phase single feeder systems
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Task 2

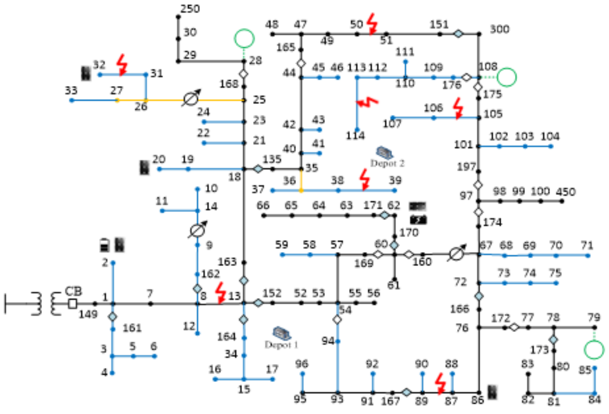
- Task 2: Development of pre-event proactive management optimization models and solution algorithms
  - Subtask 2.1: (Completion in Q1-FY19) State-of-the-art review of the pre-event management methodologies
  - Subtask 2.2: (Completion in Q2-FY19) Development of optimization model for pre-event preparation
  - Subtask 2.3: (Completion in Q3-FY19) Development of solution algorithms of pre-event optimization model.
  - Subtask 2.4: (Completion in Q4-FY19) Case studies and comparison via simulation (in Matlab or Python) using large-scale test cases under different hypothetical damage scenarios to verify the effectiveness of the method and refine algorithms as needed

- Milestones:
  - M1.2.1: (100% Completion) Development of preliminary optimization models of the pre-event preparation and post-event operation completed; the optimization models and test cases setup mechanism are presented to the IAB
  - M1.2.2: (100% Completion) Development of solution algorithms for the refined optimization models with preliminary testing results via simulation on small-scale test cases generated from subtask 4.1 and reviewed by industrial advisory board and DOE team; the resilience improvement should be at 10% in terms of served energy and reduction of outage duration
  - M1.2.3: (100% Completion) Development of solution algorithms for the refined optimization models with large-scale test cases developed in subtask 4.2; the resilience improvement should be at 10% in terms of served energy and reduction of outage duration

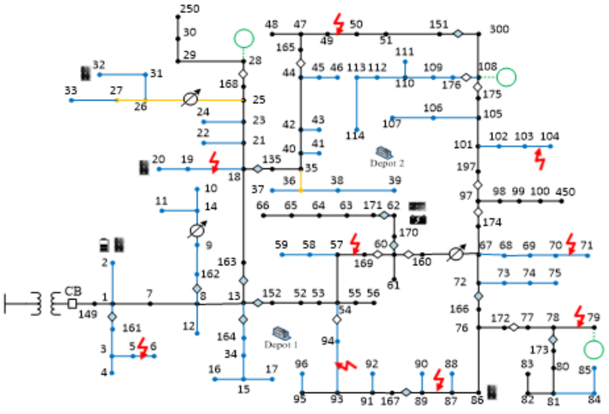
- Deliverables:
  - Optimization model and algorithm for pre-event preparations

Task 2: Stochastic Pre-Event Preparation

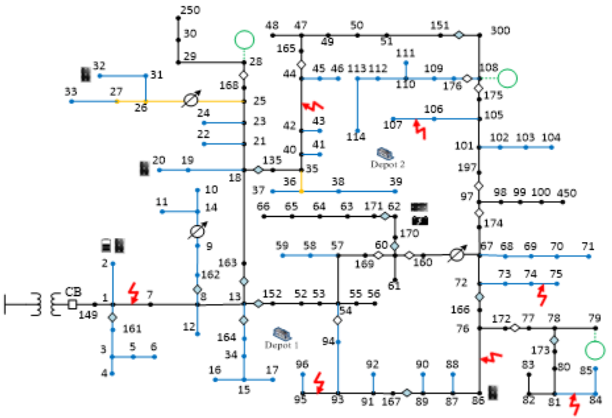
- The pre-event problem is modeled as a two-stage stochastic program
  - First stage: allocate resources
  - Second stage: operate the distribution system
  - Uncertainty: damaged lines, solar irradiance
- The uncertainty is represented by generating several possible scenarios



Scenario 1



Scenario 2



Scenario 3

Task 2: What is Stochastic Programming?

- Mathematical program in which some of the data are not known with certainty
  - Decision variables
  - Objective function
  - Constraints

Objectvie: $\min c^T x + \frac{1}{N}\sum_{s=1}^{N} Q(x, \xi_s)$

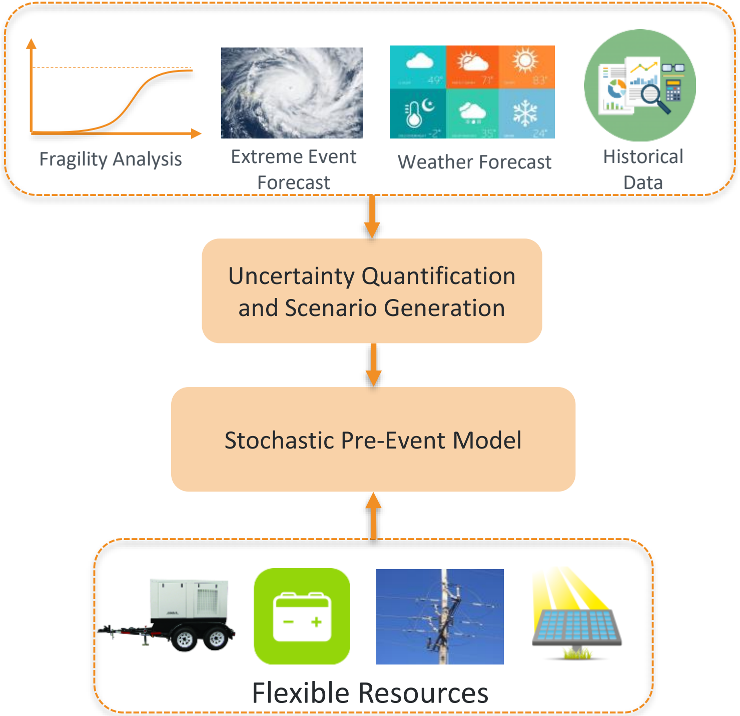
Subject to $A\,x = b$

$x \geq 0$

- Two-stage Stochastic Program
  - ✓ Given: A large number of potential scenarios
  - Stage I: Make some advance decisions (plan ahead)
  - ✓ Observe the actual input scenario
  - Stage II: Take recourse actions in response to the realization of the random variables and the first stage decisions

Task 2: Stochastic Pre-Event Model

- Uncertainty
  - Damage to the grid
  - Solar irradiance
- Objective:
  - Minimize operation costs and maximize load served
- First-stage constraints
  - Pre-position mobile generators
  - Fuel allocation
  - Pre-position crews
- Second-stage constraints
  - Generation and line flow limits
  - Unbalanced power flow
  - Fuel consumption
  - Energy Storage Charging and PV systems
  - Reconfiguration and isolation
  - Repair process



Task 2: Resource Allocation

- Types of resources to preposition
  - Mobile DERs and mobile energy storage systems
  - Fuel
  - Repair crews
- Constraints
  - Select locations for mobile energy sources
    - A mobile source is installed in one location (1)-(2)
    - The number of installed mobile sources in one location is limited (3)
  - Allocate available fuel to generators (4)-(5)
  - Allocate crews to different areas in the grid (6)-(7)

$$\sum_{i \in \Omega_{CN}} x_i^{MEG} = N^{MEG} \quad (1)$$

$$\sum_{i \in \Omega_{CN}} x_i^{MES} = N^{MES} \quad (2)$$

$$x_i^{MEG} + x_i^{MES} \leq N_i^U, \forall i \in \Omega_{CN} \quad (3)$$

$$\sum_{i \in \Omega_G} f_i \leq F^T \quad (4)$$

$$F_i^C \leq f_i \leq F_i^{max}, \forall i \in \Omega_G \quad (5)$$

$$\sum_{r \in \Omega_R} A_r = N^C \quad (6)$$

$$N_r^{Cmin} \leq A_r \leq N_r^{Cmax}, \forall\, r \in \Omega_R \quad (7)$$

Task 2: PV Systems

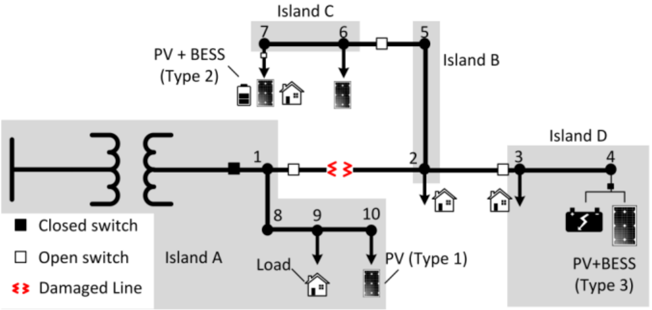
Types of PV systems considered in this project

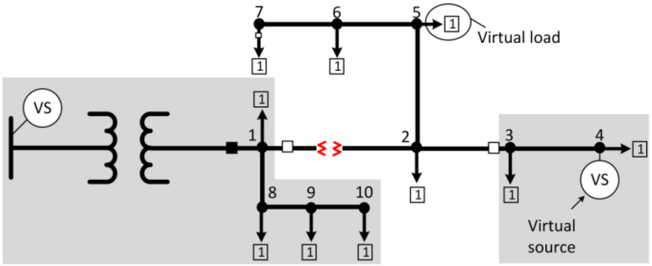
- On-grid (grid-tied) system
  - PV is disconnected if there is an outage
- Hybrid on/off-grid (PV with battery)
  - The PV system operates on-grid in normal conditions, and off-grid during an outage
- PV + battery with grid forming capabilities
  - This system can restore part of the network that is not damaged if the fault is isolated

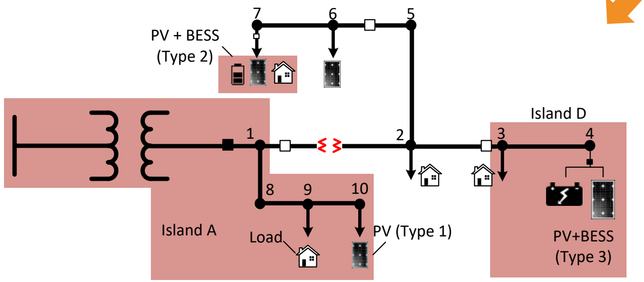
[1] K. Zipp. “What are some common types of solar PV and storage installations?" Internet: https://www.solarpowerworldonline.com/2015/10/whatare-some-common-types-of-solar-pv-and-storage-installations/, Oct. 29, 2015 [Nov. 1, 2018].
[2] C. Meehan. “What types of solar power systems can I get for my home?" Internet:https://www.solar-estimate.org/news/2017-11-15-types-solar-power-systems-homes-111517, Nov. 15, 2017 [Nov. 1, 2018].
[3] T. Kenning. “Australia’s first large-scale grid-connected solar and battery project comes online." Internet: https://www.pv-tech.org/news/australiasfirst-large-scale-grid-connected-solar-and-battery-project-comes, Feb. 19, 2018 [Nov. 1, 2018].

Task 2: PV Connectivity

- Create a virtual network
- Remove all generators and replace grid-forming ones by a virtual source
- Add a virtual load on each bus. If the virtual load is served, then the bus is energized
- Grid-connected PVs cannot operate if the bus is not energized





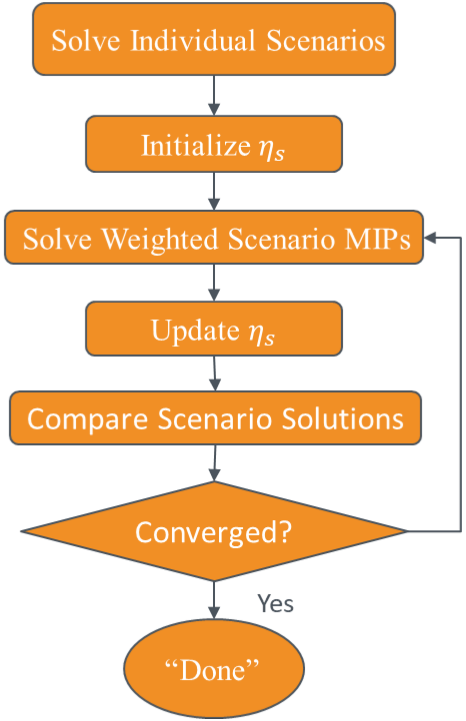


Task 2: Solution Methods

- The Extensive Form or Deterministic Equivalent
  - Write down the full variable and constraint set for all scenarios
  - Attempt to solve with a commercial MIP solver
  - Best solution, but often does not work due to memory or time limits
- Scenario-based decomposition
  - Progressive hedging / Dual decomposition
  - Pros: parallelizable, leverages specialized MIP solvers
  - Cons: Heuristic

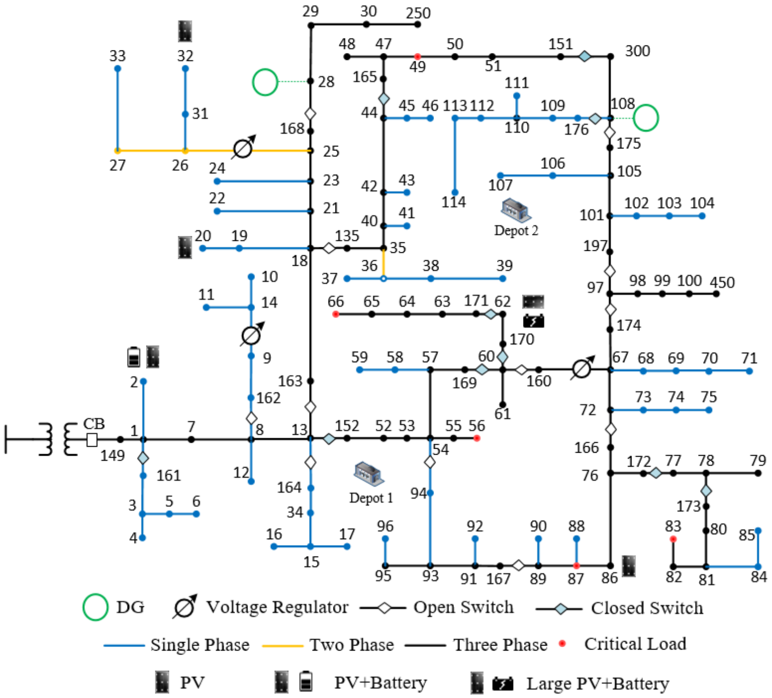
Task 2: Progressive Hedging

- Progressive hedging makes a scenario-decomposition and then obtains a solution by penalizing the scenario-problems.
- Solve each scenario independently and update penalty term until the algorithm converges
- Algorithm:
  1. Solve each scenario without penalty terms
  2. Find the average first-stage solution $\bar{x} = \sum_{\forall s} \Pr(s)\, x_s$
  3. Calculate penalty factor $\eta_s = \rho(x_s - \bar{x}_s)$
  4. Augment the penalty factor to the stochastic model and solve
  5. If $\sum_{\forall s} \Pr(s)\, ||x_s - \bar{x}_s|| > \epsilon$ go to 2
- The algorithm terminates once all first-stage decisions x_s converge to a common $\bar{x}$



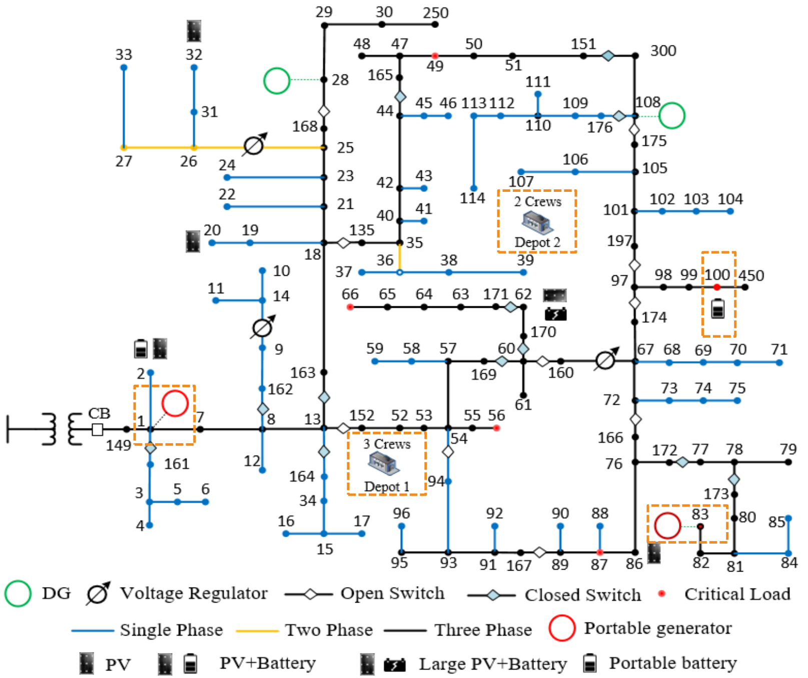
Task 2: Test Case – IEEE 123-bus System

- Modified IEEE 123-bus distribution feeder
- 3 mobile sources and 5 crews must be allocated
- 10 damage scenarios are generated using fragility models
- The proposed method is compared to a base model
- Base model:
  - Mobile generators are prepositioned at the substations
  - Extra mobile generators are prepositioned at high-priority loads
  - PV and battery storage are not considered



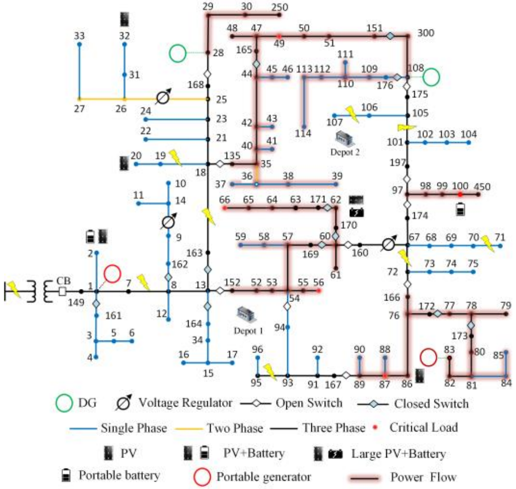
Task 2: Results - Preparation

- The computation time is approximately 90 minutes
- Mobile generators are allocated to buses 1 and 83
- A mobile battery storage is allocated to bus 100
- 3 crews → depot 1
- 2 crews → depot 2



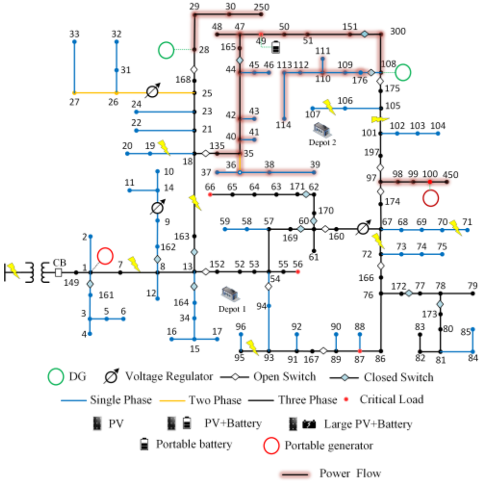
Task 2: Results – Resilience Improvement

- To evaluate the preparation results, we generate an additional scenario and test the response of the system
  - 8 damaged lines and the substation is not receiving power from the transmission system
  - Average outage duration = sum of outage durations for the loads / number of loads



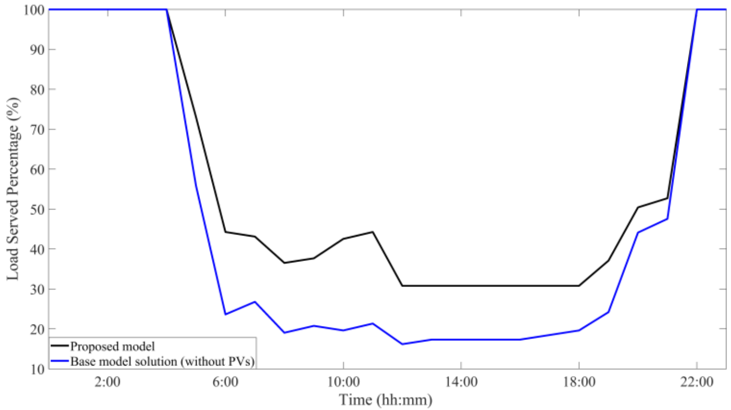
Proposed method

- total energy: 36775.44 kWh
- Average outage duration = 12.94 hrs



Base model

- total energy: 29038.88 kWh
- Average outage duration = 15.39 hrs



- Approximately **27%** percent more loads are served by the proposed method
- Outage duration decreased by **15.92%**

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Task 2: Results – Advantages of PVs

- To show the advantages of the PV systems, we test the response of the system with the proposed method and:
  - 100%, 80%, 60%, 40%, 0% penetration of PV
  - Increase the number of PVs in the system

PV Penetration Level	Load Served (kWh)
100% PV	36775.44
80% PV	36080.12
60% PV	35043.72
40% PV	33541.83
0% PV	30953.86

No. of PVs	Load Served (kWh)	Average Outage Duration
0	30953.86	14.99
5	36775.44	12.94
10	40267.91	12.27
15	41789.37	11.71
20	43359.89	11.17

Task 2

- Task 2: Development of pre-event proactive management optimization models and solution algorithms
  - Subtask 2.1: (Completion in Q1-FY19) State-of-the-art review of the pre-event management methodologies
  - Subtask 2.2: (Completion in Q2-FY19) Development of optimization model for pre-event preparation
  - Subtask 2.3: (Completion in Q3-FY19) Development of solution algorithms of pre-event optimization model.
  - Subtask 2.4: (Completion in Q4-FY19) Case studies and comparison via simulation (in Matlab or Python) using large-scale test cases under different hypothetical damage scenarios to verify the effectiveness of the method and refine algorithms as needed

- Milestones:
  - M1.2.1: (100% Completion) Development of preliminary optimization models of the pre-event preparation and post-event operation completed; the optimization models and test cases setup mechanism are presented to the IAB
  - M1.2.2: (100% Completion) Development of solution algorithms for the refined optimization models with preliminary testing results via simulation on small-scale test cases generated from subtask 4.1 and reviewed by industrial advisory board and DOE team; the resilience improvement should be at 10% in terms of served energy and reduction of outage duration
  - M1.2.3: (100% Completion) Development of solution algorithms for the refined optimization models with large-scale test cases developed in subtask 4.2; the resilience improvement should be at 10% in terms of served energy and reduction of outage duration

- Deliverables:
  - Optimization model and algorithm for pre-event preparations

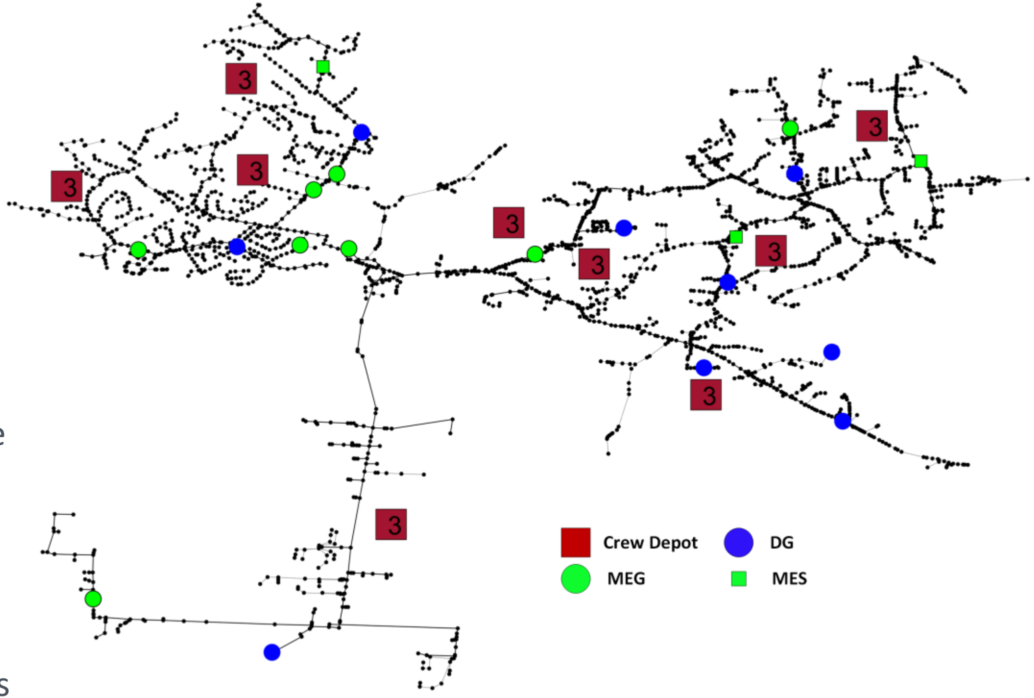
Task 2: Stochastic Pre-Event Preparation

- The pre-event problem is modeled as a two-stage stochastic program
  - First stage: allocate resources
  - Second stage: operate the distribution system
  - Uncertainty: damaged lines, solar irradiance, and load

- The uncertainty is represented by generating several possible scenarios
  - Use MRP to test the solution quality based on the limited generated damage scenarios

Task 2: Test Case: Large-Scale System

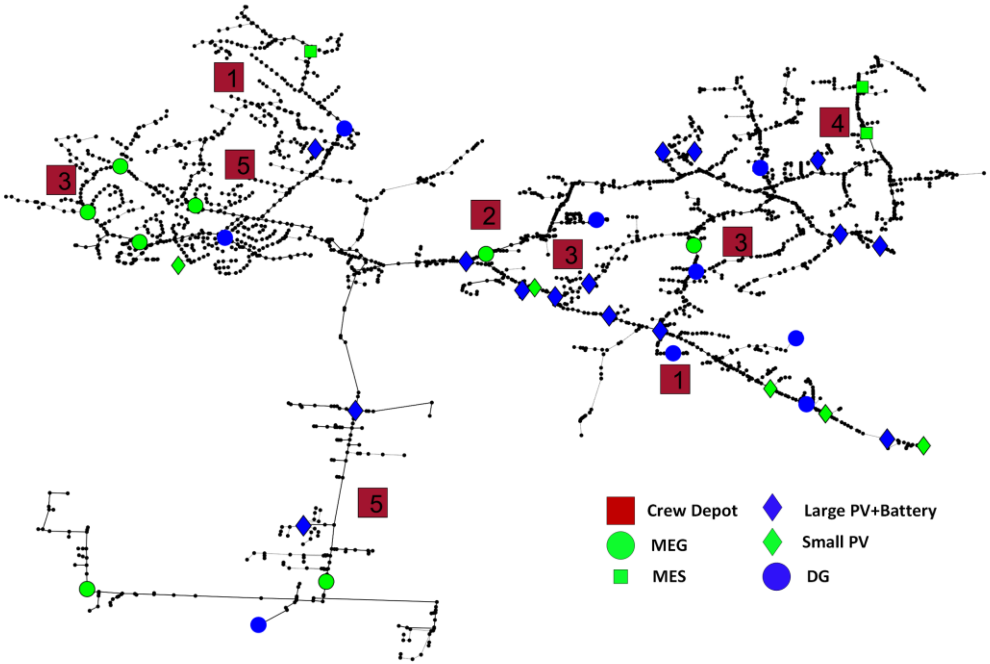
- 11 mobile sources and 27 crews must be allocated
- 10 damage scenarios are generated using fragility models
- The proposed method is compared to a base model
- Base model:
  - Mobile generators are prepositioned at the substations
  - Extra mobile generators are prepositioned at high-priority loads
  - PV and battery storage are not considered
  - Crews are allocated evenly between depots



Resource allocation in the base model.

Task 2: Results - Preparation

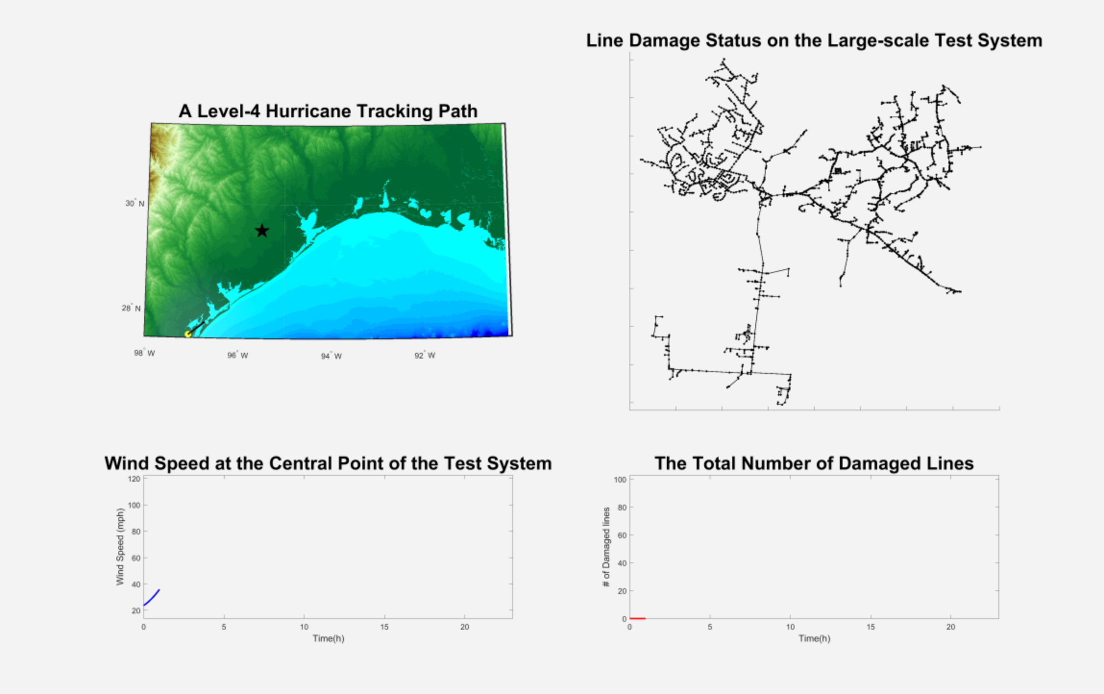
- The computation time is approximately 10.2 hours
- 8 mobile generators and 3 mobile storage are allocated
- 27 crews are dispatched to 9 depots
- The total capacity of PV can serve 33.33% load
  - 15 large PV with rated capacity of 500 kW
  - 6 small PV with rated capacity of 11kW~22kW



Resource allocation in the proposed model.

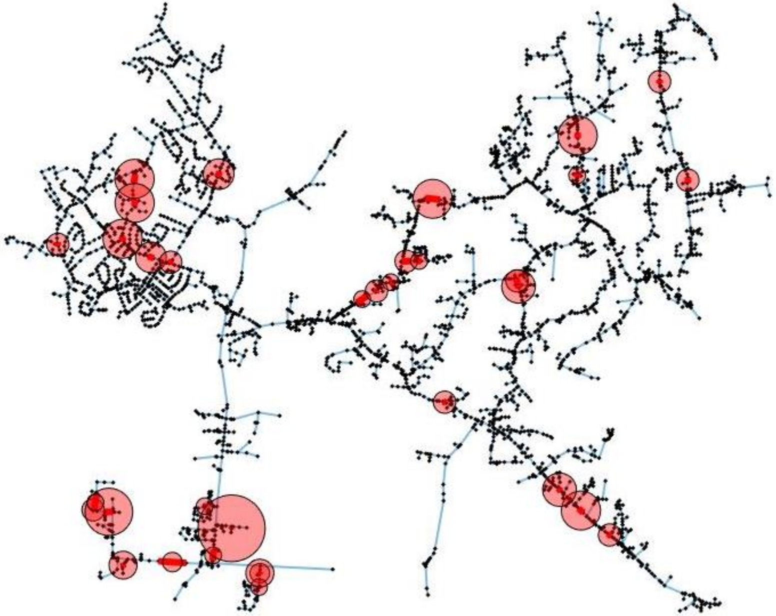
Task 2: Results – Resilience Improvement

- To evaluate the preparation results, we generate an additional scenario and test the response of the system
  - 103 damaged lines and the substation is not receiving power from the transmission system



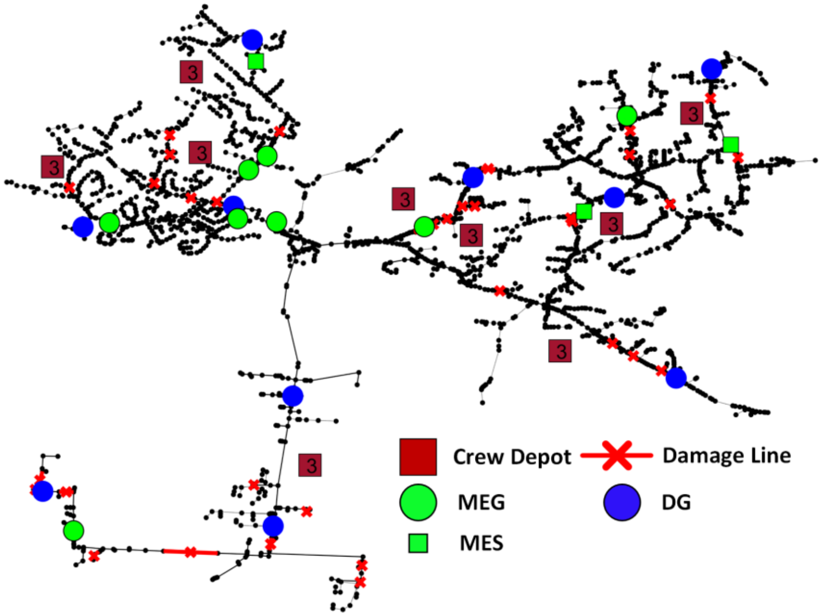
Task 2: Results – Resilience Improvement

- 103 damaged lines aggregated to 34 damaged areas
  - Aggregated the lines and nodes without defined coordinates
  - All information are preserved during aggregation: load / generation / repairing time
  - Circle size represent the repair time of corresponding damaged areas



Task 2: Test Case: Large-Scale System with Various PV Penetration Levels

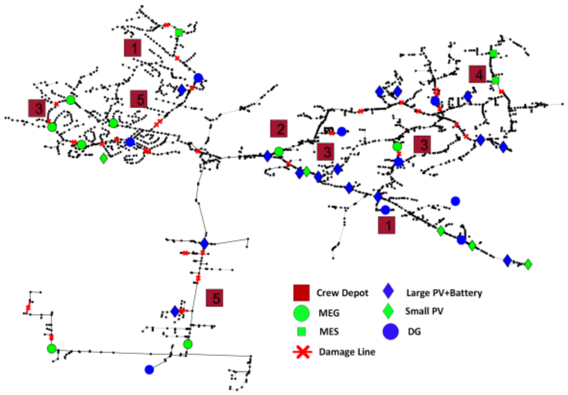
- 11 mobile sources and 27 crews must be allocated
  - The capacity of mobile sources is 500 kW
- 10 damage scenarios are generated using fragility models
- The proposed method with different level of PV penetration is compared to a base model
- Base model:
  - Mobile generators are prepositioned at the substations
  - Extra mobile generators are prepositioned at high-priority loads
  - PV and battery storage are not considered
  - Crews are allocated evenly between depots



Resource allocation in the base model.

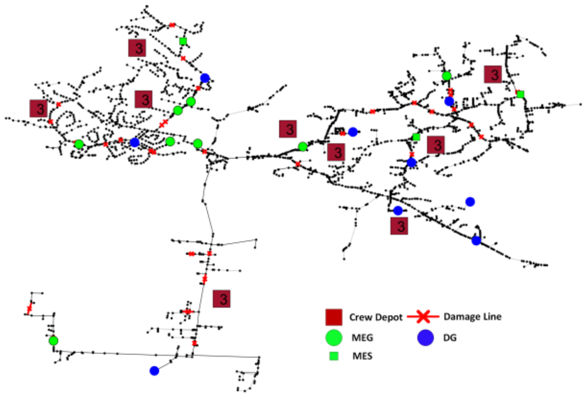
Task 2: Results – Advantages of PVs

- To evaluate the preparation results, we generate an additional scenario and test the response of the system
  - 103 damaged lines and the substation is not receiving power from the transmission system
  - Average outage duration = sum of outage durations for the loads / number of loads



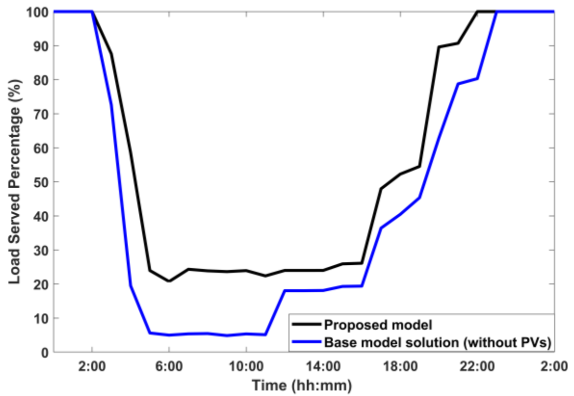
Proposed method

- total energy: 291,727.48 kWh
- Average outage duration = 11.28 hrs



Base model

- total energy: 231,422.38 kWh
- Average outage duration = 14.69 hrs



- Approximately **20.67%** percent more loads are served by the proposed method
- Outage duration decreased by **30.22%**

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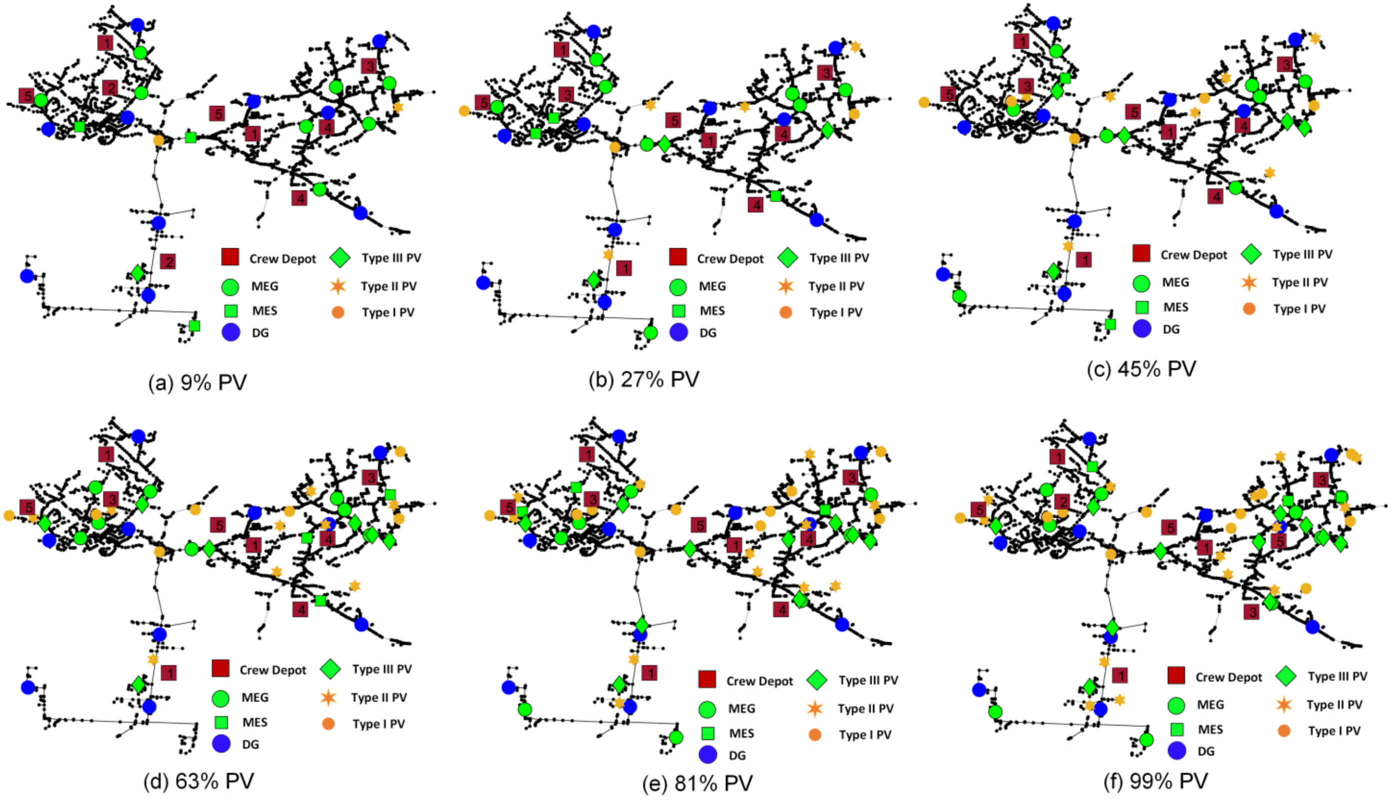
Task 2: Results – Advantages of PVs

- To show the advantages of the PV systems, we test the response of the system with various PV penetration levels
  - The total capacity of PV can serve load varying from 9% to 99%
    - Type I PV with rated capacity of 6 kW (Residential PV)
    - Type II PV with rated capacity of 48kW
    - Type III PV with rated capacity of 2000 kW
  - The result solutions will be coordinated with the post-event restoration.

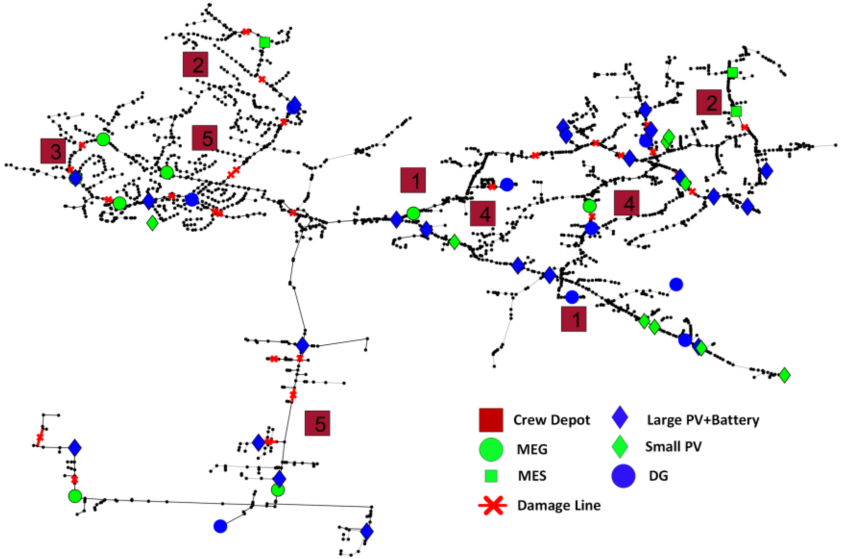
Task 2: Results – Advantages of PVs



Resource allocation in the proposed method with various PV penetration levels.

Task 2: Results – Advantages of PVs

- To show the advantages of the PV systems, we test the response of the system with high PV penetration
  - The total capacity of high PV can serve 50% load
    - 22 Large PV with rated capacity of 500 kW
    - 10 small PV with rated capacity of 11kW~22kW



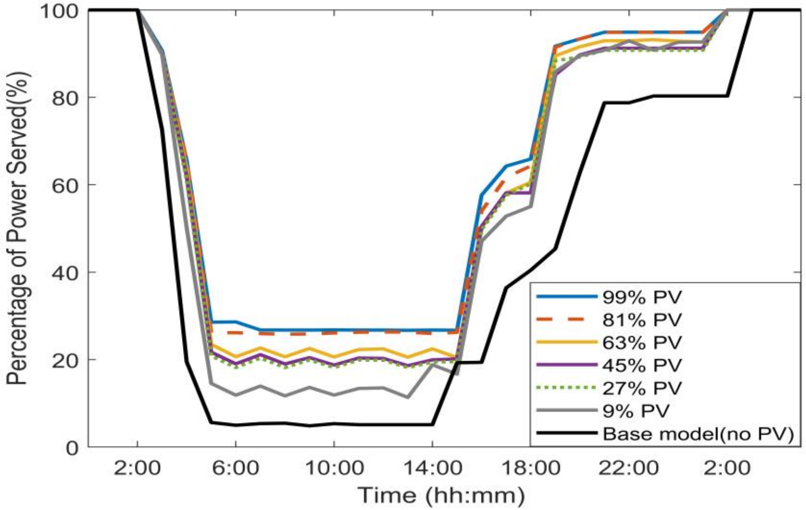
Resource allocation in the proposed model with high PV penetration

Table I. The amount of load served and average outage duration with different level of PV penetration

PV Penetration Level	Load Served (kWh)	Resilience Improvement Percentage(%)	Average Outage Duration (h)	Outage Decreased Percentage(%)
0	231,422.38		14.69	
Regular	291,727.48	20.67	11.28	30.22
High	308,361.678	24.95	10.49	40.06

Task 5: Results – Resilience Improvement

- To evaluate the preparation results, we generate an additional scenario and test the response of the system
  - 106 damaged lines and the substation is not receiving power from the transmission system
  - Average outage duration = sum of outage durations for the loads / number of loads



PV Level	Load Served (kWh)	Resilience Improvement Percentage(%)	Average Outage Duration (h)	Outage Decreased Percentage(%)
0	251210.72		14.69	
9%	318668.37	21.17	12.33	16.05
27%	335525.77	25.13	11.72	20.21
45%	336710.74	25.39	11.65	20.67
63%	344588.22	27.10	11.21	23.71
81%	360668.04	30.35	10.45	28.84
99%	364785.93	31.13	10.12	31.12

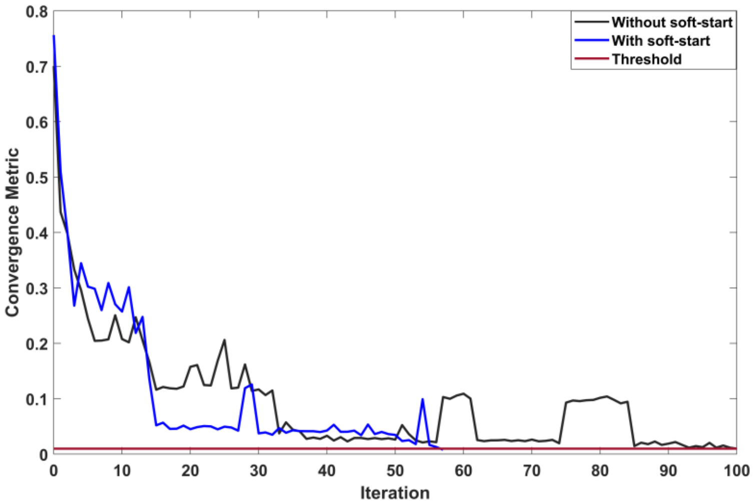
Task 2: Results – Convergence Speed

- The convergence metric of progress hedging algorithm at each iteration is:

$$g^k = \sum_{s \in S} p_r(s) \| x^k(s) - \bar{x}^k \|$$

- The convergence metric is used to evaluate the convergence speed
  - Set the threshold as 0.01
- Compare cases with and without soft-start solution
  - Soft-start: the previous computed solution in other instance

	Number of scenarios	Computation time (h)	Iteration
W/O soft start	10	24.3	100
W soft start	10	10.2	57



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Task 2: Results – Solution Validation

- To test the solution quality based on the limited generated damage scenarios
  - Use multiple replication procedure (MRP)
    - Repeat the procedure of generating 10 scenarios and solving the proposed model for 10 times
    - Construct the confidence interval (CI) for the optimal gap
      - $\Pr(\mathbf{E}\zeta(\hat{x}, s) - \zeta^* \leq \varepsilon_{CI}) \approx 0.95$, where ε_{CI} is the CI width
- The one-side CI of the proposed model's solutions in the percentage term with regard to the objective value for the optimality gap is [0, 12.48%].
  - It indicates that the proposed model's solutions with 10 scenarios are very stable and of high quality.

Task 2

- Task 2: Development of pre-event proactive management optimization models and solution algorithms
  - Subtask 2.1: (Completion in Q1-FY19) State-of-the-art review of the pre-event management methodologies
  - Subtask 2.2: (Completion in Q2-FY19) Development of optimization model for pre-event preparation
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- Milestones:
  - M1.2.1: (100% Completion) Development of preliminary optimization models of the pre-event preparation and post-event operation completed; the optimization models and test cases setup mechanism are presented to the IAB
  - M1.2.2: (100% Completion) Development of solution algorithms for the refined optimization models with preliminary testing results via simulation on small-scale test cases generated from subtask 4.1 and reviewed by industrial advisory board and DOE team; the resilience improvement should be at 10% in terms of served energy and reduction of outage duration
  - M1.2.3: (100% Completion) Development of solution algorithms for the refined optimization models with large-scale test cases developed in subtask 4.2; the resilience improvement should be at 10% in terms of served energy and reduction of outage duration

- Deliverables:
  - Optimization model and algorithm for pre-event preparations

Task Summary

Task 1: Set up an industrial advisory board (IAB) and deliver webinars

Task 2: Development of pre-event proactive management optimization models and solution algorithms.

Task 3: Development of Post-event operation and restoration optimization models and solution algorithms

Task 4: Setting up test cases used for pre-event preparation and post-event operation optimization solution algorithms

Task 5: Extensive case studies to evaluate the benefits of solar energy in resilience improvement

Task 6: Testing of the pre-event and post-event optimization via simulation using real feeder data

Task 3

- Task 3: Development of post-event operation and restoration optimization models and solution algorithms
  - Subtask 3.1: (Completion in Q1-FY19) State-of-the-art review of the post-event operation methodologies
  - Subtask 3.2: (Completion in Q3-FY19) Development of an optimal energy management optimization model and solution algorithms for islanded operation supported by DERs after the event
  - Subtask 3.3: (Completion in Q3-FY19) Development of optimal restoration and load pick up optimization model and solution algorithms using DERs, network reconfiguration, and repair crew

- Milestones:
  - M1.3.1: (100% Completion) Development of refined optimal energy management optimization model and solution algorithms with intermediate testing results based on small-scale test cases; the resilience improvement in terms of served energy will be at least 10%.
  - M1.3.2: (100% Completion) Development of optimal restoration and load pick up optimization model and solution algorithms using DERs, network reconfiguration, and repair crew and intermediate testing results based on small-scale test cases the resilience improvement in terms of reduction of outage duration will be at least 10%.
  - M1.3.3: (100% Completion) Case studies of the solution algorithms of energy management optimization and restoration optimization under large-scale test cases with three-phase multiple feeders with at least 10,000 nodes generated within required computation time (5 min for energy management optimization and 1 hour for restoration optimization) completed; the resilience improvement will be at least 10% in terms of served energy and outage duration reduction

- Deliverables:
  - Optimization model and algorithm for post-event operations

Task 3: Post-event Energy Management

- MIP problem with the following controllable decision variables:
  - DG's active and reactive power,
  - Energy storage system (ESS)'s real and reactive power;
  - PV's real and reactive power;
  - Shunt capacitor's reactive power injection;
  - Secondary voltage of the voltage regulators
  - Nodal load shedding;
  - Grid dispatch
- Three types of PV generation units

Task 3: Problem Formulation

- Objective Function

$$min \sum_s \Pr(s) \cdot \left(\sum_n \sum_t \rho_n^t \cdot \sum_\varphi P_{n,t}^{\varphi,s} + \sum_t \sum_j C_j^{t,s} + \sum_\varphi \sum_t \sum_d \omega_d \cdot \left(UD_{d,t} \cdot PD_{d,t}^{\varphi} - \right.\right.$$

s.t.

- DG, PV, ESS units' Constraints
- Nodal Generation/Load Balance
- Distribution Branch Flow Constraints

Task 3: Problem Formulation

- DG units' generation cost and operation constraints

$$C_j^{t,s} = \sum_g C_j^{fuel} \cdot w_g \cdot P_{j,g}^{t,s} \quad (2)$$

$$\sum_g P_{j,g}^{t,s} = \sum_\varphi P_{j,t}^{\varphi,s} \quad (3)$$

$$P_{j,g}^{t,s} \leq P_{j,g}^{max} \quad (4)$$

$$0 \leq P_{j,t}^{\varphi,s} \leq P_{j,\varphi}^{max} \cdot UX_{j,t} \qquad j \in NG, j \in EG \quad (5)$$

$$-Q_{j,\varphi}^{max} \cdot UX_{j,t} \leq Q_{j,t}^{\varphi,s} \leq Q_{j,\varphi}^{max} \cdot UX_{j,t} \qquad j \in NG, j \in EG \quad (6)$$

Task 3: Problem Formulation

- Curtailable load and Fixed Load Constraints

$$P_{d,t}^{\varphi,s} \leq PD_{d,t}^{\varphi} \cdot UD_{d,t} \quad (7)$$

$$Q_{d,t}^{\varphi,s} \leq QD_{d,t}^{\varphi} \cdot UD_{d,t} \quad (8)$$

- PV Generation
- Type I PV:

$$P_{v,t}^{\varphi,s} \leq PV_v^{\varphi,max} \cdot UV_{v,t} \qquad v \in V^c \quad (9)$$

$$P_{v,t}^{\varphi,s} \leq \left(\frac{1}{3}\right) \cdot A_v \cdot IR_{v,t}^{s} \cdot UV_{v,t} \qquad v \in V^c \quad (10)$$

$$-Q_v^{\varphi,max} \cdot UV_{v,t} \leq Q_{v,t}^{\varphi,s} \leq Q_v^{\varphi,max} \cdot UV_{v,t} \qquad v \in V^c \quad (11)$$

Task 3: Problem Formulation

- Types II & III PV:

$$P'^{\varphi,s}_{v,t} \leq \left(\frac{1}{3}\right) \cdot A_v \cdot IR^s_{v,t} \cdot UV_{v,t} \qquad v \in V^G \qquad (12)$$

$$P^{\varphi,s}_{v,t} = P'^{\varphi,s}_{v,t} + P^{\varphi,t,s}_{dc,v} - P^{\varphi,t,s}_{c,v} \qquad v \in V^G \qquad (13)$$

$$P'^{\varphi,s}_{v,t} + P^{\varphi,t,s}_{dc,v} - P^{\varphi,t,s}_{c,v} \leq PV^{\varphi,max}_v \cdot UV_{v,t} \qquad v \in V^G \qquad (14)$$

$$-Q^{\varphi,max}_v \cdot UV_{v,t} \leq Q^{\varphi,s}_{v,t} \leq Q^{\varphi,max}_v \cdot UV_{v,t} \qquad v \in V^G \qquad (15)$$

$$E^{\varphi,s}_{v,t} = E^{\varphi,s}_{v,t-1} + \eta^v_c \cdot P^{\varphi,t,s}_{c,v} - \frac{P^{\varphi,t,s}_{dc,v}}{\eta^v_{dc}} \qquad v \in V^G \qquad (16)$$

$$E^{min}_{v,\varphi} \leq E^{\varphi,s}_{v,t} \leq E^{max}_{v,\varphi} \qquad v \in V^G \qquad (17)$$

$$P^{\varphi,min}_{dc,v} \cdot I^{\varphi,t,s}_{dc,v} \leq P^{\varphi,t,s}_{dc,v} \leq P^{\varphi,max}_{dc,v} \cdot I^{\varphi,t,s}_{dc,v} \qquad v \in V^G \qquad (18)$$

$$P^{\varphi,min}_{c,v} \cdot I^{\varphi,t,s}_{c,v} \leq P^{\varphi,t,s}_{c,v} \leq P^{\varphi,max}_{c,v} \cdot I^{\varphi,t,s}_{c,v} \qquad v \in V^G \qquad (19)$$

$$I^{\varphi,t,s}_{c,v} + I^{\varphi,t,s}_{dc,v} \leq UV_{v,t} \qquad v \in V^G \qquad (20)$$

$$E^{\varphi,s}_{v,0} = E^{\varphi,s}_{v,ini} \qquad v \in V^G \qquad (21)$$

Task 3: Problem Formulation

- Shunt Capacitor

$$0 \leq Q_{c,t}^{\varphi,s} \leq Q_{c}^{max} \quad (22)$$

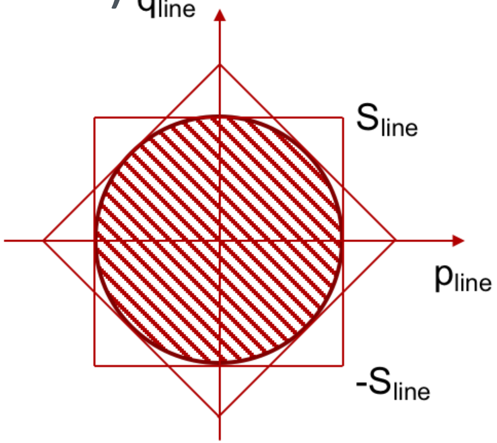
- Nodal Generation/Load balance (KCL):

$$\sum_{n \in N_b} P_{n,t}^{\varphi,s} + \sum_{j \in G_b} P_{j,t}^{\varphi,s} + \sum_{m \in M_b} \left(P_{dc,m}^{\varphi,t,s} - P_{c,m}^{\varphi,t,s}\right) + \sum_{l \in L_{t,b}} PL_{l,t}^{\varphi,s} - \sum_{l \in L_{f,b}} PL_{l,t}^{\varphi,s} + \sum_{v \in V_b} P_{v,t}^{\varphi,s} - \sum_{d \in D_b} P_{d,t}^{\varphi} = 0 \quad (23)$$

$$\sum_{n \in N_b} Q_{n,t}^{\varphi,s} + \sum_{j \in G_b} Q_{j,t}^{\varphi,s} + \sum_{m \in M_b} Q_{m}^{\varphi,t,s} + \sum_{l \in L_{t,b}} QL_{l,t}^{\varphi,s} - \sum_{l \in L_{f,b}} QL_{l,t}^{\varphi,s} + \sum_{c \in C_b} Q_{c,t}^{\varphi,s} + \sum_{v \in V_b} Q_{v,t}^{\varphi,s} - \sum_{d \in D_b} Q_{d,t}^{\varphi} = 0 \quad (24)$$

Task 3: Problem Formulation

- Distribution Branch Flow: KVL and power flow constraints
  - Network Capacity Limits (Linear Approximation)



$$-UY_{l,t} \cdot p_l^{\varphi} \cdot SL_{\varphi,l}^{max} \leq PL_{l,t}^{\varphi,s} \leq UY_{l,t} \cdot p_l^{\varphi} \cdot SL_{\varphi,l}^{max} \quad (25)$$

$$-UY_{l,t} \cdot p_l^{\varphi} \cdot SL_{\varphi,l}^{max} \leq QL_{l,t}^{\varphi,s} \leq UY_{l,t} \cdot p_l^{\varphi} \cdot SL_{\varphi,l}^{max} \quad (26)$$

$$-\sqrt{2} \cdot UY_{l,t} \cdot p_l^{\varphi} \cdot SL_{\varphi,l}^{max} \leq PL_{l,t}^{\varphi,s} + QL_{l,t}^{\varphi,s} \leq \sqrt{2} \cdot UY_{l,t} \cdot p_l^{\varphi} \cdot SL_{\varphi,l}^{max} \quad (27)$$

$$-\sqrt{2} \cdot UY_{l,t} \cdot p_l^{\varphi} \cdot SL_{\varphi,l}^{max} \leq PL_{l,t}^{\varphi,s} - QL_{l,t}^{\varphi,s} \leq \sqrt{2} \cdot UY_{l,t} \cdot p_l^{\varphi} \cdot SL_{\varphi,l}^{max} \quad (28)$$

- Distribution feeder real and reactive power dispatch limits

$$-\tan(\cos^{-1} PF_n) \cdot P_{n,t}^{\varphi,s} \leq Q_{n,t}^{\varphi,s} \leq \tan(\cos^{-1} PF_n) \cdot P_{n,t}^{\varphi,s} \quad (29)$$

Task 3: Problem Formulation

- Kirchhoff Voltage Law

$$\boldsymbol{U}_{k,t}^{s} - \boldsymbol{U}_{b,t}^{s} + \widetilde{Z}_l \cdot \left(\boldsymbol{SL}_{l,t}^{s}\right)^* + \widetilde{Z}_l^{\,*} \cdot \boldsymbol{SL}_{l,t}^{s} \le M \cdot \left(1 - UY_{l,t}\right) \cdot \boldsymbol{p}_l \qquad b \in L_f^l, k \in L_t^l \qquad (30)$$

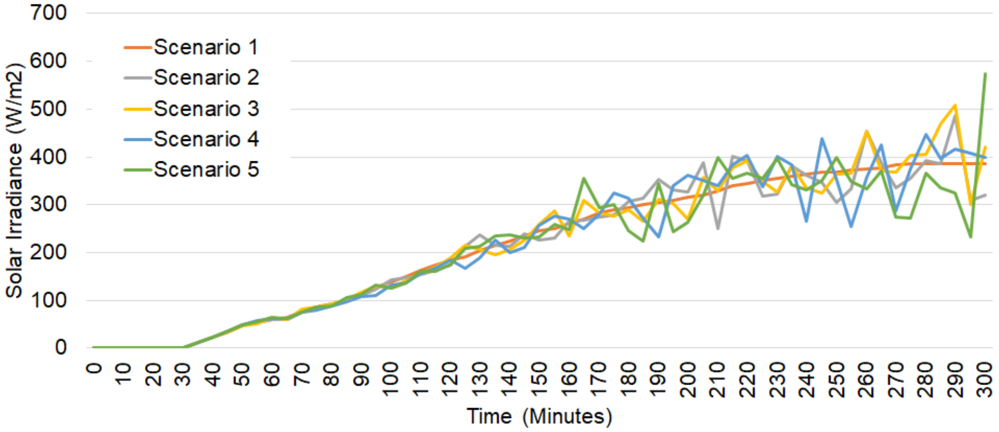
$$-M \cdot \left(1 - UY_{l,t}\right) \cdot \boldsymbol{p}_l \le \boldsymbol{U}_{k,t}^{s} - \boldsymbol{U}_{b,t}^{s} + \widetilde{Z}_l \cdot \left(\boldsymbol{SL}_{l,t}^{s}\right)^* + \widetilde{Z}_l^{\,*} \cdot \boldsymbol{SL}_{l,t}^{s} \qquad b \in L_f^l, k \in L_t^l \qquad (31)$$

$$\widetilde{Z}_l = A \odot Z_l$$

$$A = \begin{bmatrix} 1 & e^{-\frac{j2\pi}{3}} & e^{\frac{j2\pi}{3}} \\ e^{\frac{j2\pi}{3}} & 1 & e^{-\frac{j2\pi}{3}} \\ e^{-\frac{j2\pi}{3}} & e^{\frac{j2\pi}{3}} & 1 \end{bmatrix} \qquad (32)$$

Task 3: Uncertainty in the Solar Irradiance

- The forecast error for solar irradiance was considered by a normal distribution function in which the mean is the forecasted solar irradiance, and the standard deviation is progressively increasing by 0.3% for each 5 minutes.
- Five scenarios including the forecasted scenario with equal probabilities were considered for this case.



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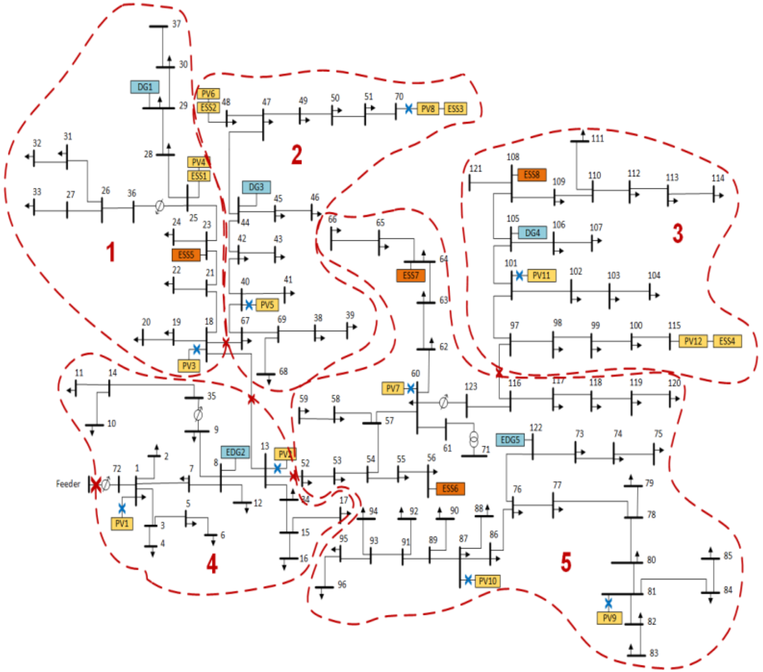
Task 3: Case Study

- IEEE 123-bus system



- PV8-ESS is Type 2
- PV4, PV6 and PV12 are grid forming PVs (Type 3)
- The rest of PVs are Type 1
- Simulations are performed on a PC with Intel Core i7 processor of 2.8GHz, and 32 GB Memory with CPLEX 12.8.0.

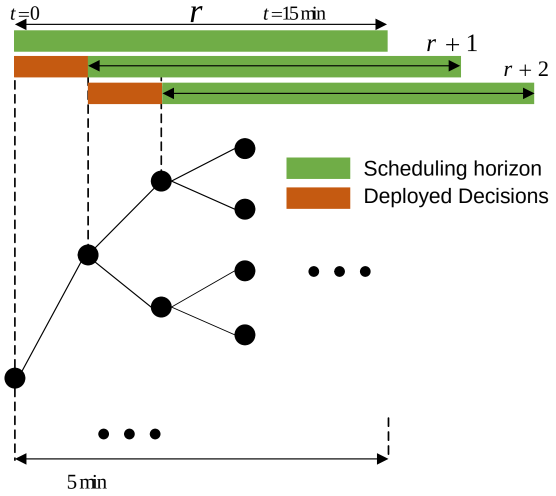
	Served load (kWh)	Percentage of served load	Cost ($)	Improvement of resilience %	Solution time (min)
With PV generation	3,343.7	20.6%	515,890.2	32.1%	42.37
Without PV generation	2,532.1	15.6%	548,028.2	0	40.52

Task 3: Rolling Horizon Approach

- The duration of the operation and the time step are selected as 15 and 5 minutes, respectively.
- The results are applied for the first 5 minutes and are updated every 5 minutes.
- The total expected demand curtailment for the first 15 minutes is 669.542 kWh. 18.1% of the demand is served.

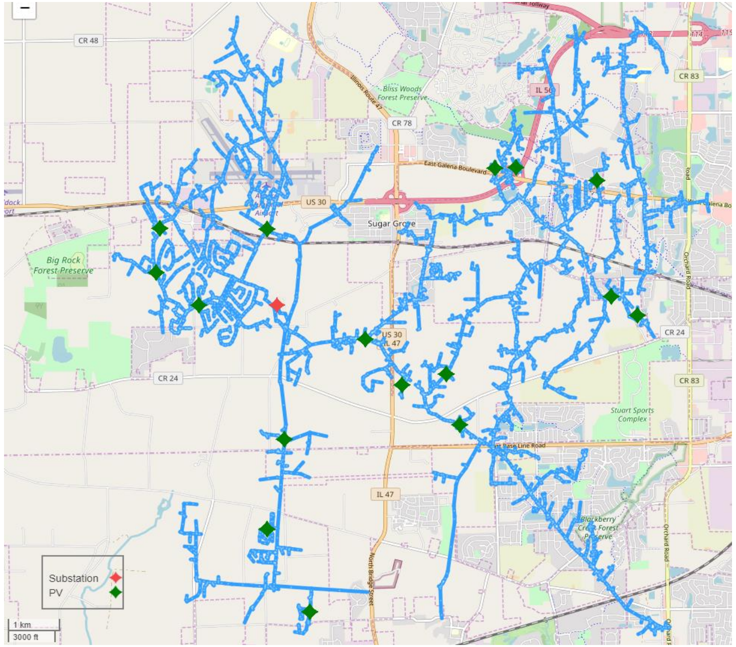
ESS (kWh)	ESS 1	ESS 2	ESS 3	ESS 4	ESS 5	ESS 6	ESS 7	ESS 8
Scen. 1-5	198.15	98.15	100	98.15	195.37	147.69	195.37	147.69

- The solution Time is 2:53 min and CPLEX Time is 0.27 sec.



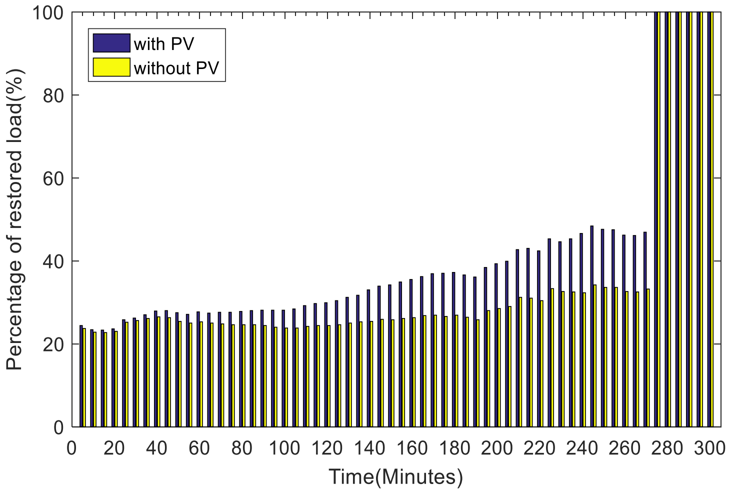
Scenario Based
Stochastic Solution

Task 3: Large-scale test system



- The large-scale system is consisted of 3 existing test systems (EPRI ckt5 system, EPRI ckt7 system, IEEE 8500 bus system) and has more than 10,000 nodes.
- 25 PV units are integrated.
- The capacities of PV1, PV2, PV6, and PV7 are 400 kW and the capacities of other PV units are 200 kW.
- PV1-PV8 are Type 3 PV units. PV9-PV12 are Type 2 PV units and the rest of the PV units are Type 1.
- The simulation is performed on a server with Dual 14 Core Intel Xeon 2.6GHz and 380 GB RAM with CPLEX 12.9.0.

Task 3: Large-scale test system



Percentage of restored load over the considered period

	Served load (kWh)	Percentage of served load	Cost ($)	Improvement of resilience %	Solution time (min)
With PV generation	61,410.6	43.8%	2,462,985.0	25.1%	31.44
Without PV generation	49,072.0	35.0%	2,848,189.4	0	18.05

- Using the rolling horizon approach to solve this problem, 35.6% of the demand is being served in the first operation horizon, i.e., 6:00-6:15 AM.
- The solution time is **42.252 sec** and the CPLEX time is 27.73 sec, which is far less than 5 minutes.

Task 3

- Task 3: Development of post-event operation and restoration optimization models and solution algorithms
  - Subtask 3.1: (Completion in Q1-FY19) State-of-the-art review of the post-event operation methodologies
  - Subtask 3.2: (Completion in Q3-FY19) Development of an optimal energy management optimization model and solution algorithms for islanded operation supported by DERs after the event
  - Subtask 3.3: (Completion in Q3-FY19) Development of optimal restoration and load pick up optimization model and solution algorithms using DERs, network reconfiguration, and repair crew

- Milestones:
  - M1.3.1: (100% Completion) Development of refined optimal energy management optimization model and solution algorithms with intermediate testing results based on small-scale test cases; the resilience improvement in terms of served energy will be at least 10%.
  - M1.3.2: (100% Completion) Development of optimal restoration and load pick up optimization model and solution algorithms using DERs, network reconfiguration, and repair crew and intermediate testing results based on small-scale test cases the resilience improvement in terms of reduction of outage duration will be at least 10%.
  - M1.3.3: (100% Completion) Case studies of the solution algorithms of energy management optimization and restoration optimization under large-scale test cases with three-phase multiple feeders with at least 10,000 nodes generated within required computation time (5 min for energy management optimization and 1 hour for restoration optimization) completed; the resilience improvement will be at least 10% in terms of served energy and outage duration reduction

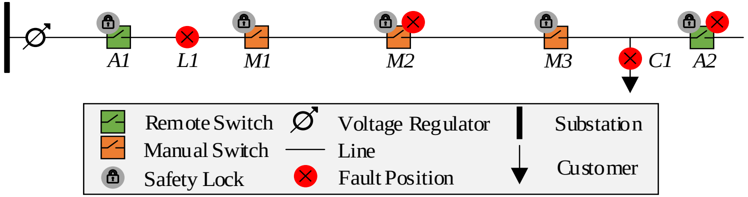
- Deliverables:
  - Optimization model and algorithm for post-event operations

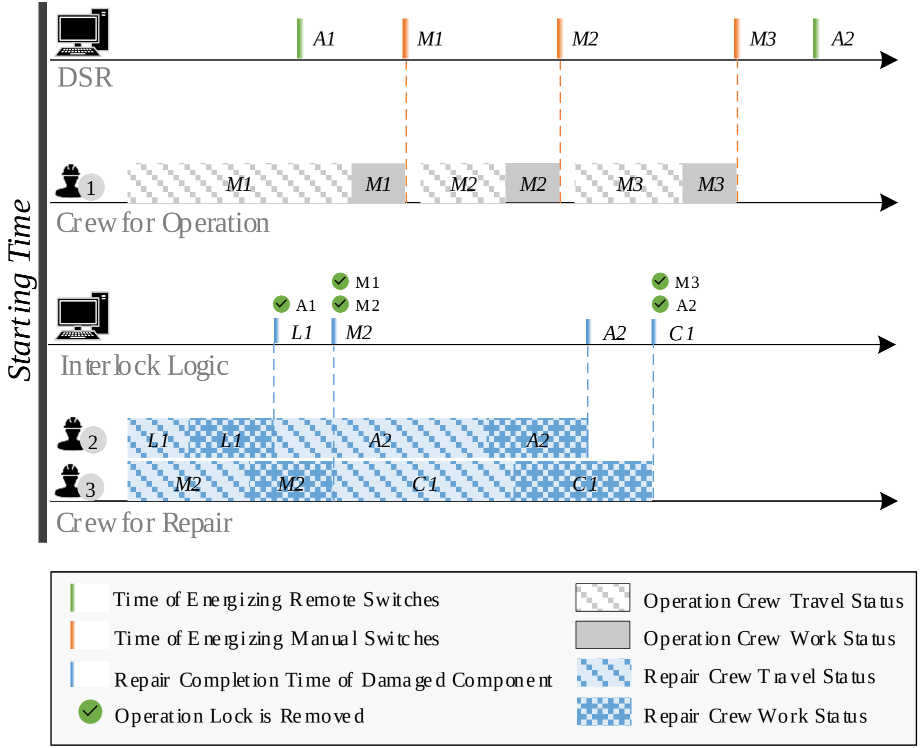
Task 3: Optimal Restoration and Repair Module

- **Restoration**: Operating **auto** and **manual** switches
  - System operator can operate auto switches
  - Crews can operate manual switches
- **Repair**: Crews will **travel** to repair and operate components **sequentially**
  - Crews can repair damaged components
- **State-of-Art**: Separate modules with limited/manual coordination
  - Sufficient for daily outages
  - Inefficient facing massive outages caused by natural disasters
- **Motivation**: Restoration and Repair are **Interdependent**
  - Faster Restoration: Crews shall follow an optimal repair sequence, so that Restoration module can pick up loads faster. Coordination among multiple crews is also critical.
  - Operational Security: Avoid energizing a line segment containing damaged components
  - Crew Security: Isolate working segments by opening upstream/downstream switches

Task 3: Optimal Restoration and Repair Module

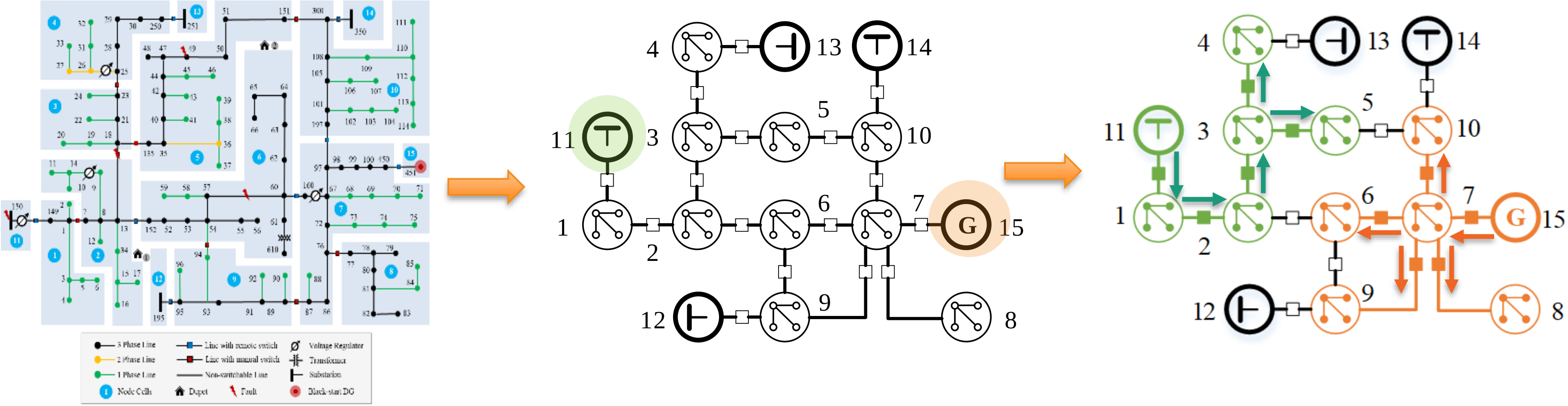
- Conceptual work flow for:
  - Restoration (DSR)
  - Operating Switch (Crew for Operation)
  - Repair (Crew for Repair)
  - Coordination (Interlock Logic)





Task 3: Optimal Restoration and Repair Module

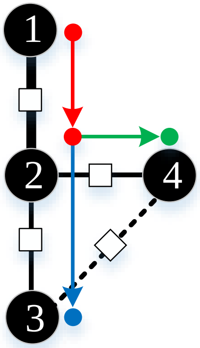
- Concept of "**cell**" and "**traveling current**"
  - System circuit can be grouped into multiple "cells" by auto and manual switches
  - A cell can contain normal/damaged DERs, line segments, and loads.
  - Restoration is a process of operating switches to **energize cells sequentially**:
  - **Energization current will travel through switches from sources to downstream cells**.



Concept of node cell. (a): Modified IEEE 123 node test feeder.
(b): Node cell representation of IEEE 123 node test feeder.

Task 3: Optimal Restoration and Repair Module

- Basic idea: Formulate restoration problem using a routing model, then integrate the crew dispatch model, which is also a routing model.
  - "cell" as the destination: n cells → $n \times n$ routing table
  - Routing table is sparse: if no switch between cell i and cell j, then $x_{ij} = x_{ji} = 0$
  - Switch as the route: switch operation time is the travel time (auto vs manual)
  - **Energization current as a travel agent**
    - Starting from diagonal element (substation cell) to off-diagonal elements (load cells)
    - One can split to Two or More: as long as within voltage and line capacity limits



(a)

x_{11}^R	x_{12}^R	0	0
x_{21}^R	0	x_{23}^R	x_{24}^R
0	x_{32}^R	0	x_{34}^R
0	x_{42}^R	x_{43}^R	0

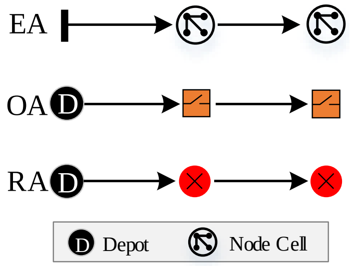
(b)

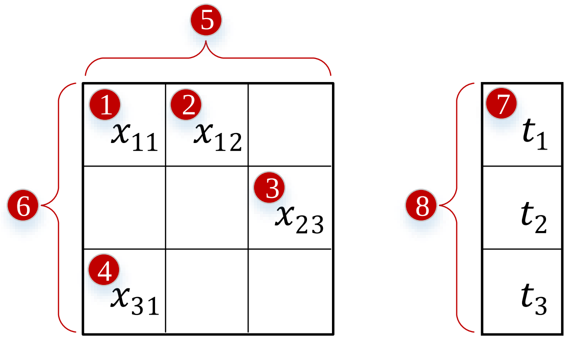
1	1	0	0
0	0	1	1
0	0	0	0
0	0	0	0

(c)

Task 3: Optimal Restoration and Repair Module

- EA (Energization Current)
- OA (Operation Crew)
- RA (Restoration Crew)
- All have **similar variable definitions**





No.	Variable	Definition
①	x_{ii}	Diagonal terms of the route table. $x_{ii} = 1$, if node i is the substation for EA or the depot for OA and RA. $x_{ii} = 0$, if node i is not the “starting point.”
②③④	$x_{ij}, i \neq j$	Off-diagonal terms of the route table. $x_{ij} = 1$, if the agent travels from node i to node j. Otherwise, $x_{ij} = 0$.
⑤⑥	-	Dimension of the route table. The route table is an $n \times n$ matrix, where n is the number of node cells for EA, the number of manual switches and depots for OA, and the number of faulted components and depots for RA.
⑦	t_i	Entry of the arrival time table. t_i represents the arrival time when an agent arrives at node i.
⑧	-	Dimension of the arrival time table. The arrival time table is an $n \times 1$ matrix, where n is the same as the dimension of the route table.

Task 3: Optimal Restoration and Repair Module

Interdependence constraints:

- Temporal interdependence: use travel table variables

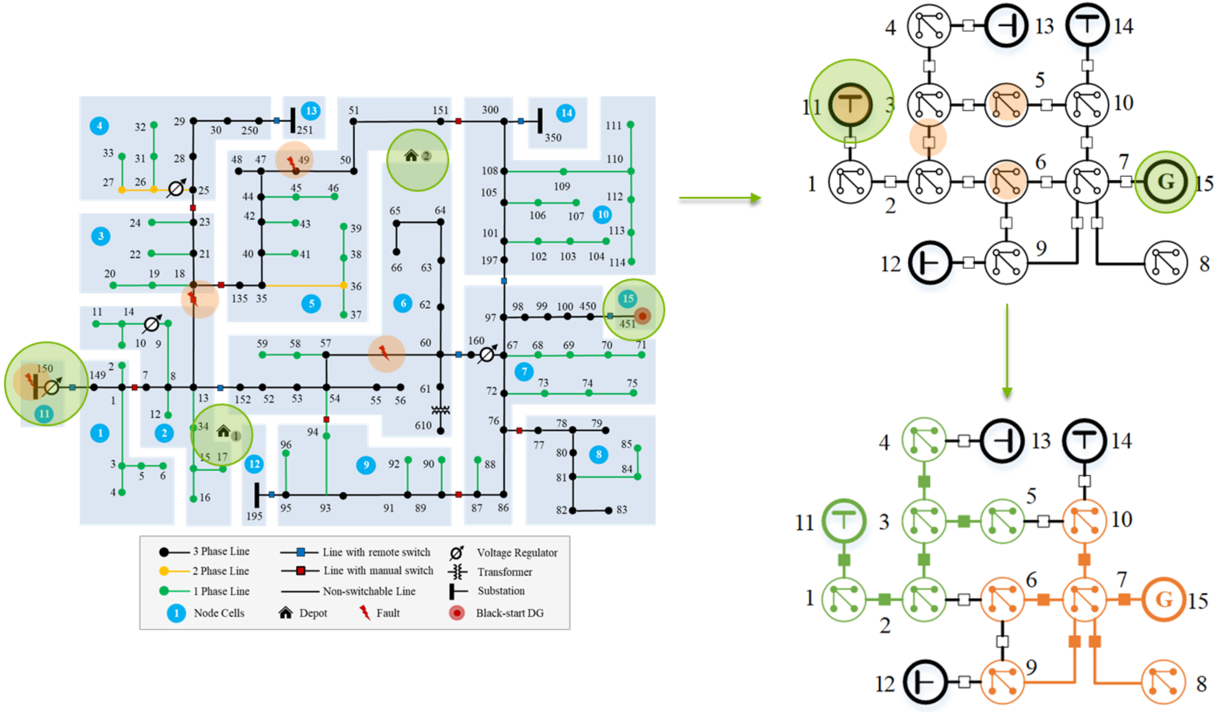
Domain			Interdependence Description	Partial Variables and Constraints
DSR	Crew for Operating Switch	Crew for Repair		
√	√		A crew operates a manually operated switch to energize components.	$x_{ij}^{O} \in \{0,1\}$: A crew can operate j (travel from i to j), if j is a manual switch. Otherwise, $x_{ij}^{O} = 0$
	√	√	A damaged switch can be operated only after being repaired.	$t_j^O > t_j^R + T_j^{RP}$: Operation time (arrival time at j from i) should be later than the repaired time.
√		√	A faulted component can be energized only after being repaired.	$t_j^E > t_j^R + T_j^{RP}$: j is a faulted component
√	√	√	To repair a faulted component, the component should be isolated by opening upstream/downstream switches to ensure crew safety. A switch cannot be energized when an operation crew is in the process of operating it.	$t_j^R + T_j^{RP} < \max\{t_i^E, t_j^E, t_k^E\}$: j is the component to be repaired

Task 3: Optimal Restoration and Repair Module

- Other Constraints
  - Standard routing model constraints
  - Power system operational constraints
  - Other interdependent constraints
- Solution Algorithm
  - Model as a MILP problem, then use off-the-shelf solver
  - Adapt from existing traveling salesman problem (TSP) solver
- Advantage
  - Prepared for large-scale systems with guaranteed solution optimality
  - Modeling complexity is significantly reduced comparing with existing methods
  - Easy to incorporate other operational logistics

Task 3: Optimal Restoration and Repair Module

- Results (IEEE 123 Bus Test System)



Task 3: Optimal Restoration and Repair Module

- Results (IEEE 123 Bus Test System)
  - Benchmark method: Existing utility restoration process [1-3]
  - Milestone 1.3.2: the resilience improvement in terms of reduction of outage duration will be at least 10%.

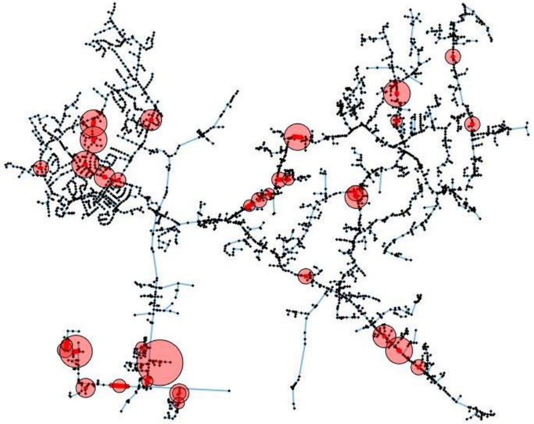
Damage No.	No DG		With DG	
	Outage Time Reduction	Outage Minutes Reduction	Outage Time Reduction	Outage Minutes Reduction
2	47.37%	40.36%	47.45%	50.29%
3	34.37%	36.86%	40.73%	55.13%
4	48.78%	37.85%	48.25%	48.27%
5	34.80%	34.17%	34.65%	46.97%
6	32.67%	48.41%	47.88%	50.55%
7	22.15%	45.32%	22.15%	53.01%
8	30.79%	41.88%	30.75%	52.64%
9	14.88%	43.71%	14.88%	51.89%

[1] Y. Tan, F. Qiu, A. K. Das, D. S. Kirschen, P. Arabshahi and J. Wang, "Scheduling Post-Disaster Repairs in Electricity Distribution Networks," in IEEE Transactions on Power Systems, vol. 34, no. 4, pp. 2611-2621, July 2019.
[2] FirstEnergy Group, "Storm Restoration Process." https://www.firstenergycorp.com/content/customer/help/outages/storm_restorationprocess.html.
[3] Edison Electric Institute, "Understanding the Electric Power Industry's Response and Restoration Process." http://www.eei.org/issuesandpolicy/electricreliability/mutualassistance/Documents/

Task 3: Post-event Restoration and Repair

- Case studies on large-scale 9500 node system
  - Multiple scenarios
  - Solve the problem using the routing-based model
  - Computation time (Target: 1 hour)
  - Outage duration improvement (Target: 10%)
- Transfer the switching sequence to SMU

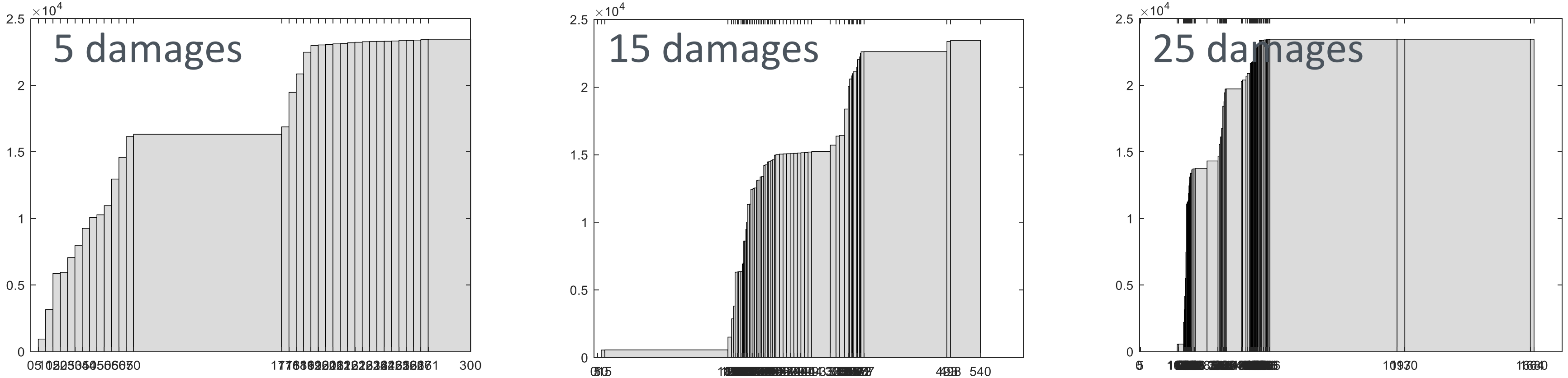
Task 3: Post-event Restoration and Repair



- Total damage number
  - 3 to 50
  - Repeat 6 times for each damage number
- Randomly generated scenarios
  - Damage location
  - Repair time for each damaged area (1 to 12 hours)
- Penetration level (regular and high)
- Substation is the slack bus
  - All PVs and DGs are in grid-following mode
  - In order to compare with the traditional method

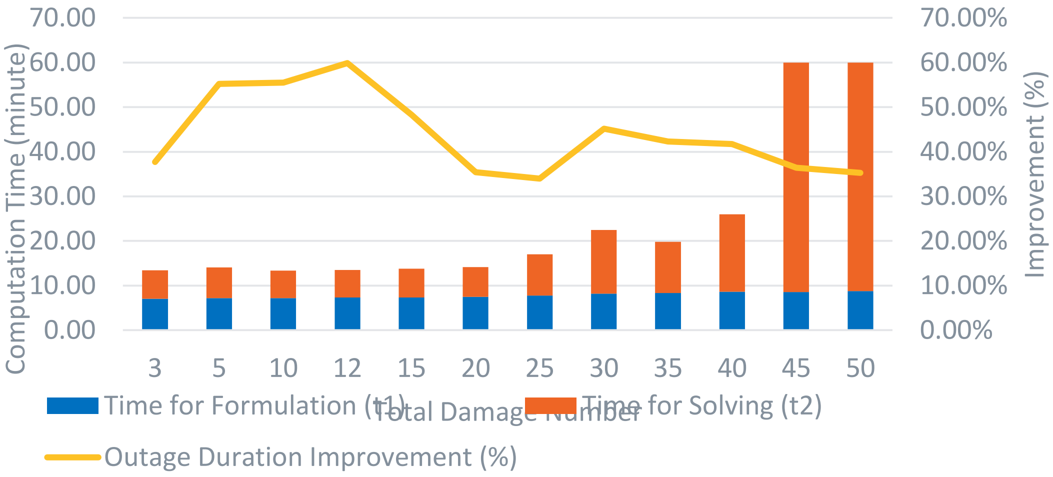
Task 3: Post-event Restoration and Repair

- Total restored load (kW) along time (minute)
- Minimal interval between two switching: 5 minutes



Task 3: Post-event Restoration and Repair

- Computation time and outage duration improvement
  - Improvement is beyond 30%
  - Feasible solutions can always be achieved within 1 hour
  - Traditional method cannot restore all the loads in some cases



Task 3

- Task 3: Development of post-event operation and restoration optimization models and solution algorithms
  - Subtask 3.1: (Completion in Q1-FY19) State-of-the-art review of the post-event operation methodologies
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- Deliverables:
  - Optimization model and algorithm for post-event operations

Task Summary

Task 1: Set up an industrial advisory board (IAB) and deliver webinars

Task 2: Development of pre-event proactive management optimization models and solution algorithms.

Task 3: Development of Post-event operation and restoration optimization models and solution algorithms

Task 4: Setting up test cases used for pre-event preparation and post-event operation optimization solution algorithms

Task 5: Extensive case studies to evaluate the benefits of solar energy in resilience improvement

Task 6: Testing of the pre-event and post-event optimization via simulation using real feeder data

Task 5

- Task 5: Extensive case studies to evaluate the benefits of solar energy in resilience improvement
  - Subtask 5.1: (Completion in Q2-FY20) Conduct extensive case studies based on large-scale test cases to evaluate the resilience benefits of solar energy at different penetration levels and coordination of solar energy with other flexible resources. The impact of the resource availability from the pre-event preparation to the post-event operation will be evaluated via sensitivity analysis. The impact of coordination between pre-event preparation optimization and post-event operation optimization will be assessed in the case studies

- Milestones:
  - M2.5.1: (100% Completion) Case studies on the evaluation of benefits of solar energy and its coordination with other flexible resources in grid resilience improvement; impact of coordination between pre-event and post-event optimization

- Deliverables:
  - Additional extensive case studies as verification

Task 5: Coordinated Post-event Operation

- Coordination between pre-event preparation and post-event operation:
  - Pre-event preparation determines the optimal location of mobile DG/ESS and allocation of crews.
  - Pre-event preparation impacts restoration process.
  - Restoration outcomes (line repairing and switching action sequences) influence post-event operation.
- Case Study: large-scale test system concatenated by three large-scale systems (EPRI ckt5 system, EPRI ckt7 system, IEEE 8500-bus system)

Task 5: Case Studies with Different PV Penetrations

Case	PV Penetration%	Number of Type 1 PVs	Number of Type 2 PVs	Number of Type 3 PVs
Case 1	9	8	1	1
Case 2	18	16	3	2
Case 3	27	24	4	3
Case 4	36	32	6	4
Case 5	45	40	7	5
Case 6	54	48	7	6
Case 7	63	63	9	7
Case 8	72	64	10	8
Case 9	81	72	12	9
Case 10	90	80	13	10
Case 11	99	88	15	11
Case 12	99	208	0	11

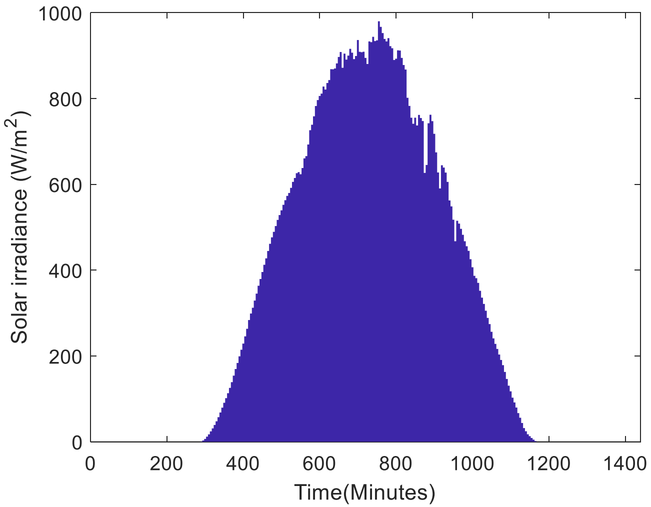

Fig 5.1 Solar irradiance profile

- 10 fixed DGs, 8 mobile DGs and 3 mobile ESSs are integrated.
- 34 areas are damaged and substation is not available for the first 6 hours.
- Rolling horizon approach is used for 15-minute horizon operation.
- The results are updated every 5 minutes.

Task 5: Case Study-Simulation Outputs

Case	Total restoration time (min)	Percentage of unserved load %	Total Unserved energy (kWh)	Percentage of unserved critical load	Unserved energy for critical load (kWh)	Percentage of unserved noncritical load (kWh)	Unserved energy for noncritical load (kWh)	Solution time (min)
Case 1	684	30.11	81,766.81	25.31	12,123.40	31.14	69,643.41	88.03
Case 2	618	32.62	80,397.84	29.32	12,744.72	33.32	67,653.12	78.87
Case 3	494	38.17	75,586.50	36.58	12,775.38	38.51	62,811.12	58.08
Case 4	615	29.57	72,321.08	26.48	11,425.79	30.23	60,895.29	74.66
Case 5	611	31.81	77,809.39	28.01	12,082.57	32.62	65,726.78	84.08
Case 6	565	33.19	74,868.55	29.88	11,887.37	33.90	62,981.11	76.87
Case 7	610	29.03	70,425.19	26.39	11,295.11	29.59	59,130.09	82.63
Case 8	659	25.85	67,671.85	22.72	10,490.35	26.52	57,181.50	90.10
Case 9	494	33.06	65,461.43	29.66	10,357.41	33.78	55,103.97	67.52
Case 10	506	31.95	65,205.71	29.07	10,463.93	32.56	54,741.80	69.79
Case 11	494	35.09	69,481.68	31.76	11,091.62	35.80	58,389.98	67.60
Case 12	494	35.62	71,871.06	31.28	10,924.63	37.37	60,946.43	65.70

Task 5: Case Study-Simulation Outputs

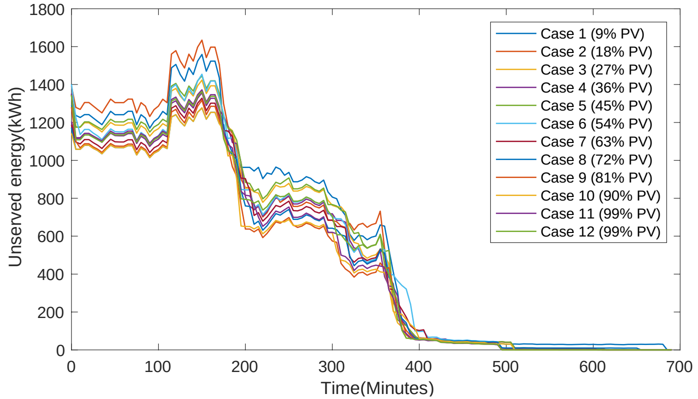

Fig. 5.2 Profiles of total unserved load under different PV penetration levels

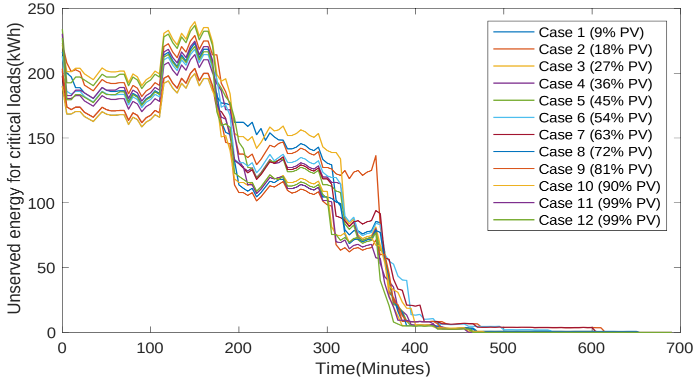

Fig. 5.3 Profiles of total unserved critical load under different PV penetration levels

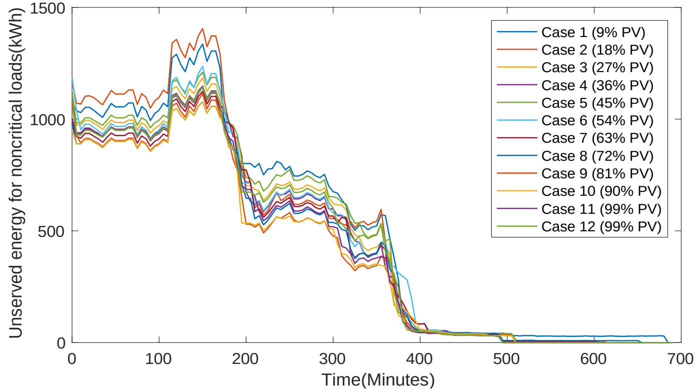

Fig. 5.4 Profiles of total unserved noncritical load under different PV penetration levels

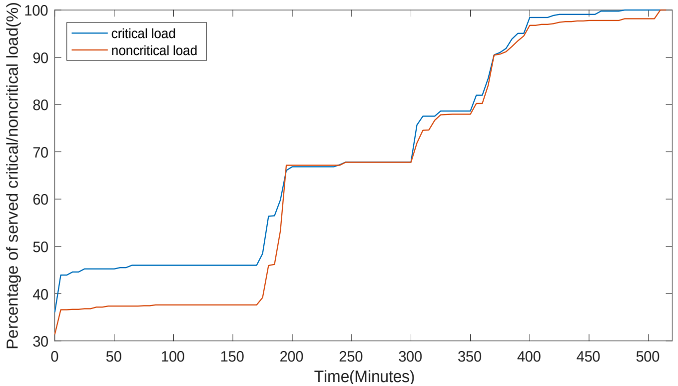

Fig. 5.5 Percentage of served critical and noncritical load under 90% PV penetration level (Case 10)

Task 5: Case Study-Simulation Outputs

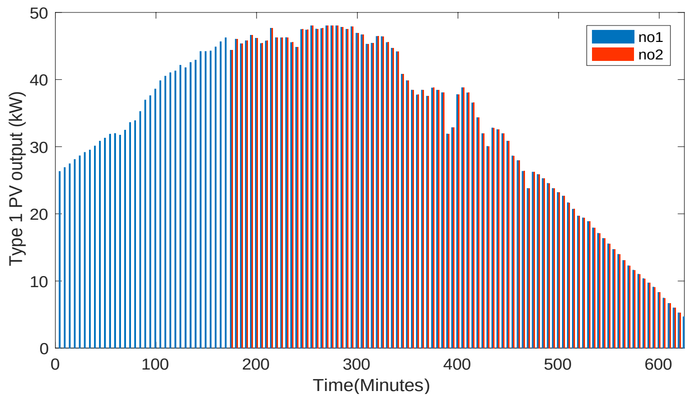

Fig. 5.6 Profiles of type 1 PV output for Case 2 (18% PV)

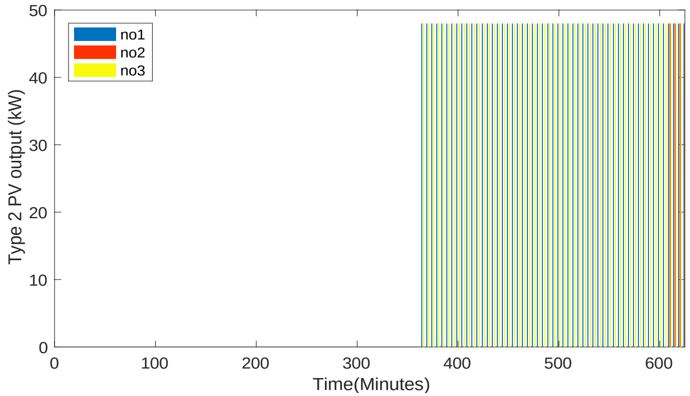

Fig. 5.7 Profiles of type 2 PV output for Case 2 (18% PV)

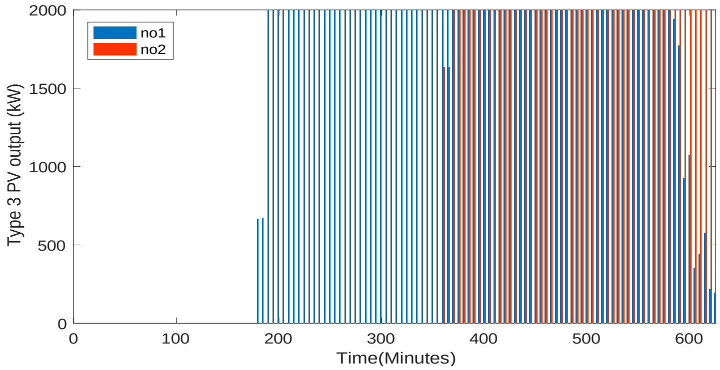

Fig. 5.8 Profiles of type 3 PV output for Case 2 (18% PV)

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Task 5: Post-event restoration

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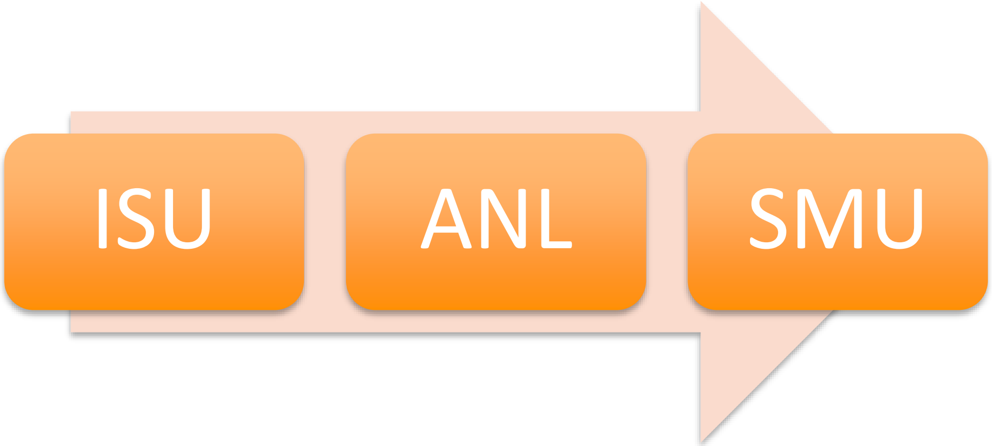
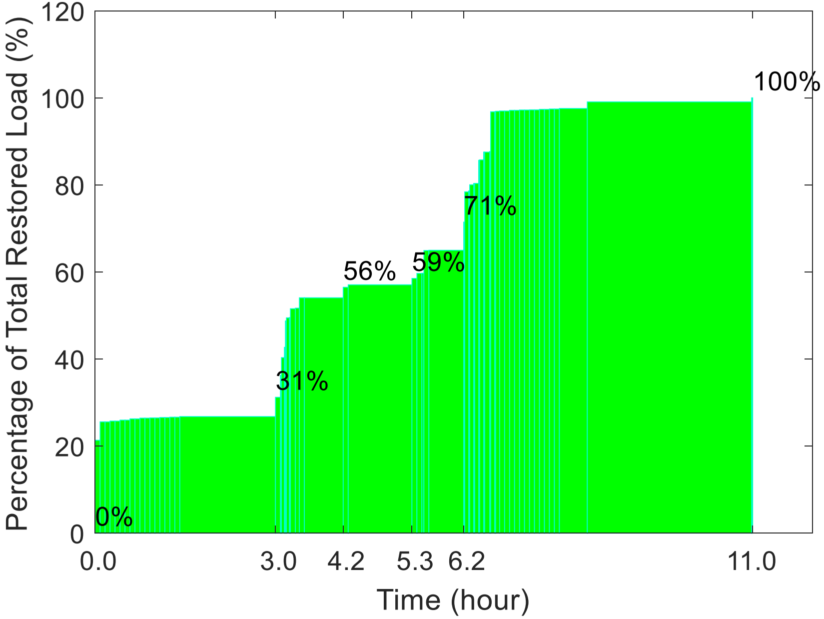
- The case studies performed by SMU have incorporated the restoration solutions provided by ANL.



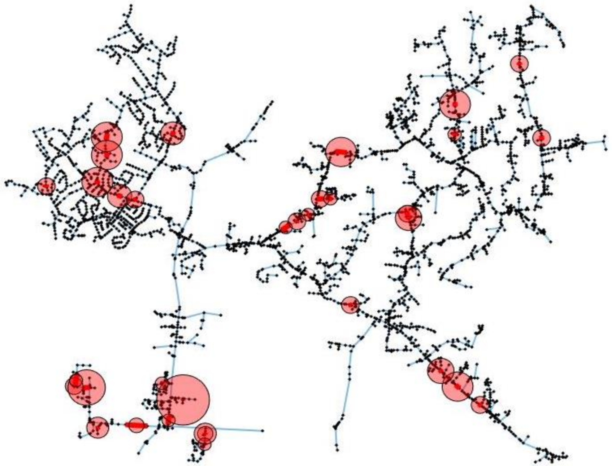
Task 5: Post-event restoration

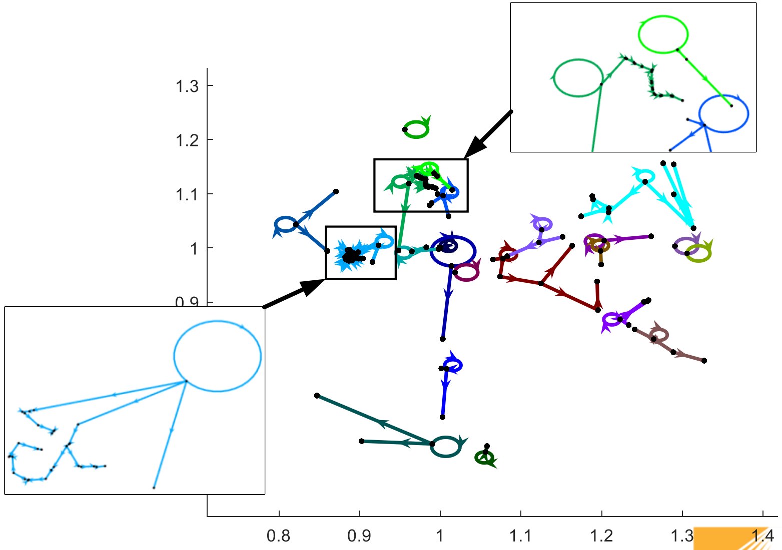
- An example based on 72% penetration case
- Percentage of total restored load along time during restoration
- The last load is picked up at 11th hour



Task 5: Post-event restoration

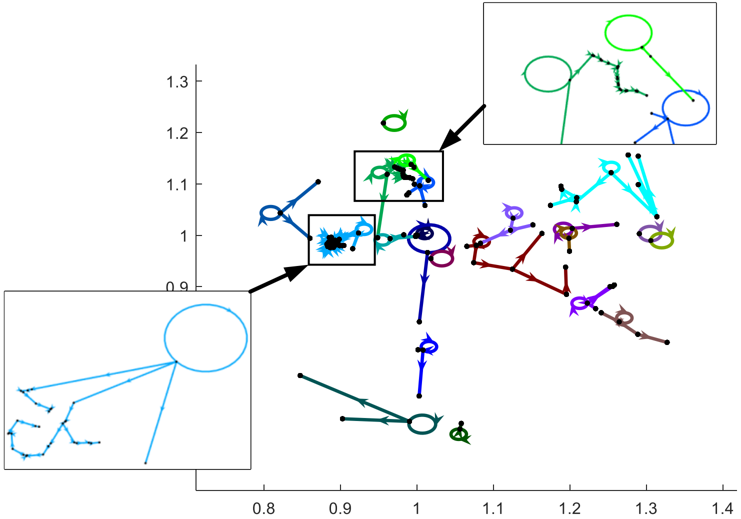
- Based on 72% penetration case
- The energization sequence for the electric power network
- Each node represents a part of distribution circuit
- Arrows represent the energization currents

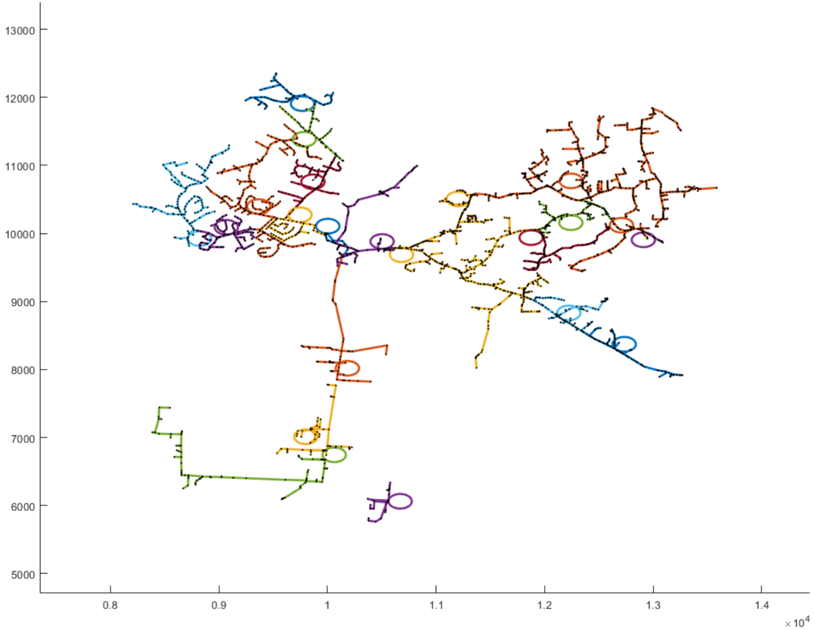




Task 5: Post-event restoration

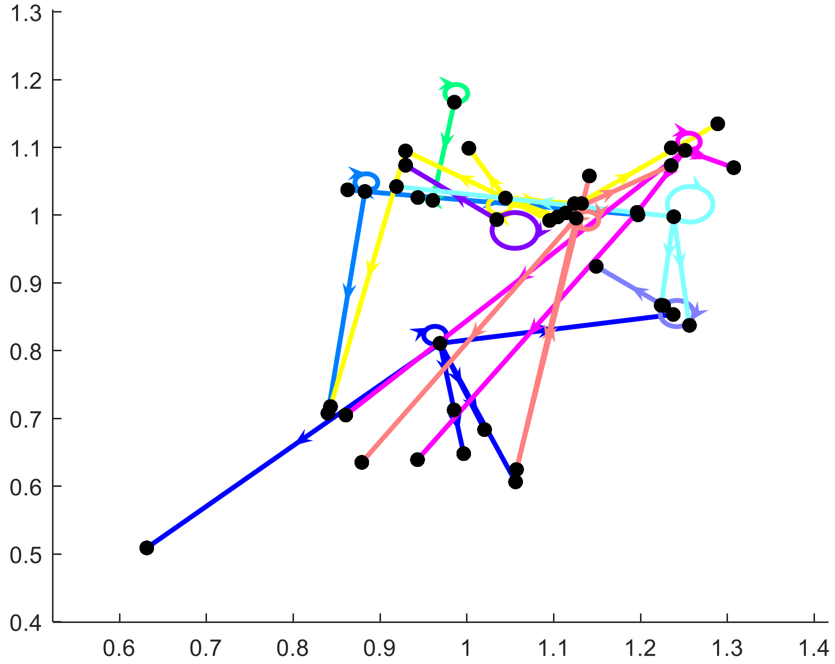
- Based on 72% penetration case
- Single-line diagram of energized test system supported by all the power sources





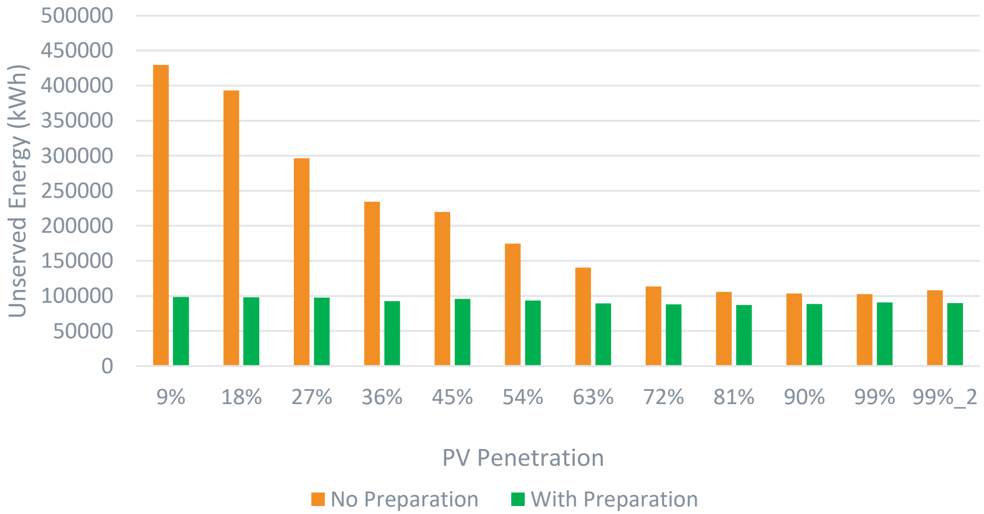
Task 5: Post-event restoration

- Based on 72% penetration case
- Dispatch sequence for repair crews
- Each circle represents a depot
- Crews labeled by different colors



Task 5: Extended Case Studies

- **Comments: Verify of the benefit of proper before event preparation can help on post event restoration**
  - No preparation: Mobile DGs are placed at high-priority loads. Crews are evenly allocated among depots.
  - Locational value of PV, DG, and Crew are maximized



Task 5: Extended Case Studies

- **Comments: Verify all damages will be repaired even after loads are served**

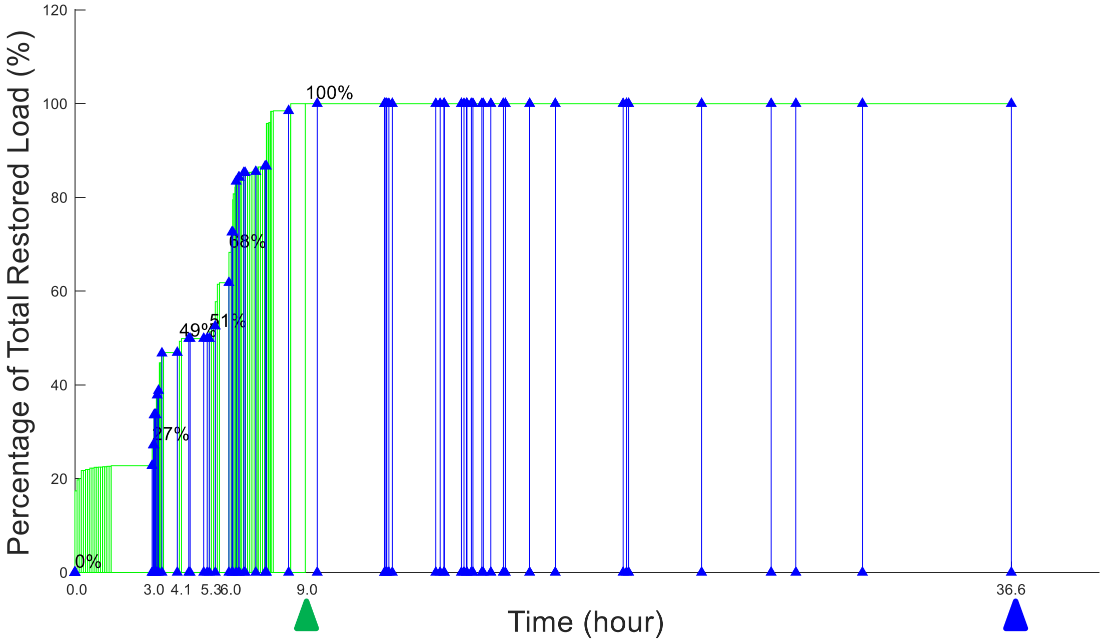
- Constraint to ensure all the damaged components should be repaired

$$\sum_{i=1}^{n_{crew}} RouteTable(i,j) = 1, for\ j \in \{damaged\ components\}$$

- This constraint requires that for each damaged component, it must be visited by one repair crew.

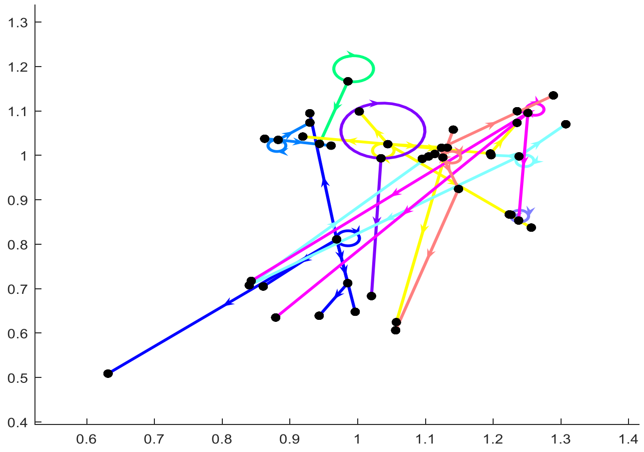
Task 5: Extended Case Studies

- Based on 90% penetration case
- Most PVs are assumed to be damaged (Not required to be repaired to pick associated nodes)
- Repair all damaged components (at 36 hours) after 100% load restoration (at 9 hour)

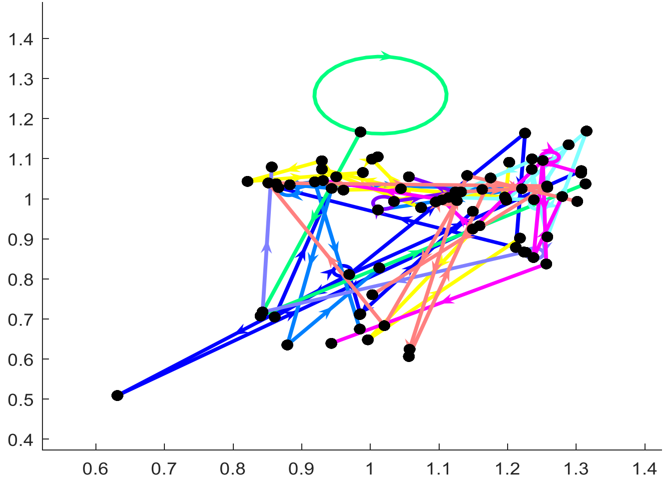


Task 5: Extended Case Studies

- Based on 90% penetration case
- Compares the crew repair sequences



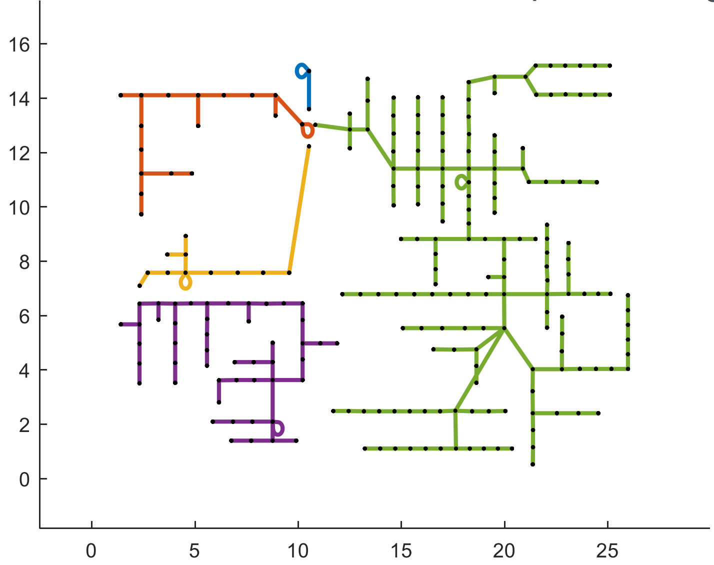
Contain damage components that must be repaired

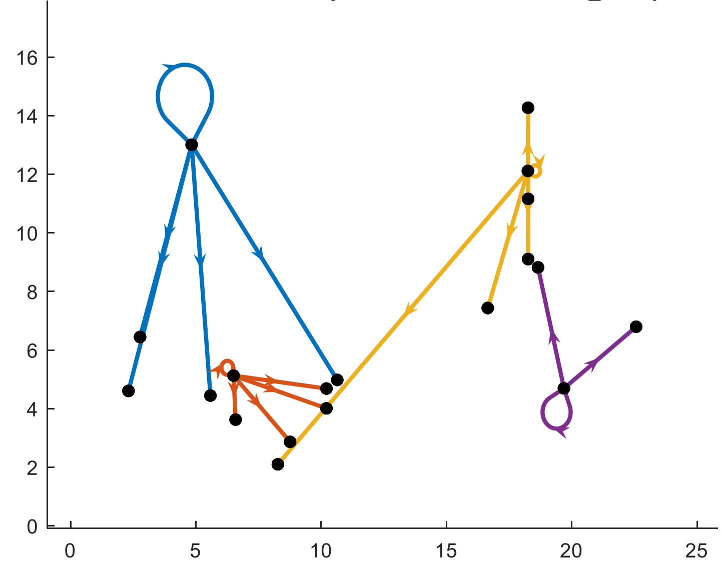


Contain damage components that can be repaired after restoring all the loads

Task 5: Results – Additional Comparison on Real Feeder

- **Verify of the benefit of proper pre-event preparation can help on post event restoration**
  - 50% PV Penetration
  - Base model: Mobile DGs are placed at high-priority loads. Crews are evenly allocated among depots.





Task 5: Results – Additional Comparison on Real Feeder

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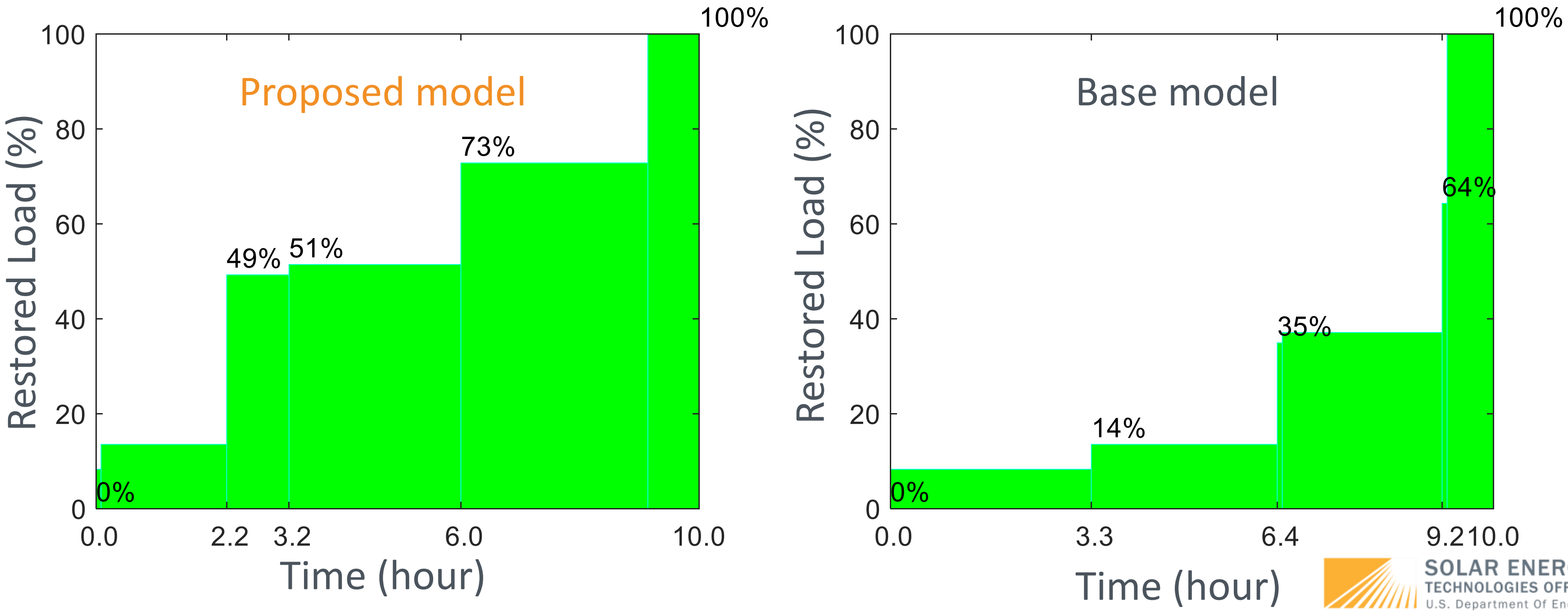
  - Base model: Mobile DGs are placed at high-priority loads. Crews are evenly allocated among depots.



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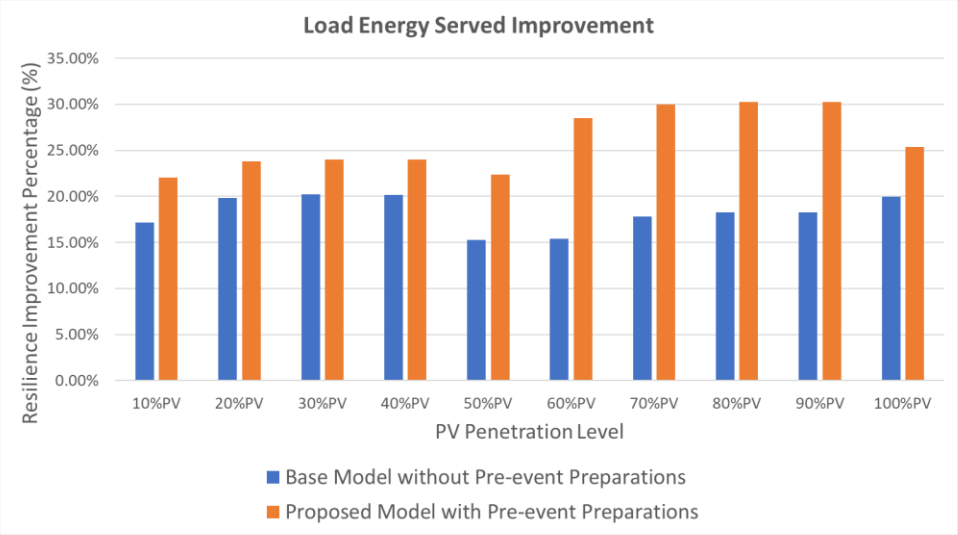
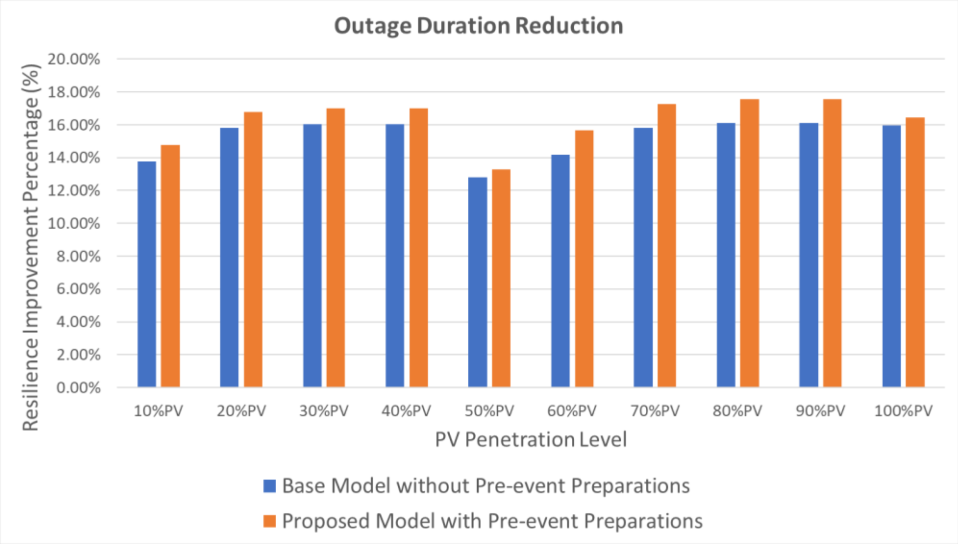
Task 5: Results – Additional Comparison on Real Feeder

- Additional comparison on real feeder system between
  - Base Model without Pre-event Preparations
  - Proposed Model with Pre-event Preparations





Task 5

- Task 5: Extensive case studies to evaluate the benefits of solar energy in resilience improvement
  - Subtask 5.1: (Completion in Q2-FY20) Conduct extensive case studies based on large-scale test cases to evaluate the resilience benefits of solar energy at different penetration levels and coordination of solar energy with other flexible resources. The impact of the resource availability from the pre-event preparation to the post-event operation will be evaluated via sensitivity analysis. The impact of coordination between pre-event preparation optimization and post-event operation optimization will be assessed in the case studies

- Milestones:
  - M2.5.1: (100% Completion) Case studies on the evaluation of benefits of solar energy and its coordination with other flexible resources in grid resilience improvement; impact of coordination between pre-event and post-event optimization

- Deliverables:
  - Additional extensive case studies as verification

Task Summary

Task 1: Set up an industrial advisory board (IAB) and deliver webinars

Task 2: Development of pre-event proactive management optimization models and solution algorithms.

Task 3: Development of Post-event operation and restoration optimization models and solution algorithms

Task 4: Setting up test cases used for pre-event preparation and post-event operation optimization solution algorithms

Task 5: Extensive case studies to evaluate the benefits of solar energy in resilience improvement

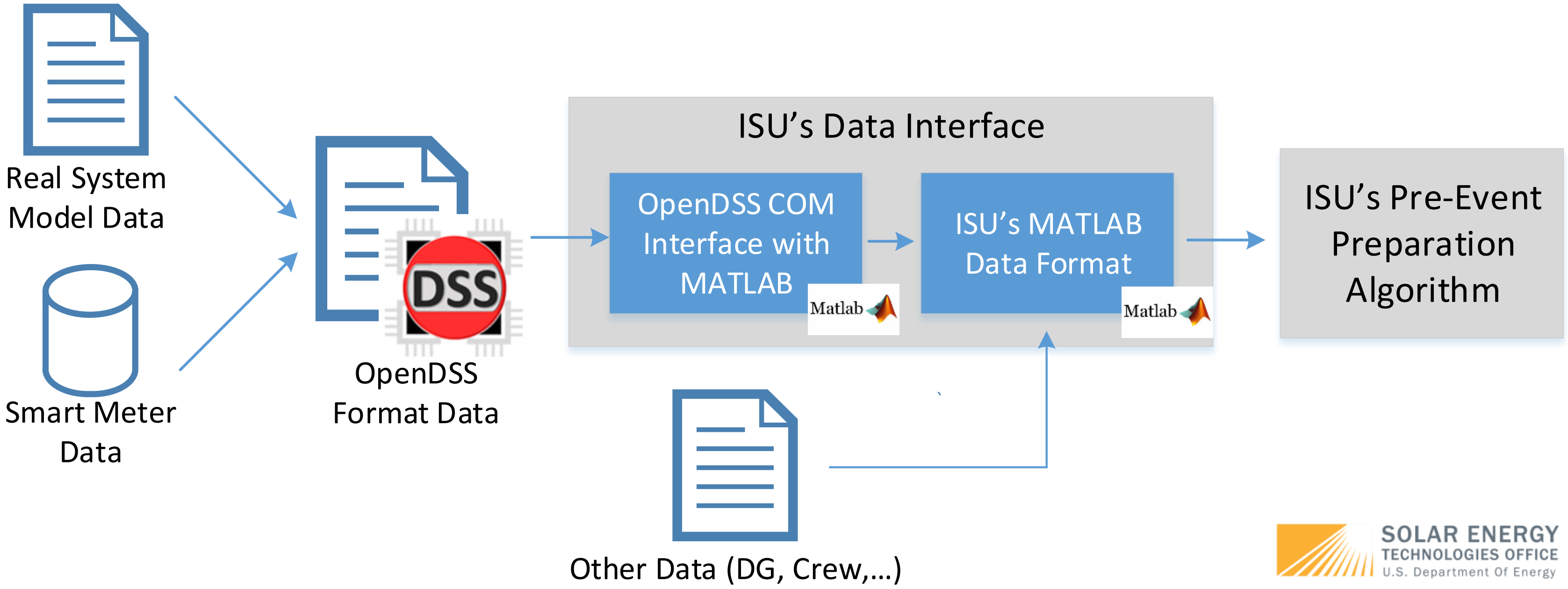
Task 6: Testing of the pre-event and post-event optimization via simulation using real feeder data

Task 6

- Task 6: Testing of the pre-event and post-event optimization via simulation using real feeder data
  - **Subtask 6.1: (Completion in Q2-FY20) Continue real feeder data preparation for the testing**
  - Subtask 6.2: (Completion in Q2-FY20) Testing of the pre-event preparation optimization model and solution algorithms via simulation using real feeder data provided by utility partners (e.g., City of Bloomfield utility, Algona Municipal Utilities)
  - Subtask 6.3: (Completion in Q2-FY20) Testing of the post-event operation optimization model and solution algorithms via simulation using real feeder data provided by utility partners (e.g., City of Bloomfield utility, Algona Municipal Utilities).
- Milestones:
  - **M2.6.1: (100% Completion) Data interface development in software platform (e.g., Matlab or Python) for the real feeder data provided by utility partners.**
  - M2.6.2: (100% Completion) Case studies of pre-event preparation optimization under real feeder data within required computation time (e.g., 4 hours) completed and results being reviewed by the utility; the resilience improvement will be at least 10% in terms of served energy and outage duration reduction
  - M2.6.3: (100% Completion) Case studies of post-event operation optimization under real feeder data within required computation time (5 min for energy management optimization and 1 hour for restoration optimization) completed and results being reviewed by the utility; the resilience improvement will be at least 10% in terms of served energy and outage duration reduction
- Deliverables:
  - Data interface to unify pre-event and post-event optimization solutions
  - Real feeder test case using developed pre-event preparation and post-event operation framework

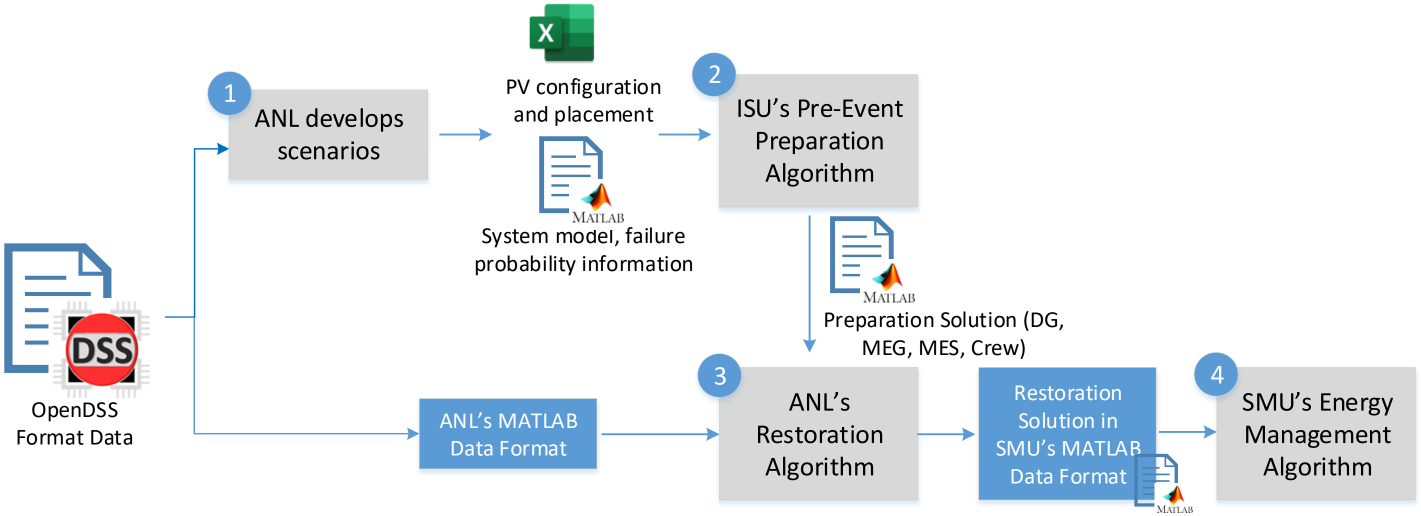
Task 6: Data interface development

- **Data Interface Development at ISU**
  - The midwest distribution system with one-year smart meter data has been implemented in the Opendss and the required input data for this project can be extracted by using MATLAB.



Task 6: Data interface development

- **Data Interface Development at ANL**
  - ANL team has developed a similar data interface to import system model from OpenDSS data file. ANL team also developed the data interfaces to import the pre-event preparation solutions provided by ISU, and re-format the post-event restoration solution provided for SMU.
- Both **theoretically and functionally integrated** optimization framework



Task 6

- Task 6: Testing of the pre-event and post-event optimization via simulation using real feeder data
  - Subtask 6.1: (Completion in Q2-FY20) Continue real feeder data preparation for the testing
  - **Subtask 6.2: (Completion in Q2-FY20) Testing of the pre-event preparation optimization model and solution algorithms via simulation using real feeder data provided by utility partners (e.g., City of Bloomfield utility, Algona Municipal Utilities)**
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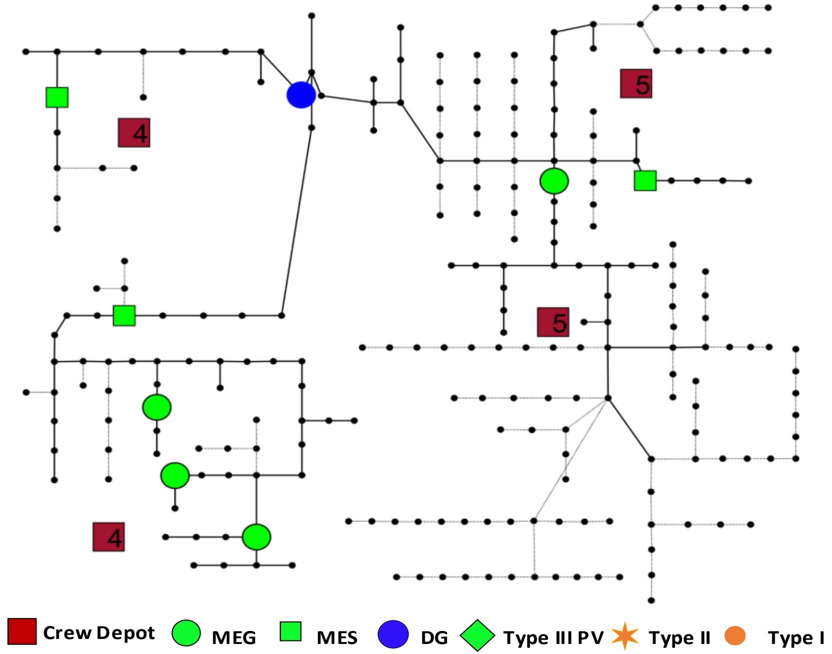
- Milestones:
  - M2.6.1: (100% Completion) Data interface development in software platform (e.g., Matlab or Python) for the real feeder data provided by utility partners.
  - **M2.6.2: (100% Completion) Case studies of pre-event preparation optimization under real feeder data within required computation time (e.g., 4 hours) completed and results being reviewed by the utility; the resilience improvement will be at least 10% in terms of served energy and outage duration reduction**
  - M2.6.3: (100% Completion) Case studies of post-event operation optimization under real feeder data within required computation time (5 min for energy management optimization and 1 hour for restoration optimization) completed and results being reviewed by the utility; the resilience improvement will be at least 10% in terms of served energy and outage duration reduction
- Deliverables:
  - Data interface to unify pre-event and post-event optimization solutions
  - Real feeder test case using developed pre-event preparation and post-event operation framework

Task 6: Test Case: Real Feeder System with Various PV Penetration Levels

- Mobile sources and 18 crews must be allocated
  - The capacity of mobile sources is 100 kW
- 10 damage scenarios are generated using fragility models
- The proposed method with different level of PV penetration is compared to a base model
- Base model:
  - Mobile generators are prepositioned at the substations
  - Extra mobile generators are prepositioned at high-priority loads
  - PV and battery storage are not considered
  - Crews are allocated evenly between depots

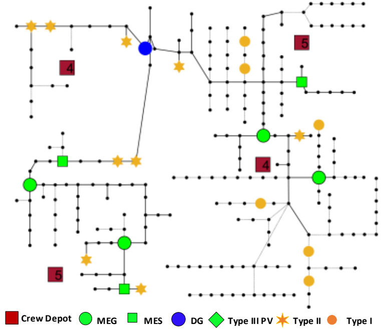


Resource allocation in the base model.

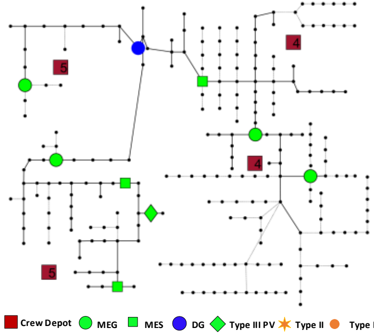
Task 6: Results – Advantages of PVs

- To show the advantages of the PV systems, we test the response of the system with various PV penetration levels
  - The total capacity of PV can serve load varying from 0% to 100%
    - Type I PV with rated capacity of 5 kW (Residential PV)
    - Type II PV with rated capacity of 12 kW
    - Type III PV with rated capacity of 600 kW
  - The result solutions will be coordinated with the post-event restoration.

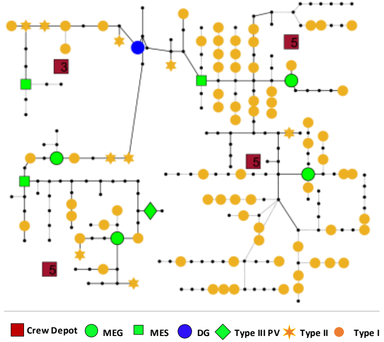
Task 6: Results – Advantages of PVs



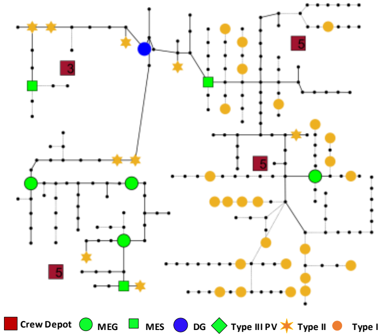
10% PV Penetration



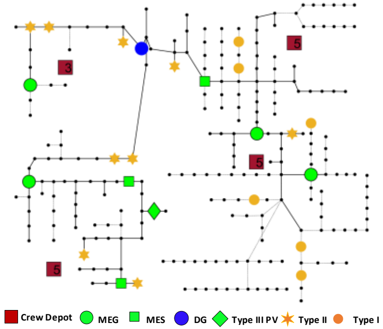
50% PV Penetration



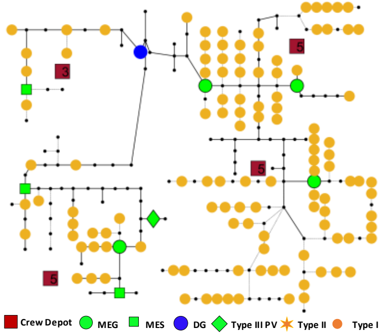
90% PV Penetration



20% PV Penetration



60% PV Penetration



100% PV Penetration

Resource allocation in the proposed method with various PV penetration levels.

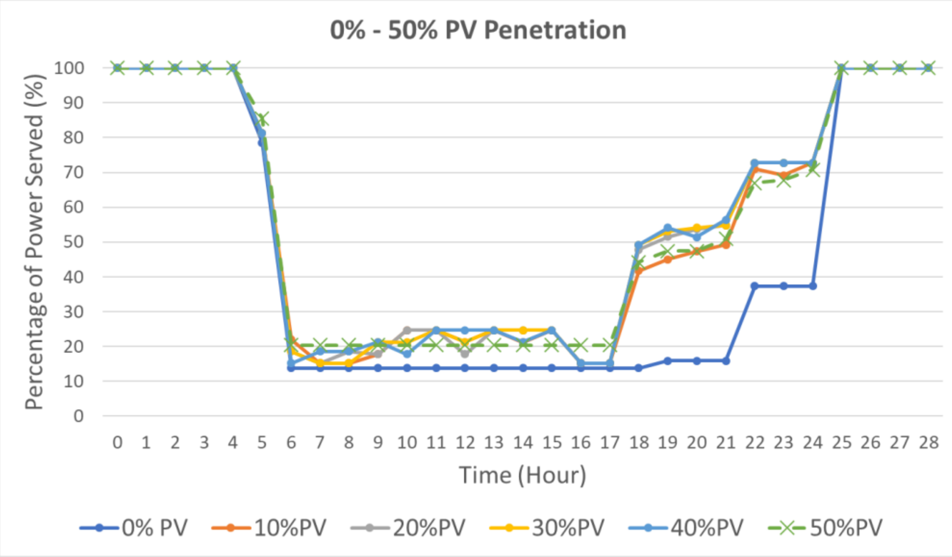
Task 6: Results – Resilience Improvement

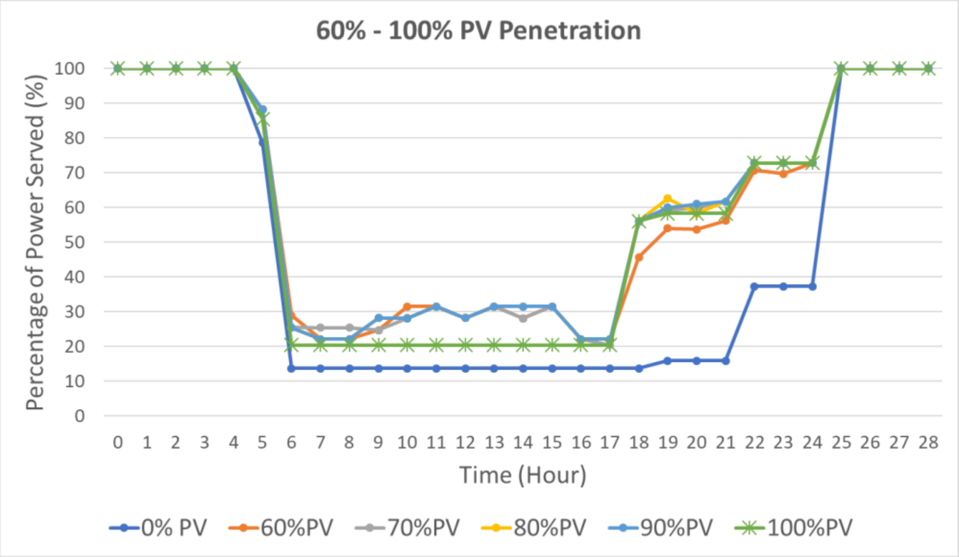
- To evaluate the preparation results, we test the response of the system under various PV scenarios
  - Resilience improvement > 10% (**Complete Milestone 2.6.2 requirement**)
  - Computation time ~ 2.5 hours < 4 hours (**Complete Milestone 2.6.2 requirement**)

PV Penetration Level	Load Energy Served (kWh)	Resilience Improvement (%)	Average Outage Duration (h)	Resilience Improvement (%)
0%	10891.0827		15.81122449	
10%	13968.8007	22.03%	13.4744898	14.78%
20%	14292.4097	23.80%	13.15816327	16.78%
30%	14333.5634	24.02%	13.12244898	17.01%
40%	14329.59736	24.00%	13.12244904	17.01%
50%	14023.9017	22.34%	13.70918367	13.29%
60%	15228.621	28.48%	13.33673469	15.65%
70%	15551.5442	29.97%	13.08163265	17.26%
80%	15607.2284	30.22%	13.03571429	17.55%
90%	15607.2284	30.22%	13.03571429	17.55%
100%	14589.4421	25.35%	13.21428571	16.42%

Task 6: Results – Resilience Improvement

- To evaluate the preparation results, we test the response of the system under various PV scenarios
  - Temporal behavior of system performance in load energy served percentage
  - 15 damaged lines and the substation is not receiving power from the transmission system





Task 6

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  - Subtask 6.1: (Completion in Q2-FY20) Continue real feeder data preparation for the testing
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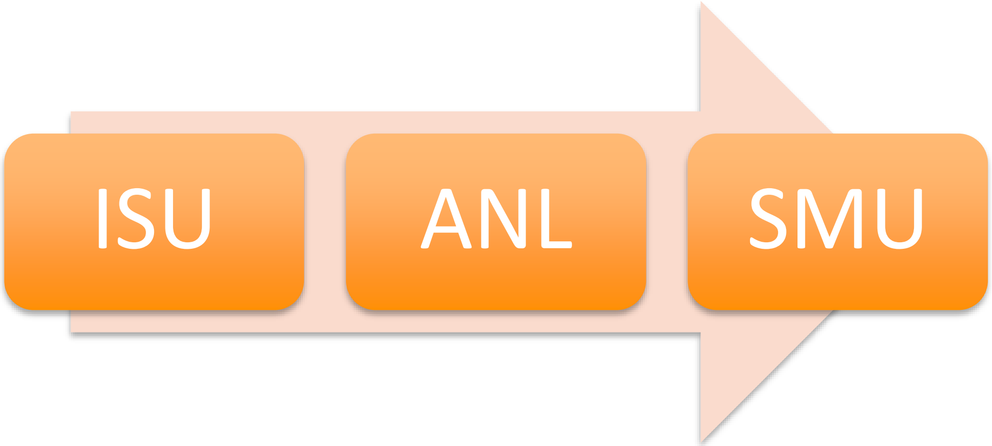
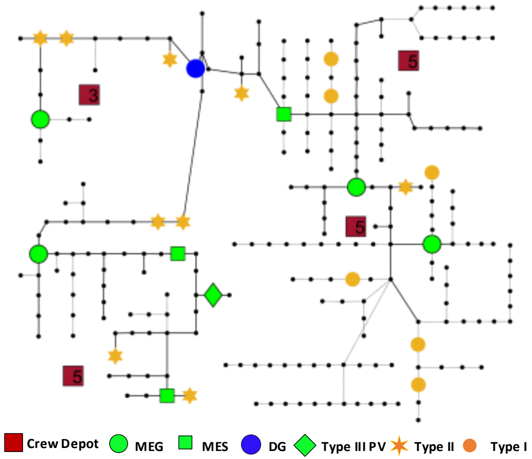
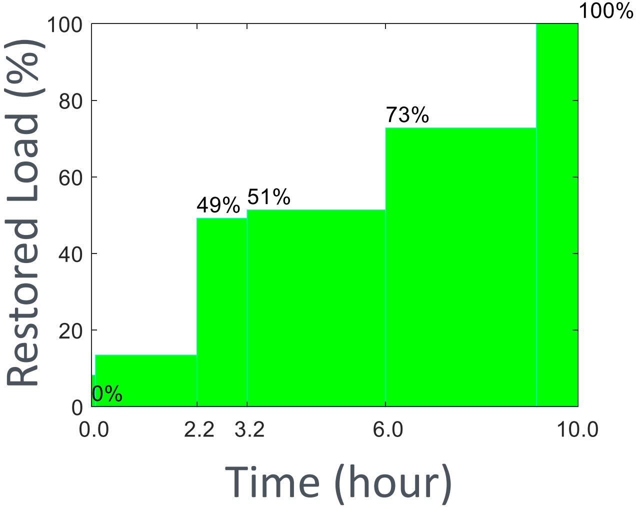


Task 6: Post-event restoration

- An example based on 60% penetration case
- Percentage of total restored load along time during restoration
- The last load is picked up at 10^{th} hour



60% PV Penetration



Task 6: Post-event restoration

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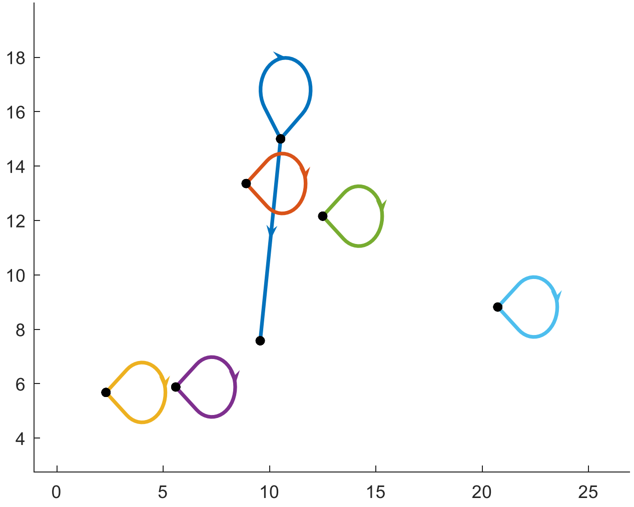

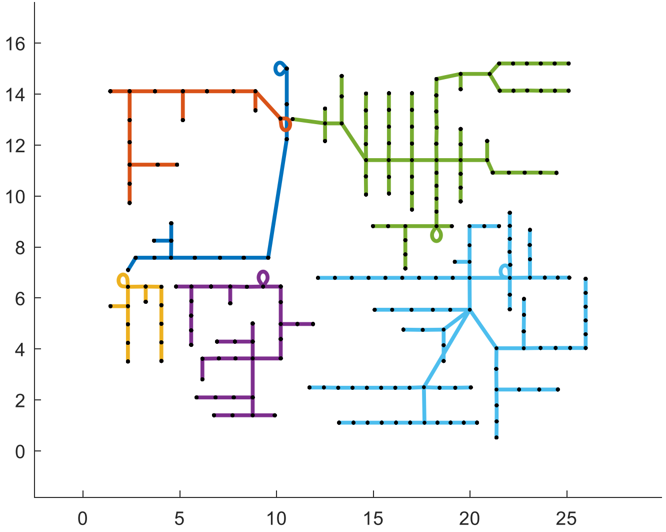

Task 6: Post-event restoration

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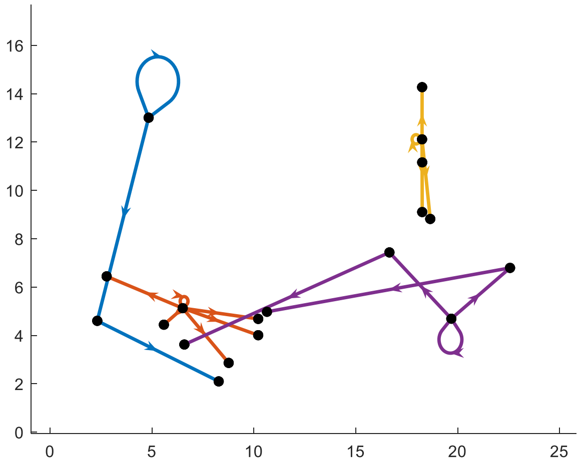
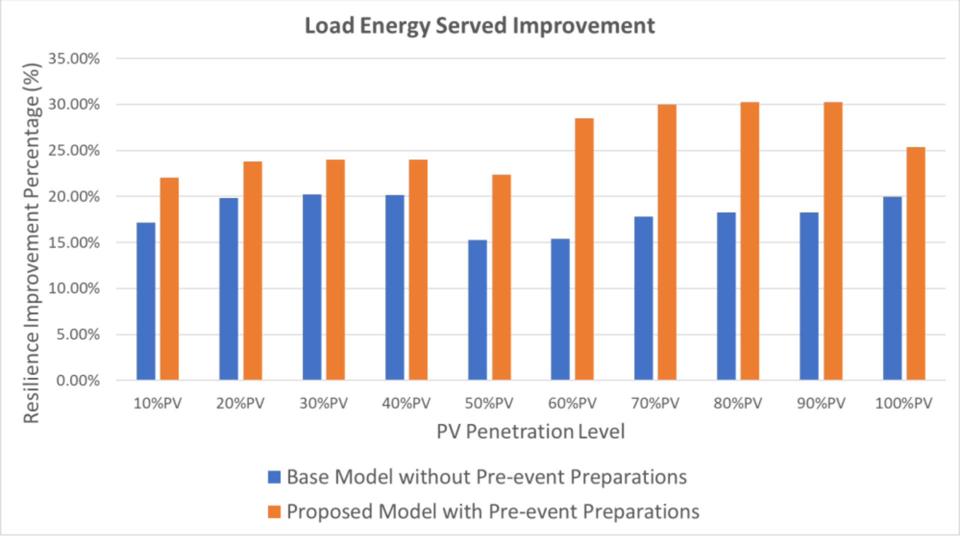
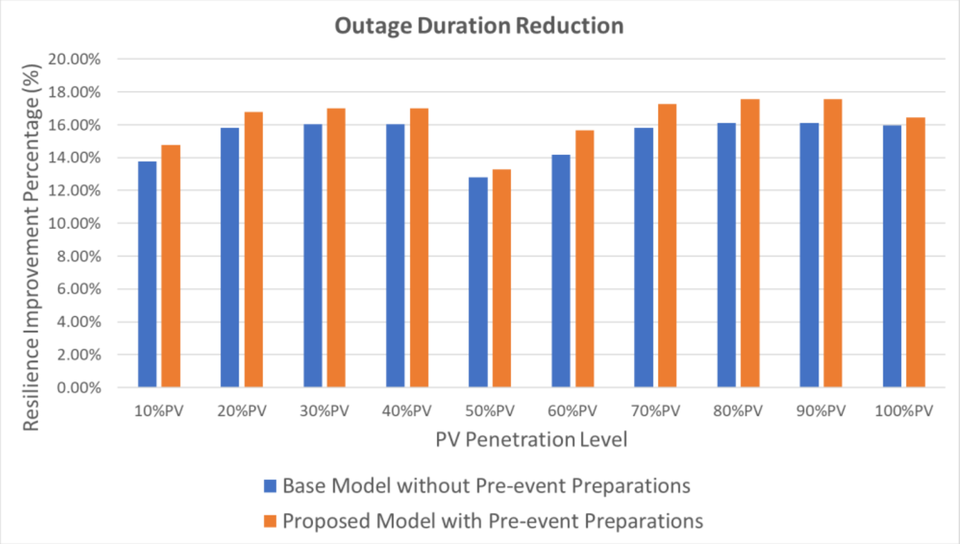
- Crews labeled by different colors



Task 6: Post-event restoration

- Average computation time: less than 1 min < 1 hour (Milestone requirement)
- Average resilience improvement: beyond 20% > 10% (Milestone requirement)





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- Deliverables:
  - Data interface to unify pre-event and post-event optimization solutions
  - Real feeder test case using developed pre-event preparation and post-event operation framework

Task 6: the post-event operation optimization

- The proposed post-event operation optimization is tested on a real feeder system located in Midwest U.S.

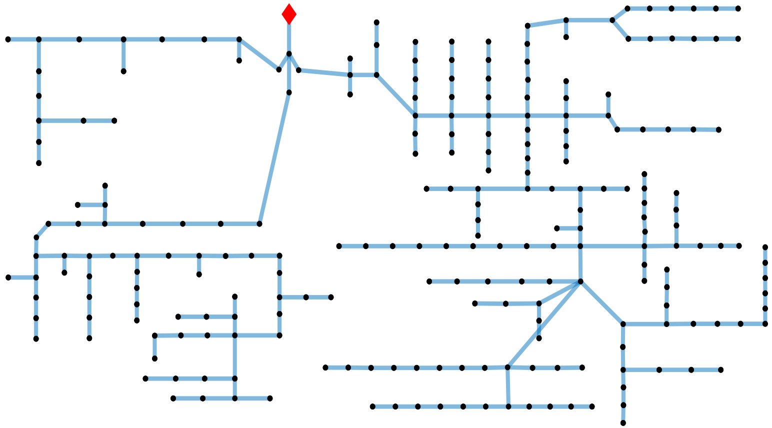

Fig 6.1 The network topology of the real feeder system

- 240 nodes, 233 lines and 9 switches
- 15 area are damaged.
- The main feeder is not available.

Task 6: Post-event Energy Management

- 11 cases to evaluate the benefits of solar energy.
- 11 base cases without coordination between pre-event preparation and post-event operation are used for comparison.

Case	Base case	PV penetration %	Number of Type-1 PVs	Number of Type-2 PVs	Number of Type-3 PVs
Case 1	Case 1b	0	0	0	0
Case 2	Case 2b	10	6	7	0
Case 3	Case 3b	20	25	9	0
Case 4	Case 4b	30	49	9	0
Case 5	Case 5b	40	72	9	0
Case 6	Case 6b	50	0	0	1
Case 7	Case 7b	60	6	7	1
Case 8	Case 8b	70	25	9	1
Case 9	Case 9b	80	49	9	1
Case 10	Case 10b	90	72	9	1
Case 11	Case 11b	100	117	0	1

Type	Size
Type III – Large Utility PV	600 kW
Type II – Midsize PV	12 kW
Type I – Residential PV	5 kW

- 2 fixed DGs, 4 mobile DGs and 3 mobile ESSs are integrated.
- Rolling horizon approach is used for 15-minute horizon operation.
- The results are updated every 5 minutes.

Task 6: Case Study-Simulation Outputs

Case	Percentage of unserved load %	Total Unserved energy (kWh)	Percentage of unserved critical load %	Unserved energy for critical load (kWh)	Percentage of unserved noncritical load %	Unserved energy for noncritical load (kWh)	Improvement of resilience %	Solution time (min)
Case 1	43.60	5,169.55	46.68	2,450.39	41.16	2,719.17	0	7.38
Case 1b	43.60	5,169.55	46.68	2,450.39	41.16	2,719.17	-	7.38
Case 2	30.45	3,610.05	21.52	1,129.52	37.55	2,480.53	23.3	7.20
Case 2b	43.20	5,121.79	46.14	2,422.03	40.86	2,699.76	-	7.37
Case 3	27.30	3,236.65	23.22	1,218.99	30.54	2,017.66	28.9	7.46
Case 3b	42.93	5,089.77	46.04	2,417.87	40.44	2,671.90	-	7.28
Case 4	19.63	2,327.38	18.64	978.59	20.41	1,348.79	42.5	7.78
Case 4b	42.90	5,086.73	46.00	2,414.83	40.44	2,671.90	-	7.50
Case 5	19.33	2,291.94	18.04	947.17	20.35	1,344.77	43.0	7.33
Case 5b	45.93	5,445.93	48.89	2,566.16	43.59	2,879.77	-	7.63
Case 6	24.61	2,918.43	17.84	936.28	30.00	1,982.15	33.7	7.42
Case 6b	49.99	5,927.41	53.98	2,833.66	46.83	3,093.75	-	6.93
Case 7	22.88	2,712.87	17.83	936.12	26.89	1,776.75	36.7	7.53
Case 7b	48.96	5,804.79	53.92	2,830.55	45.02	2,974.24	-	7.05
Case 8	19.51	2,312.59	17.78	933.62	20.87	1,378.97	42.7	7.62
Case 8b	48.78	5,782.88	53.84	2,826.39	44.75	2,956.49	-	7.33
Case 9	18.51	2,194.60	17.07	896.02	19.65	1,298.58	44.5	7.78
Case 9b	48.75	5,779.84	53.78	2,823.35	44.75	2,956.49	-	7.56
Case 10	18.62	2,208.21	17.07	896.02	19.86	1,312.19	44.3	8.06
Case 10b	44.90	5,840.58	49.22	2,834.63	41.47	3,005.95	-	8.40
Case 11	18.13	2,149.12	18.69	981.12	17.68	1,168.00	45.2	8.13
Case 11b	49.18	5,831.07	53.70	2,818.98	45.59	3,012.09	-	7.76

Task 6: Case Study-Simulation Outputs

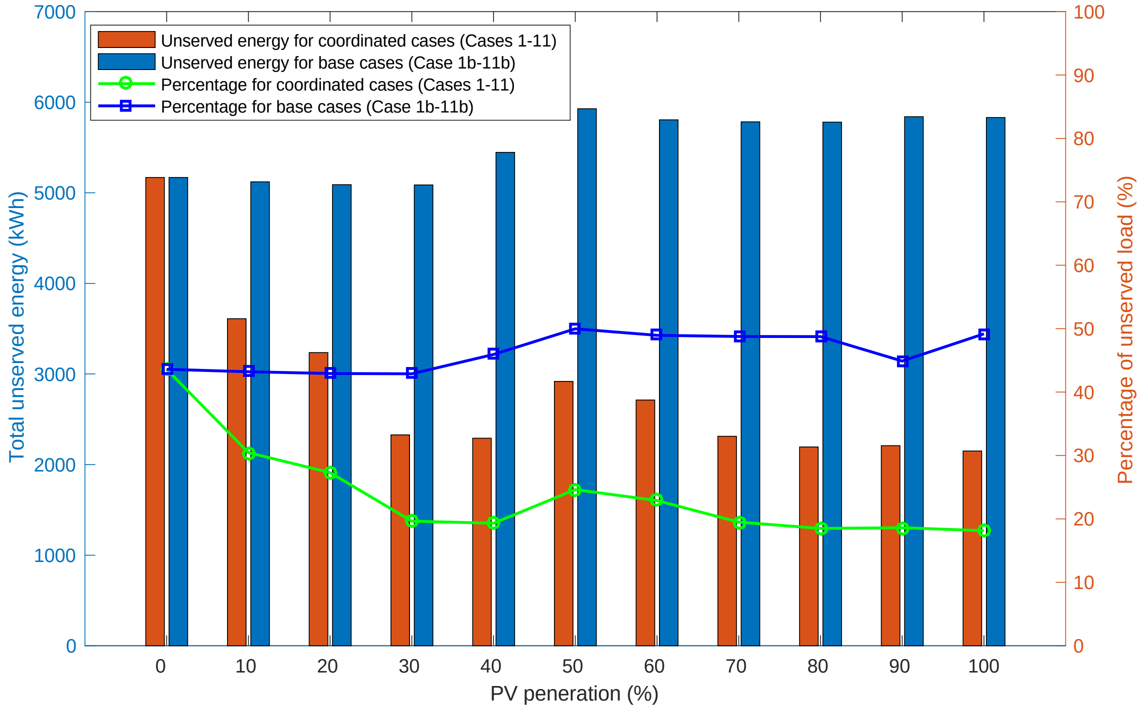

Fig. 6.2 Total unserved energy and percentage of unserved energy for the coordinated cases and base cases with different PV penetration level

Task 6: Case Study-Simulation Outputs

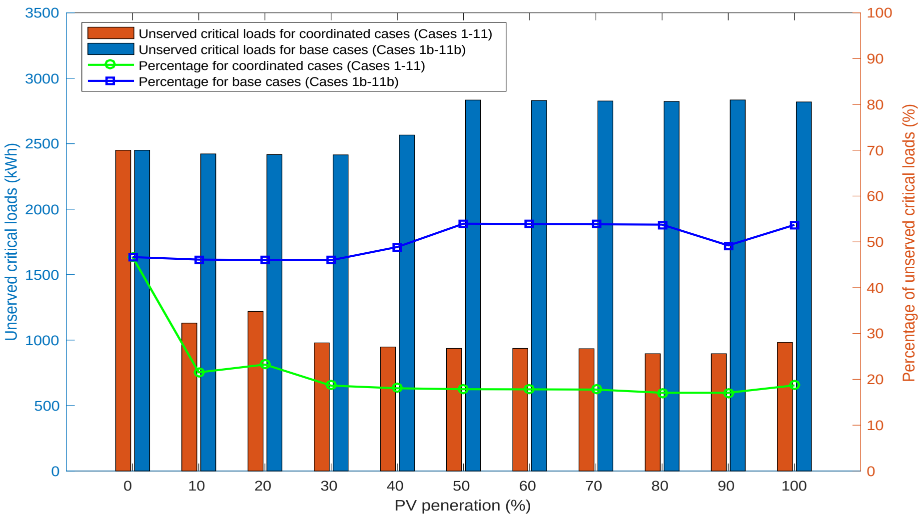

Fig. 6.3 Total unserved critical load and the percentage of unserved critical loads for the coordinated cases and base cases with different PV penetration level

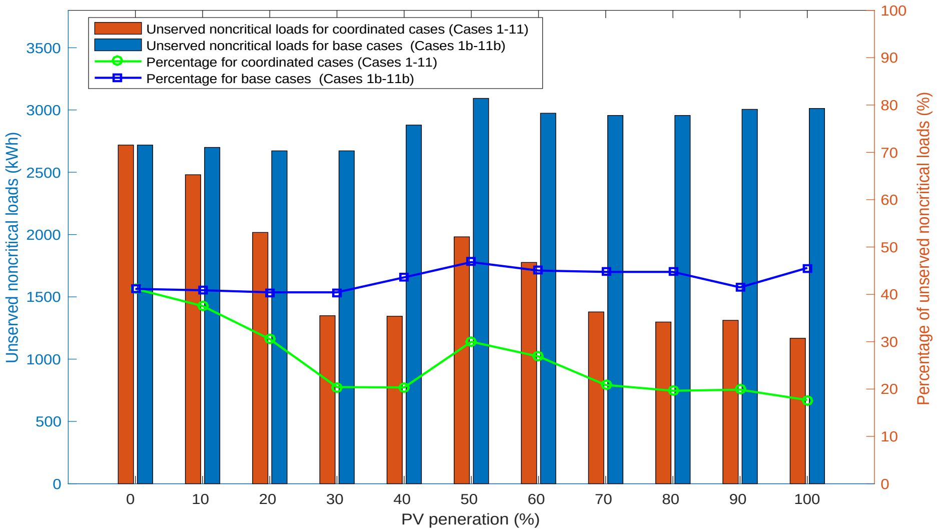

Fig. 6.4 Total unserved noncritical load and the percentage of unserved noncritical loads for the coordinated cases and base cases with different PV penetration level

Task 6: Case Study-Simulation Outputs

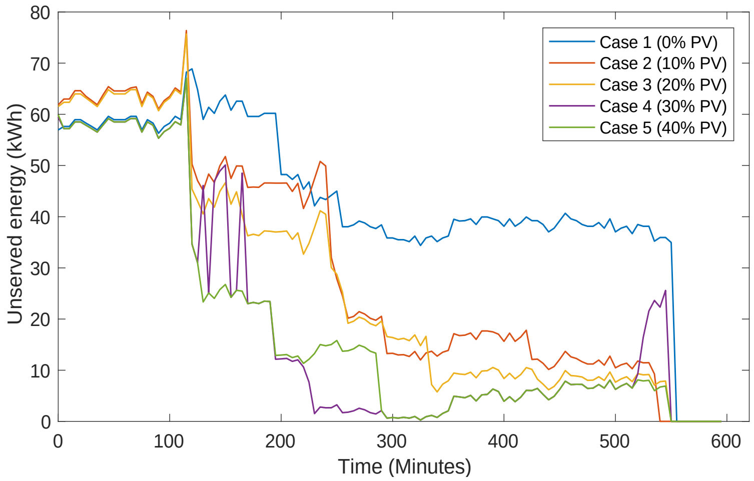

Fig. 6.5 Profiles of total unserved load for Cases 1-5

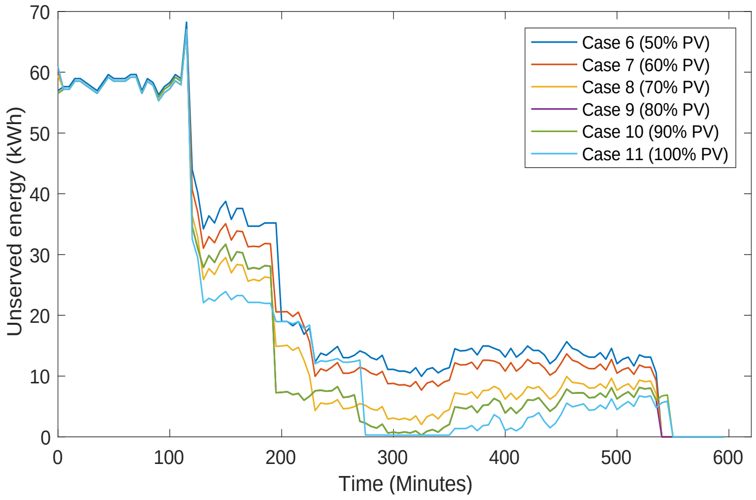

Fig. 6.6 Profiles of total unserved load for Cases 6-11

Task 6: Case Study-Simulation Outputs

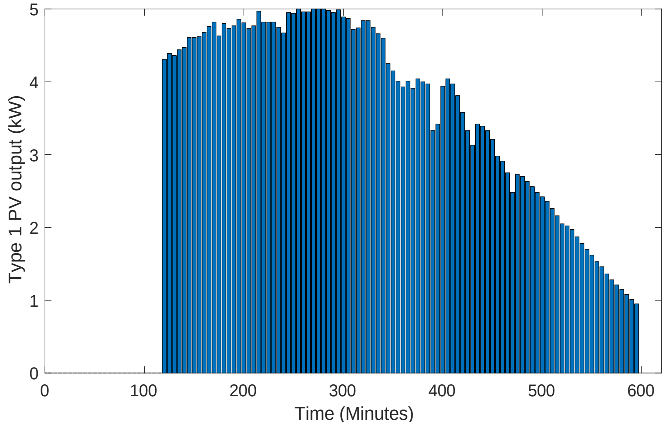

Fig. 6.7 Output of a Type-1 PV with 60% PV penetration level (Case 7)

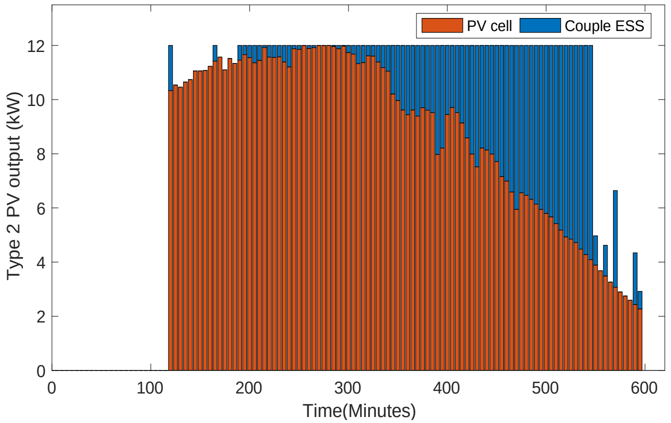

Fig. 6.8 Output of a Type-2 PVs with 60% PV penetration level (Case 7)

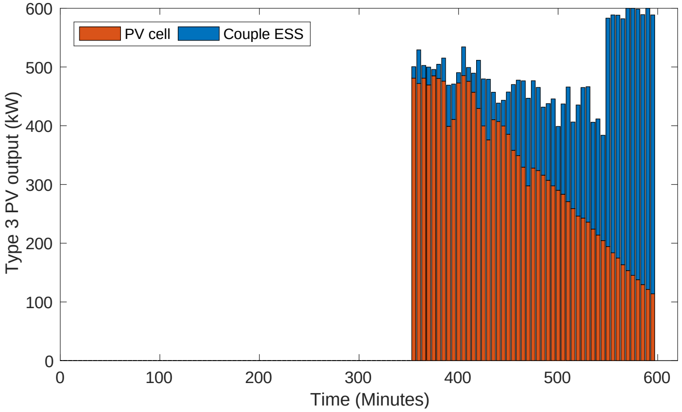

Fig. 6.9 Output of a Type-3 PVs with 60% PV penetration level (Case 7)

Task 6: Case Study for 5-day Operation

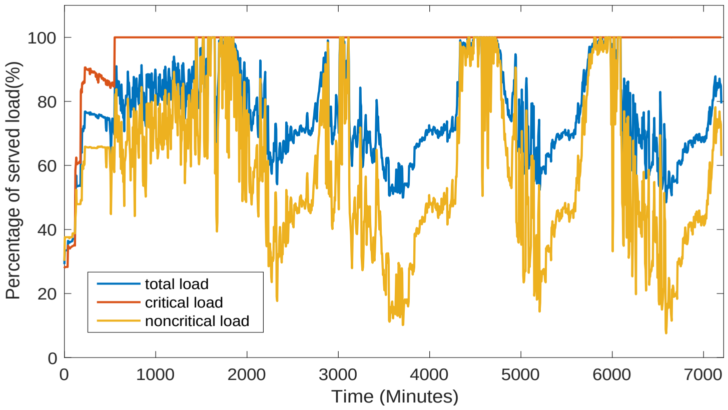

Fig. 6.10 Percentage of total served load, served critical/non-critical loads for the 5-day operation with 60% PV penetration

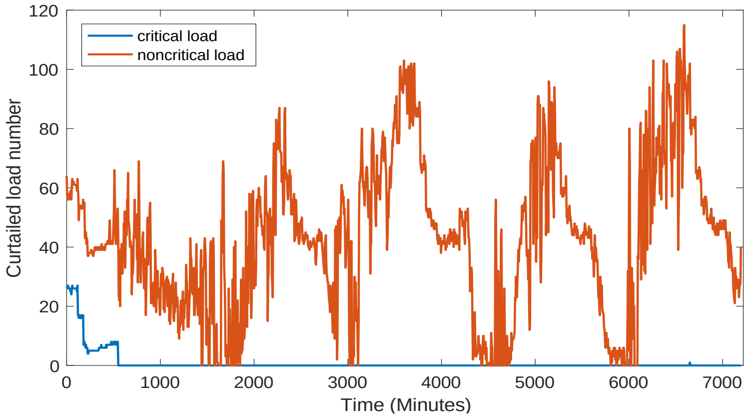

Fig. 6.11 The number of unserved critical/noncritical loads over time for the 5-day operation with 60% PV penetration

Total restoration time (min)	Percentage of unserved load %	Total Unserved energy (kWh)	Percentage of unserved critical load	Unserved energy for critical load (kWh)	Percentage of unserved noncritical load (kWh)	Unserved energy for noncritical load (kWh)	Solution time
549	24.02	26,675.8	2.08	1,022.7	41.45	25,653.1	106.42 min

- The solution time for each 15-minute rolling horizon optimization is approximately 4.4 seconds.

Task 6: Case Study-Simulation Outputs

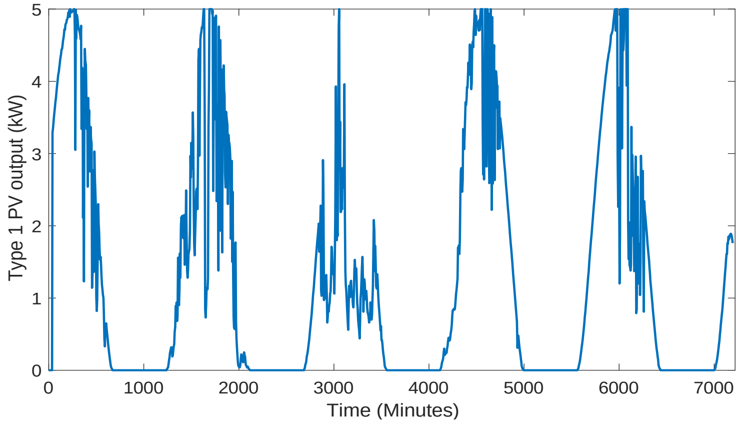

Fig. 6.12 PV output profile of a Type-1 PV for the 5-day operation

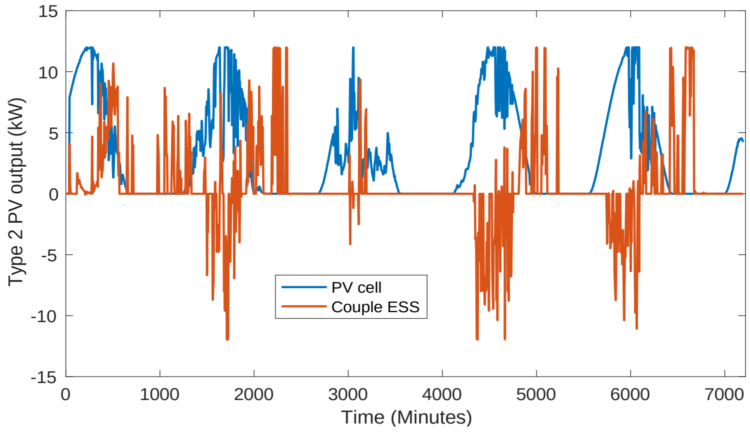

Fig. 6.13 PV output profile of a Type-2 PV for the 5-day operation

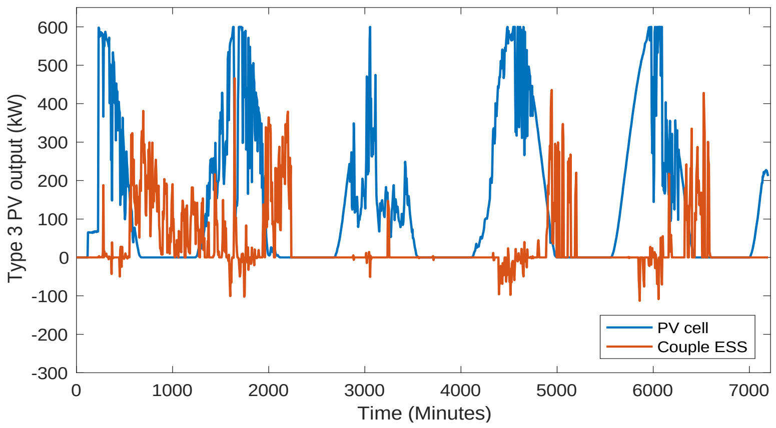

Fig. 6.14 PV output profile of a Type-3 PV for the 5-day operation

Task 6

- Task 6: Testing of the pre-event and post-event optimization via simulation using real feeder data
  - Subtask 6.1: (Completion in Q2-FY20) Continue real feeder data preparation for the testing
  - Subtask 6.2: (Completion in Q2-FY20) Testing of the pre-event preparation optimization model and solution algorithms via simulation using real feeder data provided by utility partners (e.g., City of Bloomfield utility, Algona Municipal Utilities)
  - Subtask 6.3: (Completion in Q2-FY20) Testing of the post-event operation optimization model and solution algorithms via simulation using real feeder data provided by utility partners (e.g., City of Bloomfield utility, Algona Municipal Utilities).
- Milestones:
  - M2.6.1: (100% Completion) Data interface development in software platform (e.g., Matlab or Python) for the real feeder data provided by utility partners.
  - M2.6.2: (100% Completion) Case studies of pre-event preparation optimization under real feeder data within required computation time (e.g., 4 hours) completed and results being reviewed by the utility; the resilience improvement will be at least 10% in terms of served energy and outage duration reduction
  - M2.6.3: (100% Completion) Case studies of post-event operation optimization under real feeder data within required computation time (5 min for energy management optimization and 1 hour for restoration optimization) completed and results being reviewed by the utility; the resilience improvement will be at least 10% in terms of served energy and outage duration reduction
- Deliverables:
  - Data interface to unify pre-event and post-event optimization solutions
  - Real feeder test case using developed pre-event preparation and post-event operation framework

Publications

- Peer-reviewed journal article
  - 1. Arif, Anmar, Zhaoyu Wang, Bo Chen, and Bo Chen. "Repair and resource scheduling in unbalanced distribution systems using neighborhood search." IEEE Transactions on Smart Grid 11, no. 1 (2020): 673-685.
  - 2. Arif, Anmar, Zhaoyu Wang, Chen Chen, and Bo Chen. "A Stochastic Multi-Commodity Logistic Model for Disaster Preparation in Distribution Systems." IEEE Transactions on Smart Grid 11, no. 1 (2019): 565-576.
  - 3. Chen, Bo, Zhigang Ye, Chen Chen, and Jianhui Wang. "Toward a MILP modeling framework for distribution system restoration." IEEE Transactions on Power Systems 34, no. 3 (2018): 1749-1760.
  - 4. Chen, Bo, Zhigang Ye, Chen Chen, Jianhui Wang, Tao Ding, and Zhaohong Bie. "Toward a synthetic model for distribution system restoration and crew dispatch." IEEE Transactions on Power Systems 34, no. 3 (2018): 2228-2239.
- Conference publication
  - 1. Shanshan Ma, Nichelle'Le Carrington, Arif, Anmar, and Zhaoyu Wang. “Resilience assessment of self-healing distribution systems under extreme weather events.” 2019 IEEE PES General Meeting, Atlanta, Aug. 2019. (Best Paper Award)
- Two journal papers under review
- Presented in 7 conferences
- Foster the collaboration with S&C Electric Company through a Cooperative Research and Development Agreement (CRADA)

Conclusion

- Grid resilience can be further enhanced by coordinating solar energy and other DERs through the developed framework
- The developed framework can leverage the controllability, flexibility and locational value of solar energy
- The coordination between pre-event preparation and post-event operation, uncertainty, and model scalability are addressed in this project.

Path Forward

- Integrated optimization framework considering smart inverter control policies and protective relay settings.
- Interdependency of communication systems
- Comprehensive risk-based optimization

Project Team

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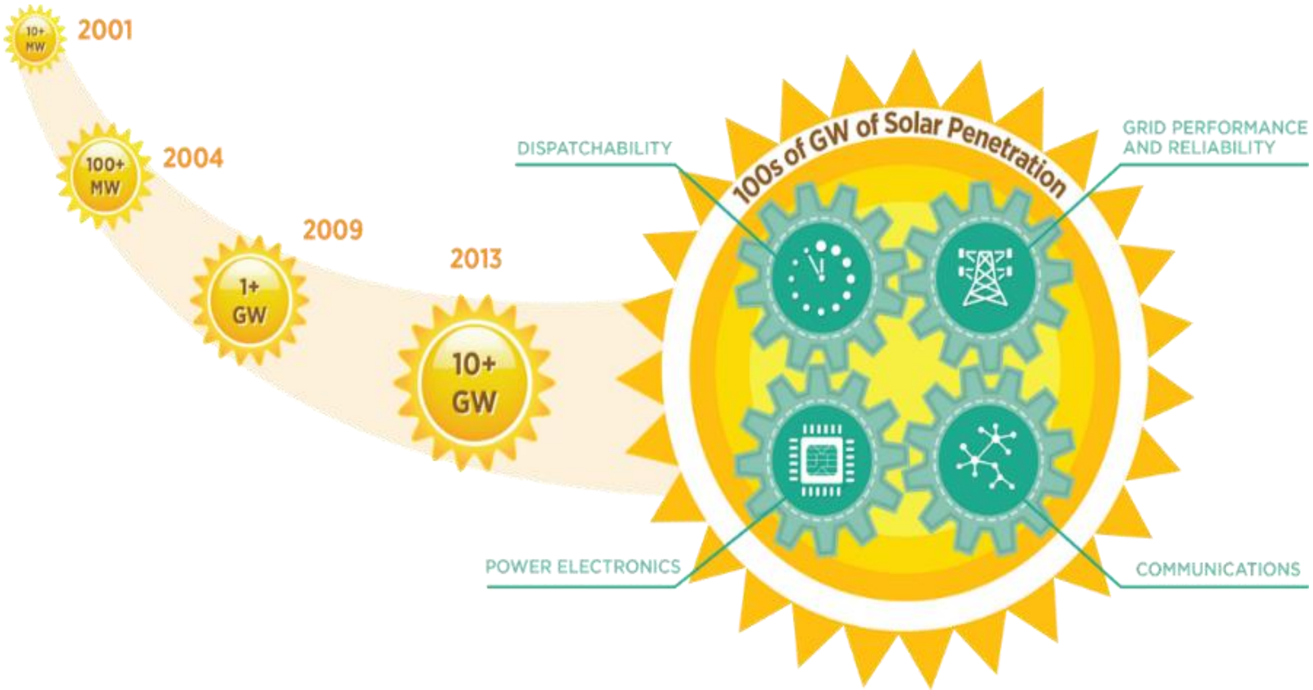
- Algona: John Bilsten
- Bloomfield: Chris Ball

Questions?



10+ MW
2001
100+ MW
2004
1+ GW
2009
10+ GW
2013
100s of GW of Solar Penetration
DISPATCHABILITY
GRID PERFORMANCE AND RELIABILITY
POWER ELECTRONICS
COMMUNICATIONS