The Role of Energy Supply Mobility on Resilience of Solar-Integrated Electric Distribution Grids

Mostafa Nazemi
Ph.D. Candidate

Department of Electrical and Computer Engineering
The George Washington University

Agenda

❑ More and More Urgent to Enhance Resilience

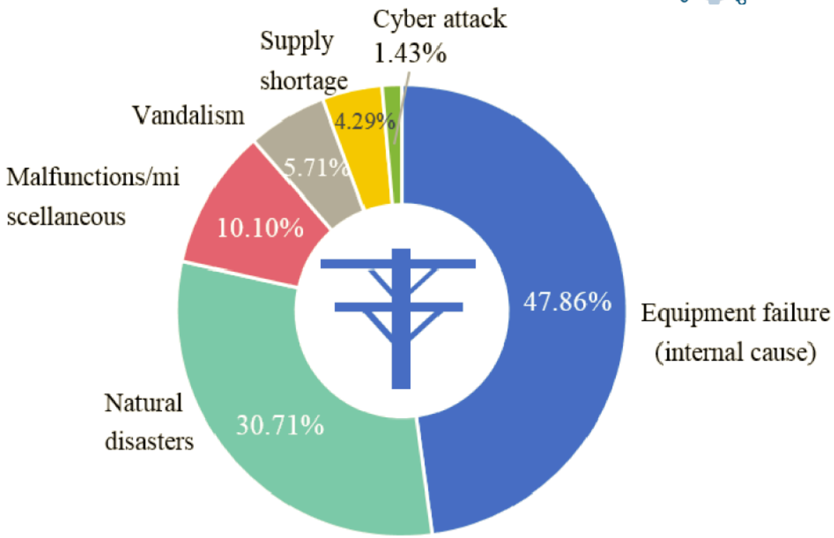
Large Blackouts in the United States

Statistics for Outage Cause Categories

	% of events	Mean size in MW	Mean size in customers
Earthquake	0.8	1,408	375,900
Tornado	2.8	367	115,439
Hurricane/Tropical Storm	4.2	1,309	782,695
Ice Storm	5	1,152	343,448
Lightning	11.3	270	70,944
Wind/Rain	14.8	793	185,199
Other cold weather	5.5	542	150,255
Fire	5.2	431	111,244
Intentional attack	1.6	340	24,572
Supply shortage	5.3	341	138,957
Other external cause	4.8	710	246,071
Equipment Failure	29.7	379	57,140
Operator Error	10.1	489	105,322
Voltage reduction	7.7	153	212,900
Volunteer reduction	5.9	190	134,543

Source: *Trends in the History of Large Blackouts in the United States*, http://www.uvm.edu/~phines/publications/2008/Hines_2008_blackouts.pdf.

Notes: Totals are greater than 100% because some events fall into multiple initiating-event categories.



Power outage causes for 140 worldwide outage data (1965 - 2012)

❑ Objective: Enhanced Resilience

How can we accurately "detect" or "foresee" a disruptive phenomenon and a consequent electricity outage?

How can we efficiently "plan" to "mitigate" or "recover from" the electricity outages?

Source: Google Images

❑ Long-Term Resilience and Short-Term Resilience

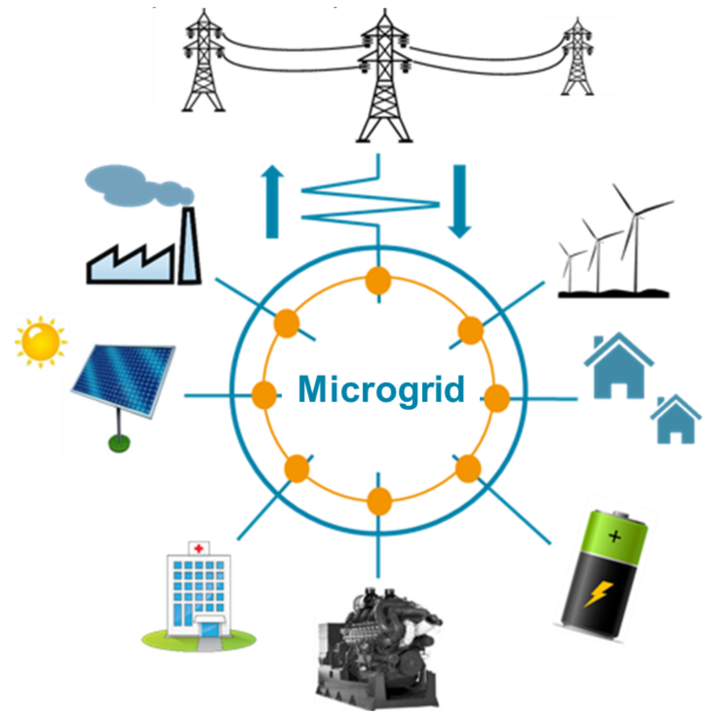
Long-Term Structural Resilience (Hardening the Grid):

❖ Battery Storage System

❖ Distributed Energy Resources (DERs)

❖ Advanced Metering Infrastructure (AMI)

❖ Microgrids Planning and Formation



Source: Google Images

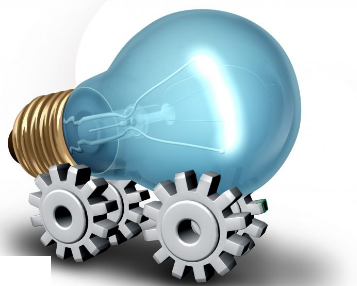
❑ Long-Term Resilience and Short-Term Resilience

Short-Term Operational Resilience (Mitigation and Restoration):

❖ Mobile Power Sources (MPSs)

- ➢ **Electric Vehicles (EVs)**
- ➢ **Mobile Energy Storage System (MESSs)**
- ➢ **Mobile Emergency Generators (MEGs)**

❖ Remote-Controlled Switches (RCS)



❖ Microgrids Operation and Control

Research Gaps:

❑ Coordination of MPS dispatch with RCS
❑ Investigation of the impact of repair plans
❑ Investigation of the impact of Solar Energy

Source: Google Images

Agenda

1 **Introduction**

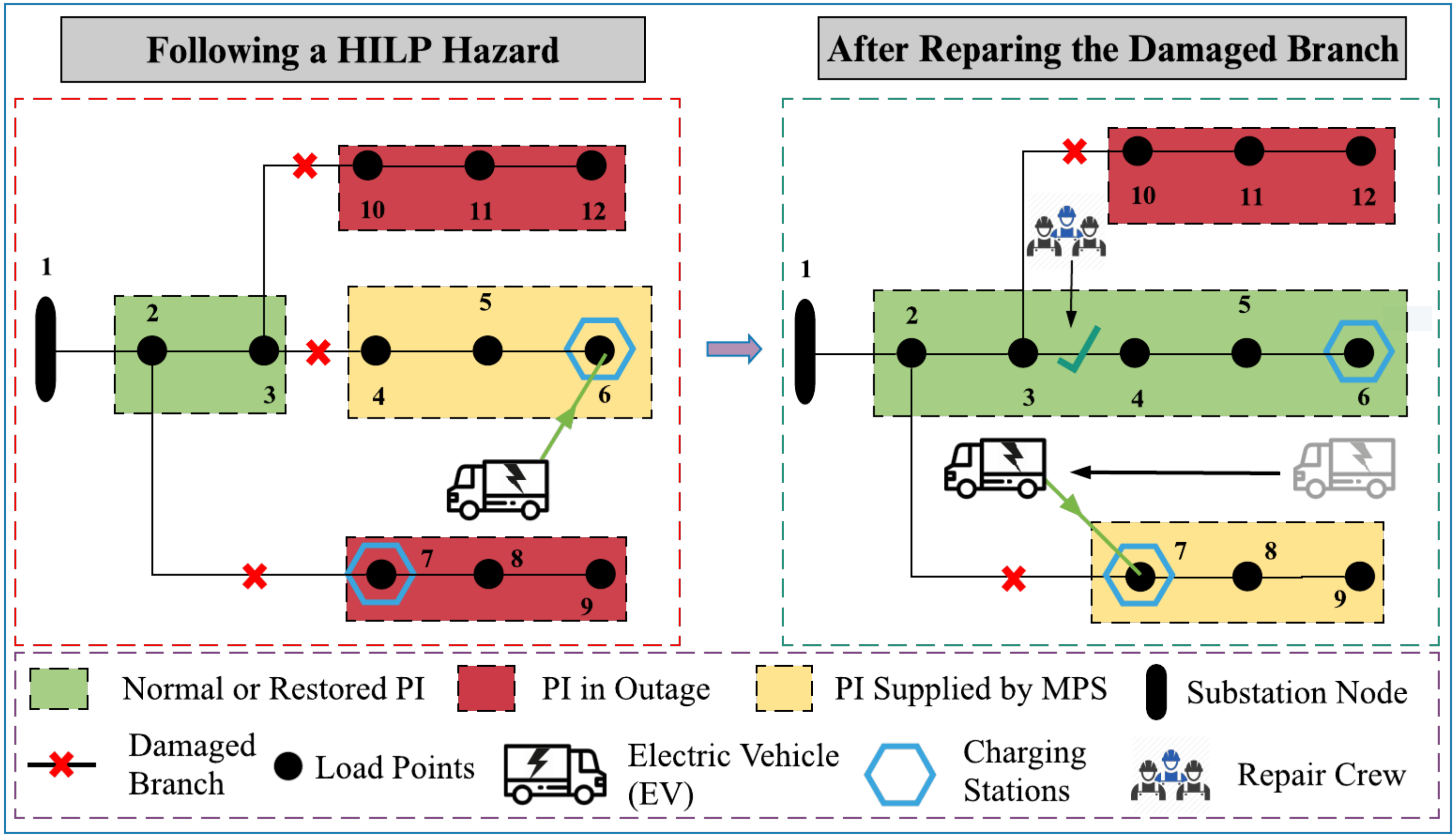
2 Mobile Power Sources: Methodology

3 Case Study and Numerical Results

4 Conclusions

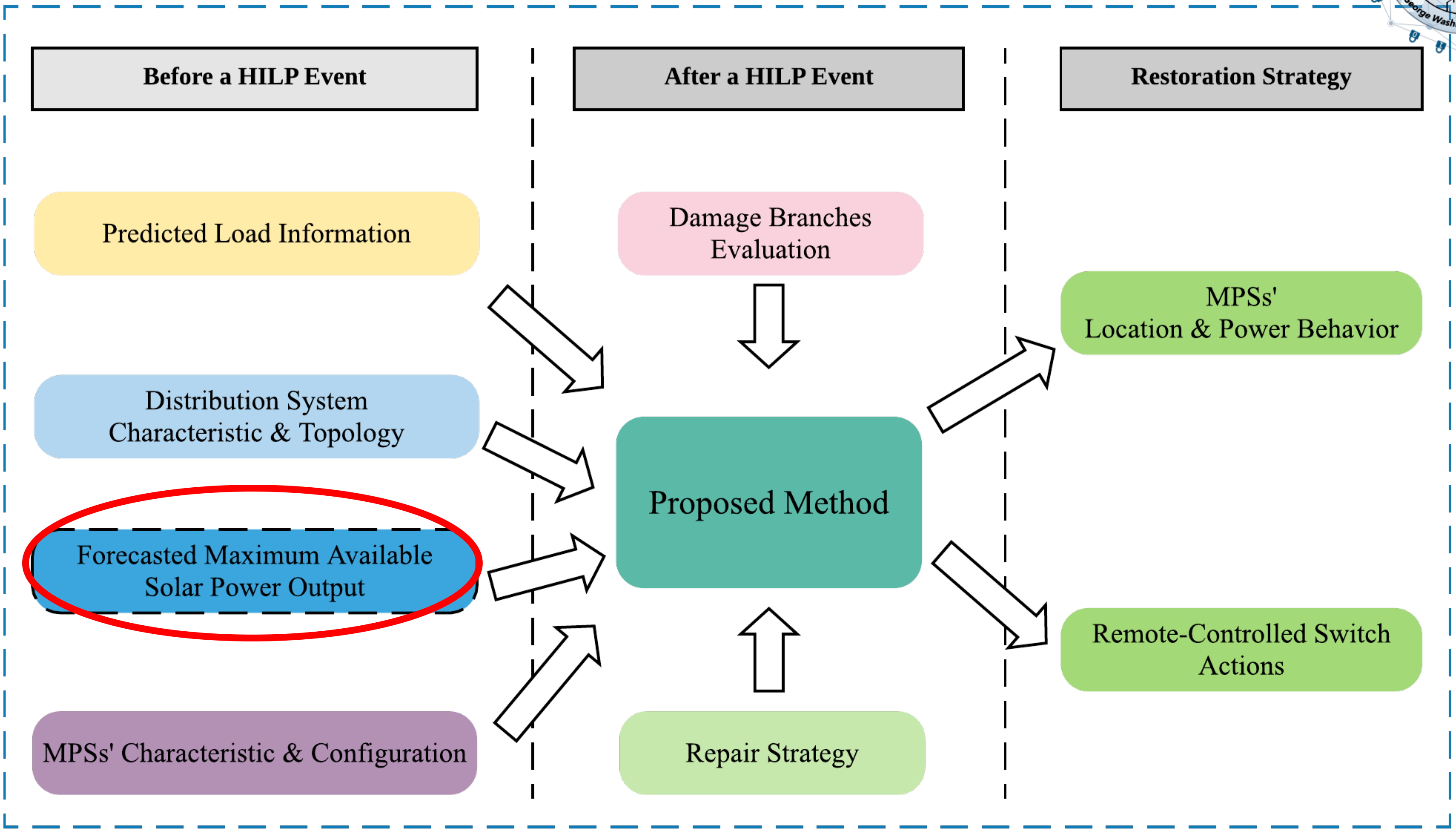
Mobile Power Sources: Methodology

❑ Mobile Power Sources for Facilitating Restoration



Simple illustrative diagram of MPSs' assistance on enhancing resilience

❑ Mobile Power Sources for Facilitating Restoration



Framework of the proposed method coordinating PV generation in facilitating the restoration

Mobile Power Sources: Methodology

❑ Extended Formulation

Objective Function:

$$\max\Big(\sum_{t\in\mathbf{T}}\sum_{i\in\mathbf{B}}\chi_i\cdot pd_{i,t}-\sum_{t\in\mathbf{T}}\sum_{m\in\mathbf{M}}C_m^{\mathrm{tr}}\cdot\varphi_{m,t}-\sum_{t\in\mathbf{T}}\sum_{m\in\{\mathbf{S},\mathbf{V}\}}C_m^{\mathrm{P}}\cdot(p_{m,t}^{\mathrm{ch}}+p_{m,t}^{\mathrm{dch}})$$
$$-\sum_{t\in\mathbf{T}}\sum_{m\in\mathbf{G}}\delta_m\cdot p_{m,t}-\sum_{t\in\mathbf{T}}\sum_{i\in\mathbf{B}}\mathrm{PVC}\cdot p_{i,t}^{\mathrm{SC}}\Big)$$

Cost of loss of solar energy ($/kWh)

Curtailed power of solar farm connected to node *i* at time *t* (kW)

Modified Constraints: (Power balance)

$$\sum_{(j,i)\in\mathbf{L}}pf_{ji,t}-\sum_{(i,j)\in\mathbf{L}}pf_{ij,t}=pd_{i,t}-pg_{i,t}-p_{i,t}^{\mathrm{mps}}-p_{i,t}^{s},\quad\forall i\in\mathbf{B},\forall t\in\mathbf{T}$$

Utilized real power generated by solar farm (kW)

Additional Constraints:

$$p_{i,t}^{\mathrm{SC}}=\overline{P}_{i,t}^{s}-p_{i,t}^{s},\quad\forall i\in\mathbf{B},\forall t\in\mathbf{T}$$

$$0\le p_{i,t}^{s}\le\overline{P}_{i,t}^{s},\quad\forall i\in\mathbf{B},\forall t\in\mathbf{T}$$

$\overline{P}_{i,t}^{s}$ = Maximum available real power generated by solar farm, (kW)

Agenda

1 **Introduction**

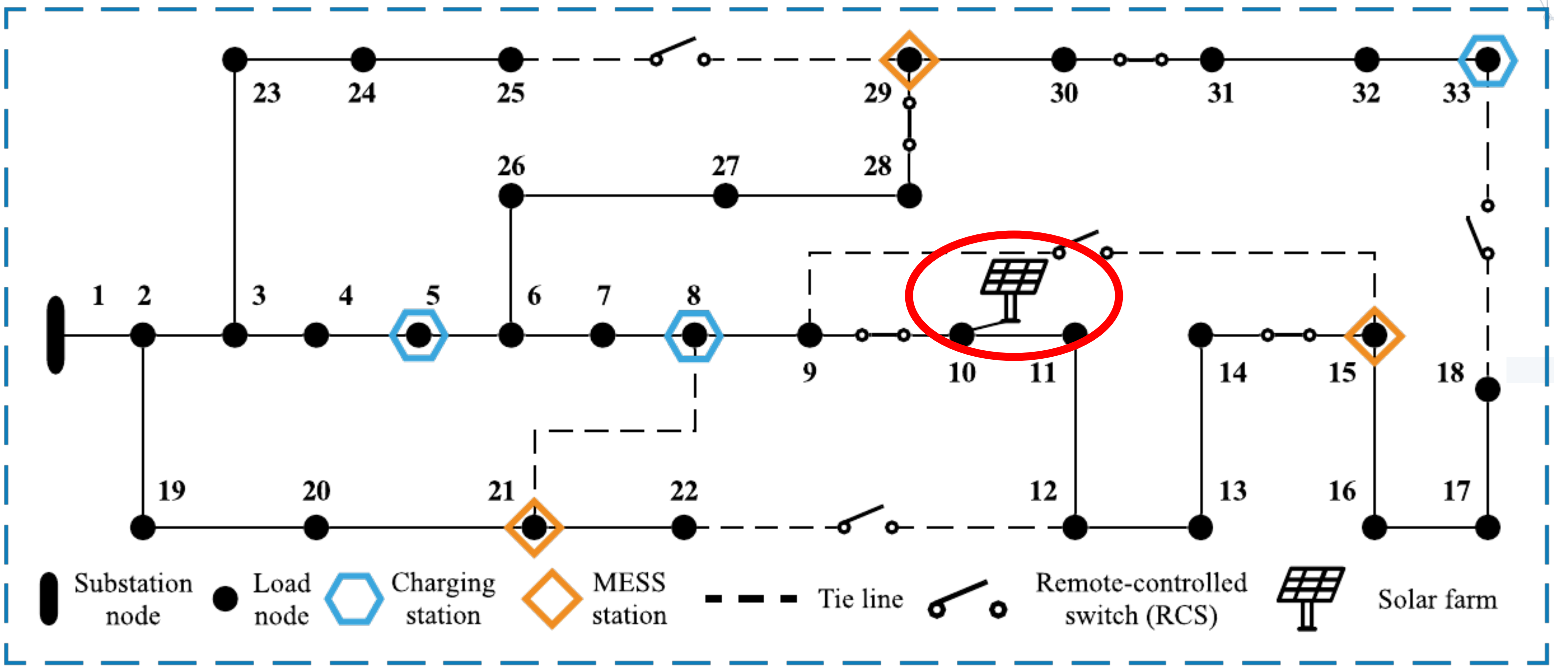
2 Mobile Power Sources: Methodology

3 Case Study and Numerical Results

4 Conclusions

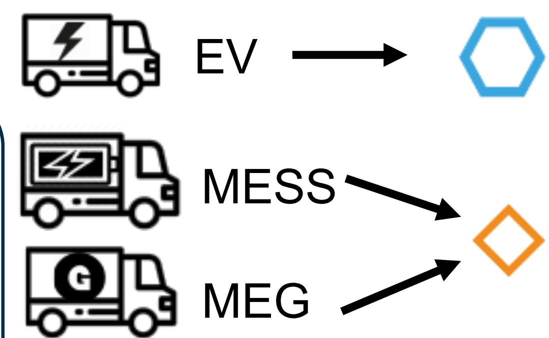
Case Study: MPSs with PV Generation

❑ Case Studies with PV Generation

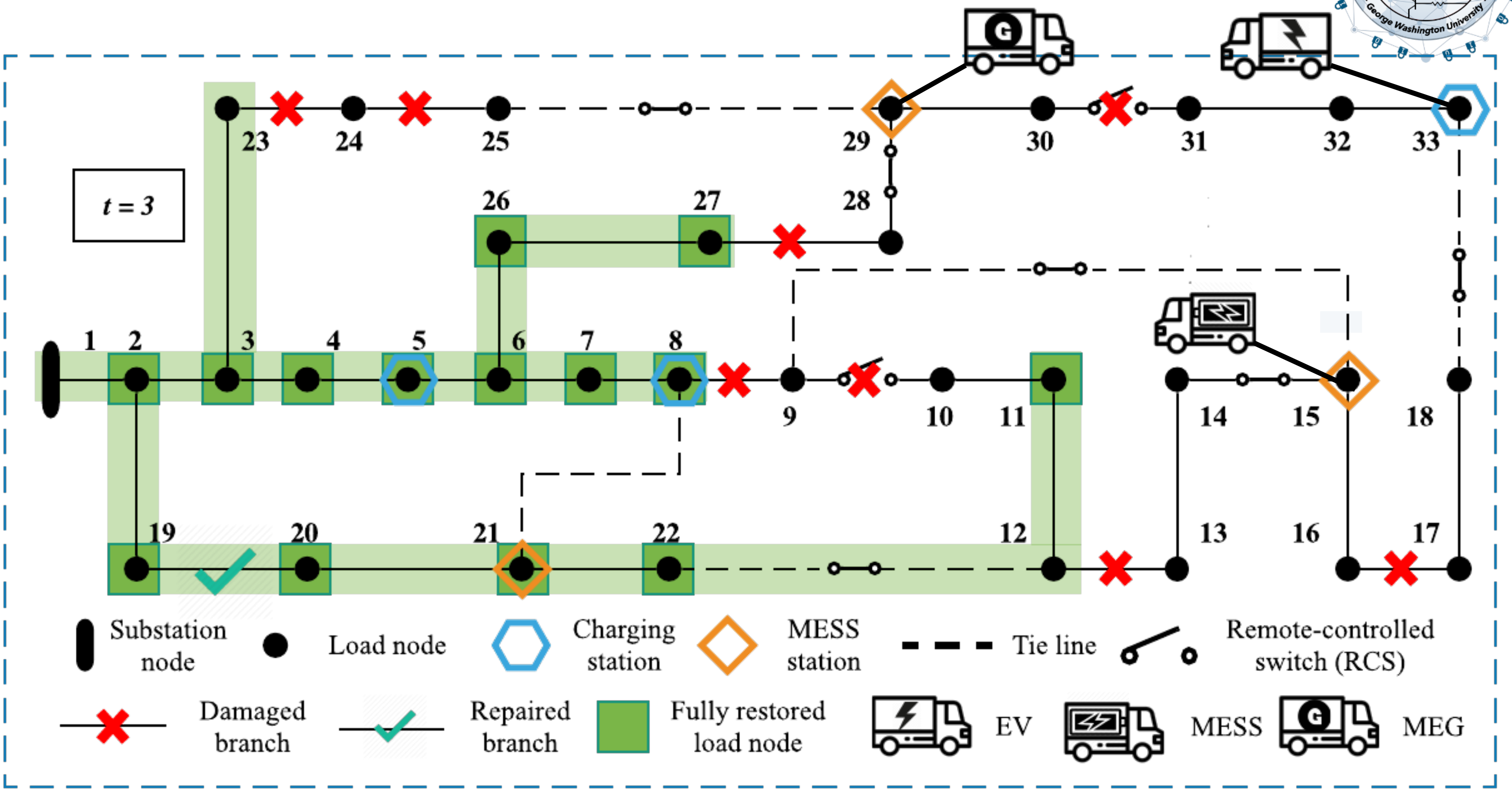


Case Study: 33-Node Test System

- ❑ **37** Distribution Lines (including **5** Tie Lines) and **1** Substation Node
- ❑ Hourly Total Dynamic Demand: **3715 kW (Peak)** in **32** Load Points
- ❑ **3** Charging Stations**, 3** MESS Stations**, 8** RCSs
- ❑ **500 kW Solar Farm** Located at Node **10**

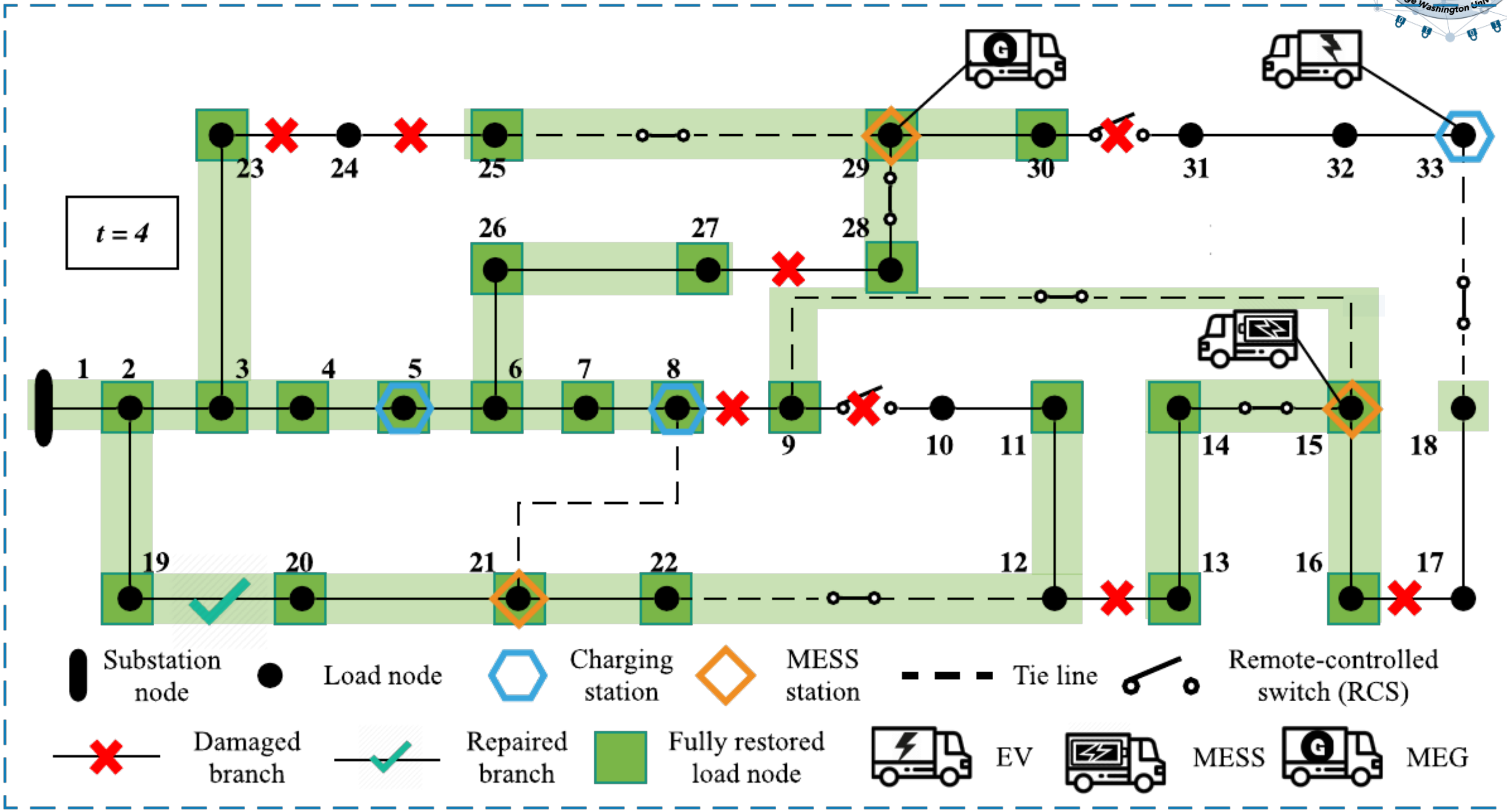


❑ Numerical Results - Restoration Process



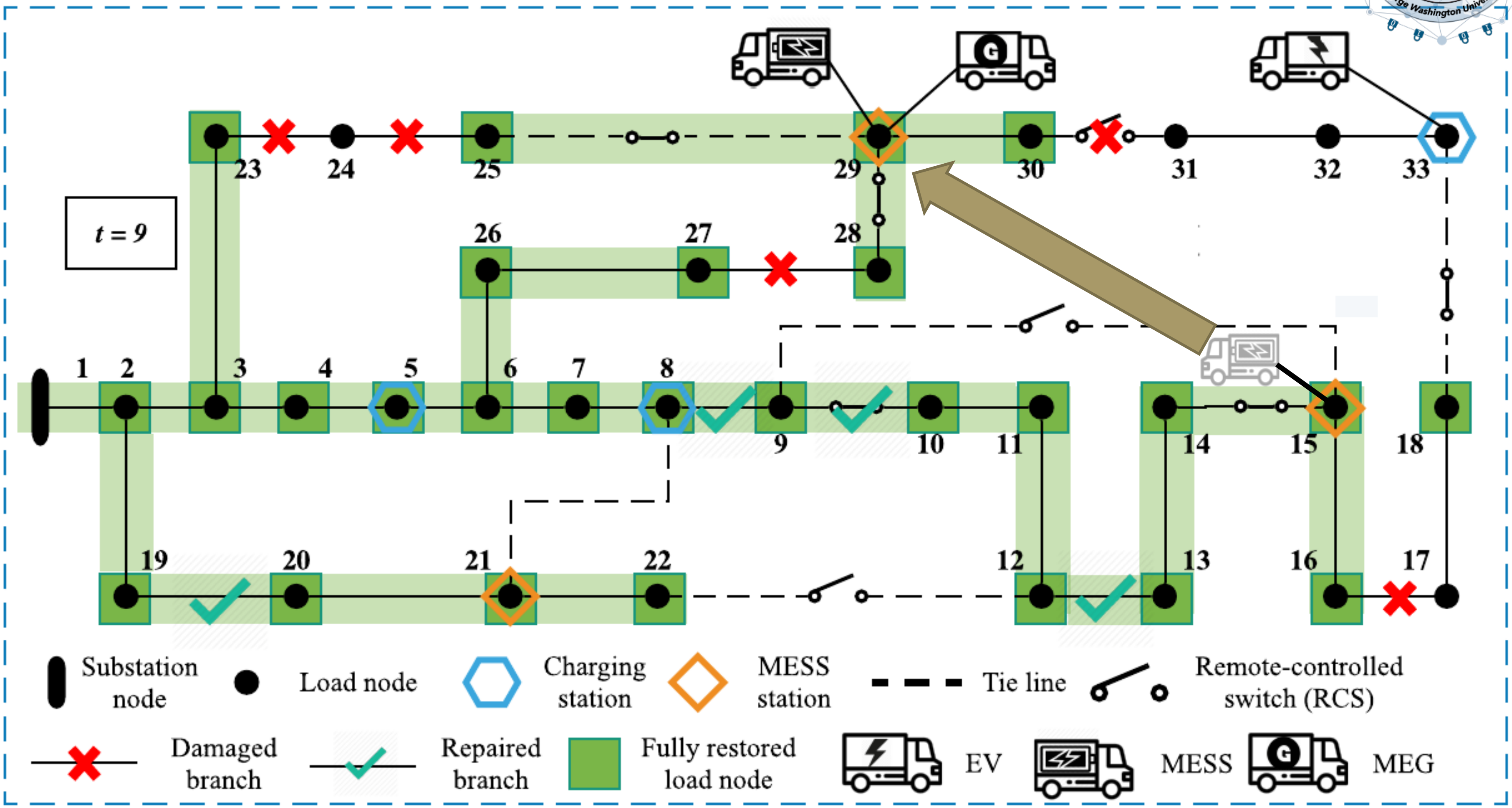
$t = 3$

❑ Numerical Results - Restoration Process



t = 4

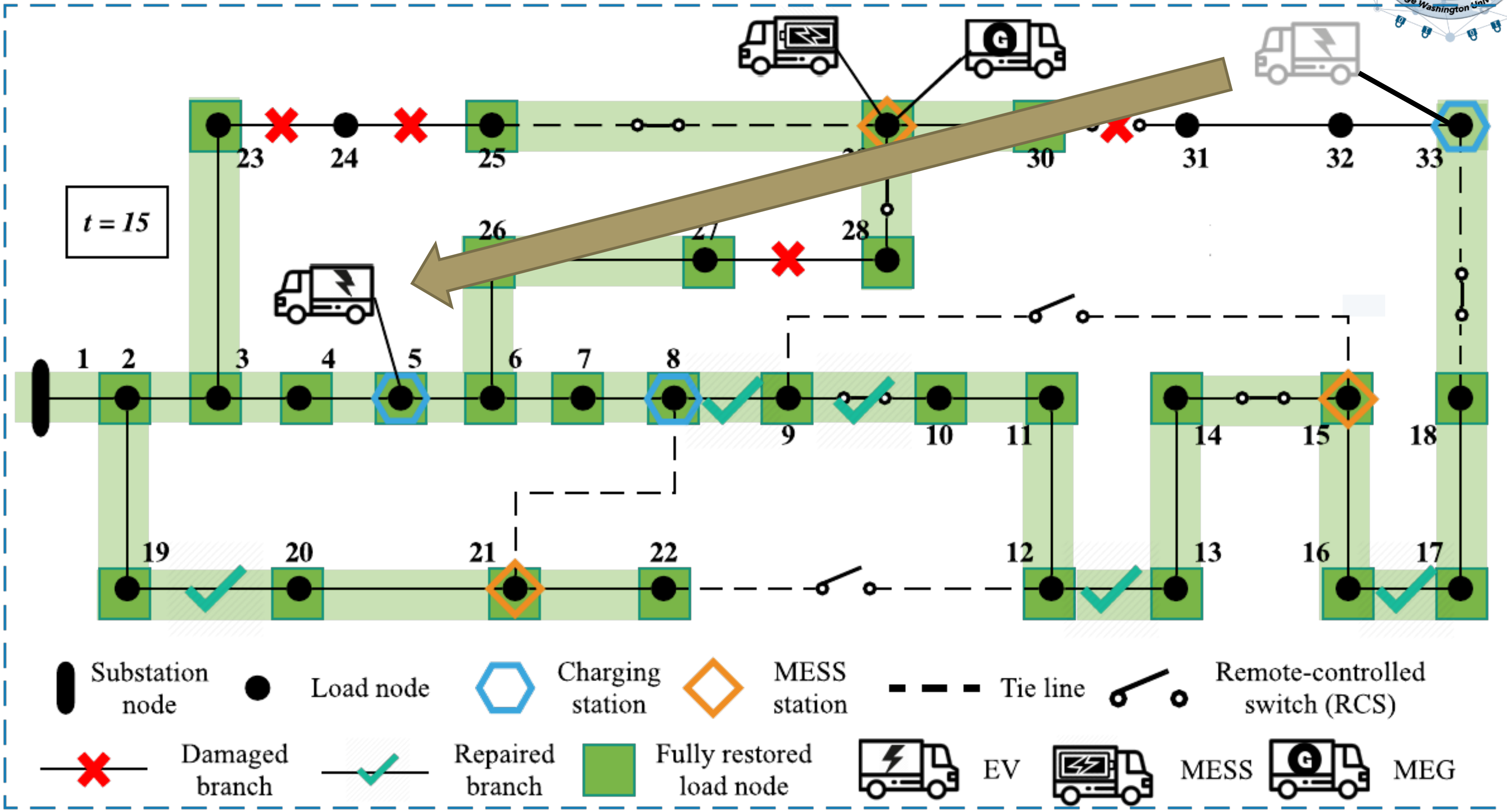
Numerical Results - Restoration Process



t = 9

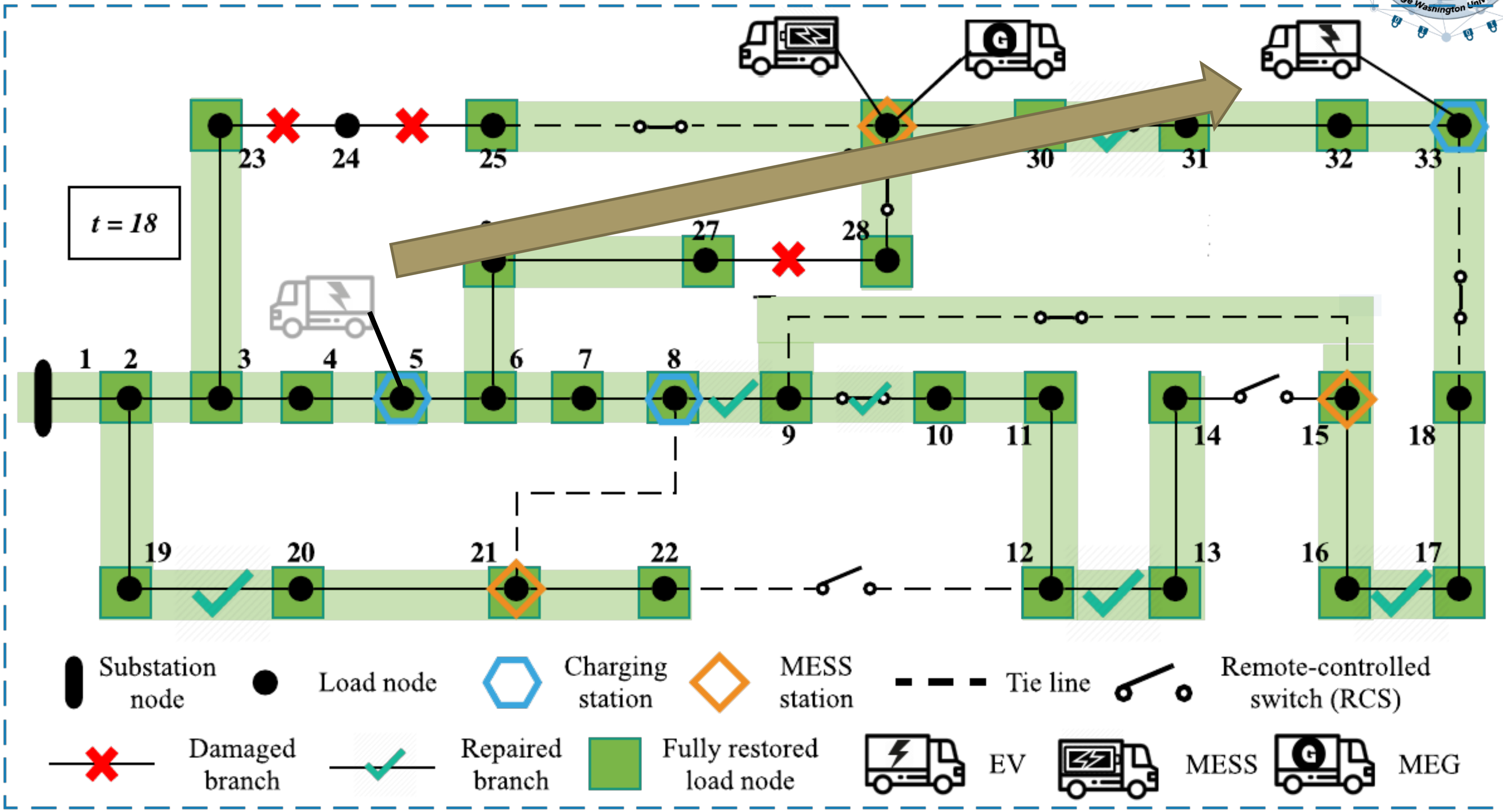
Mobile Power Sources: Methodology & Case Study

❑ Numerical Results - Restoration Process



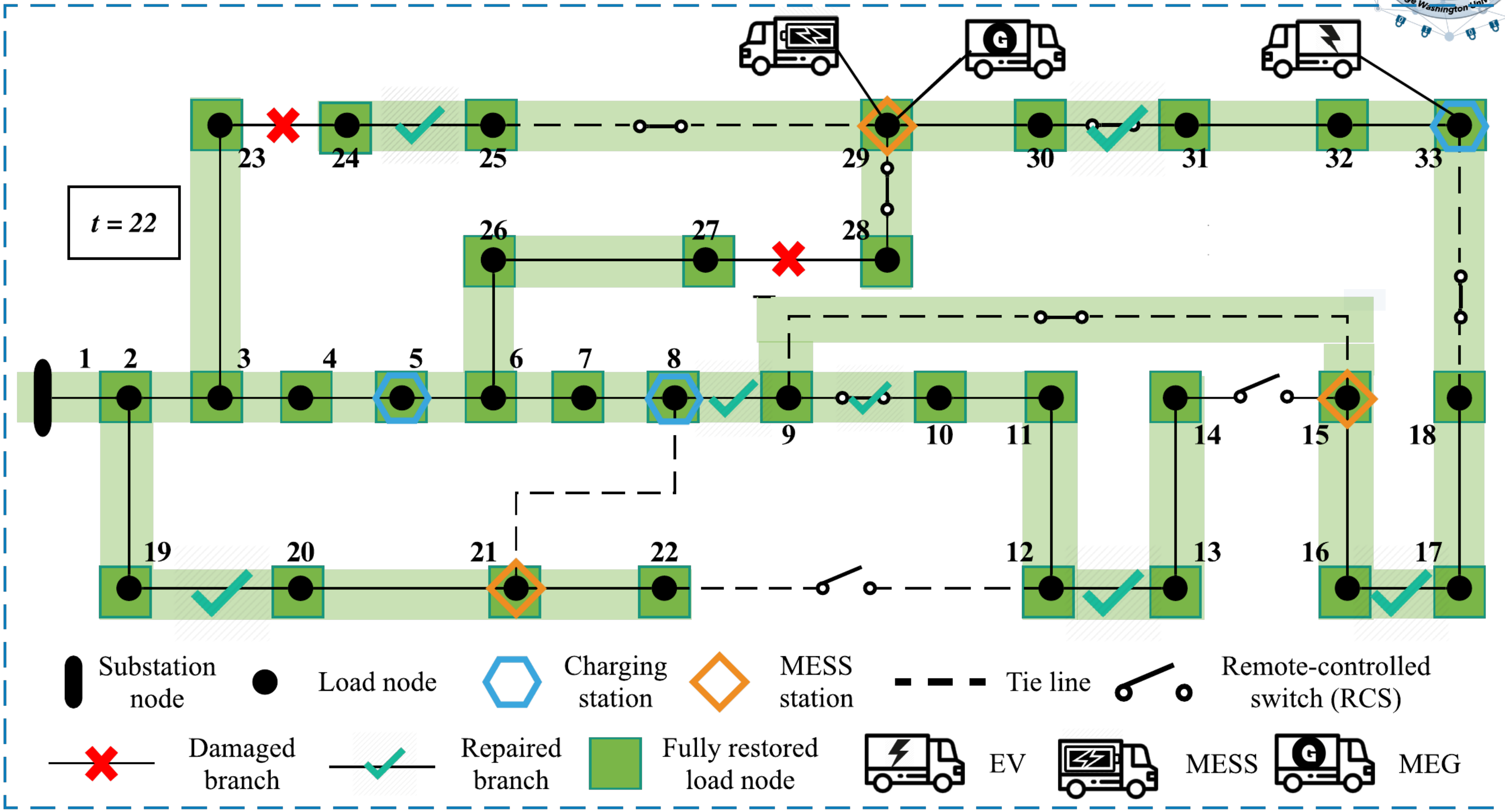
t = 15

❑ Numerical Results - Restoration Process



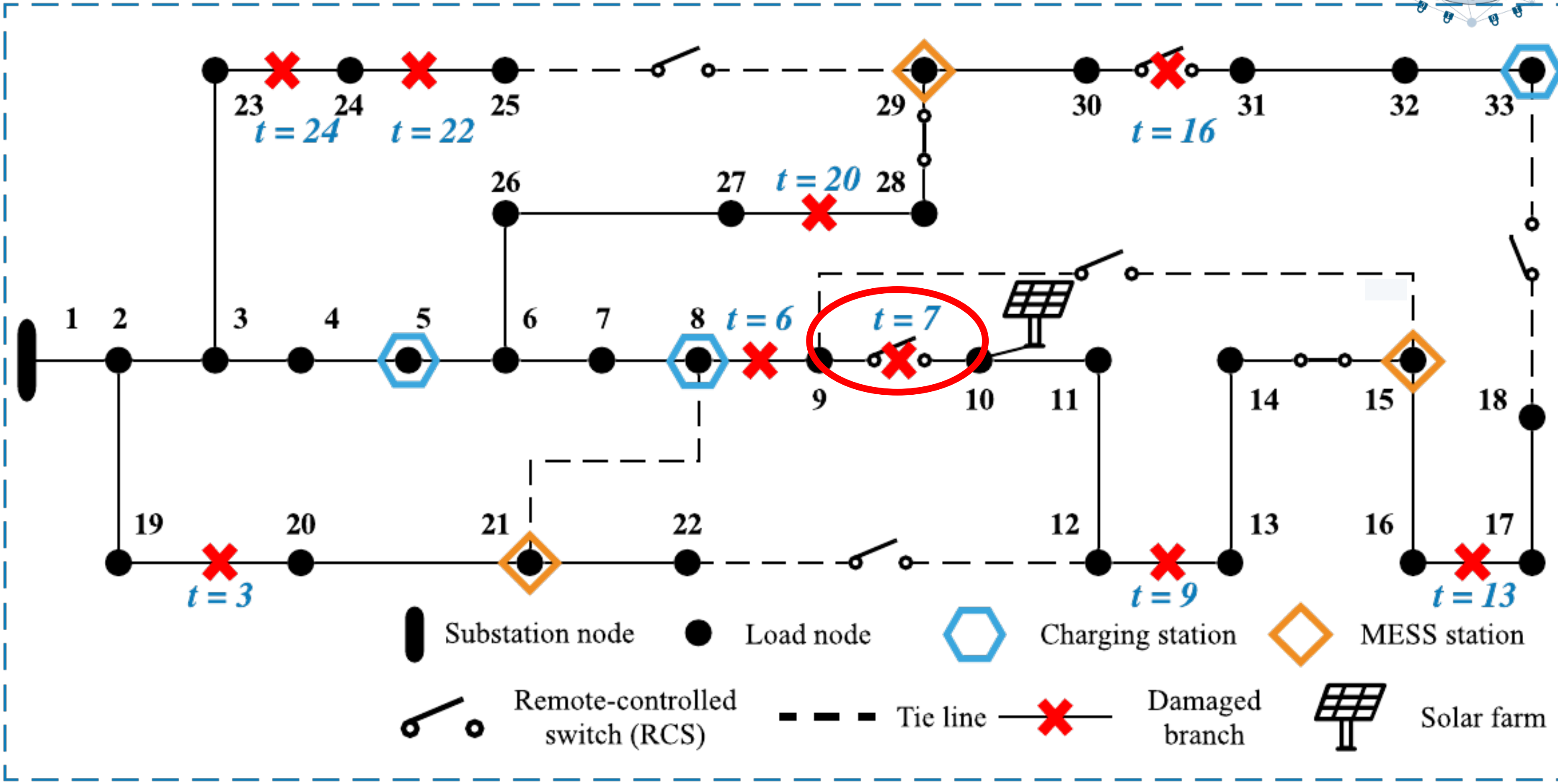
t = 18

❑ Numerical Results - Restoration Process



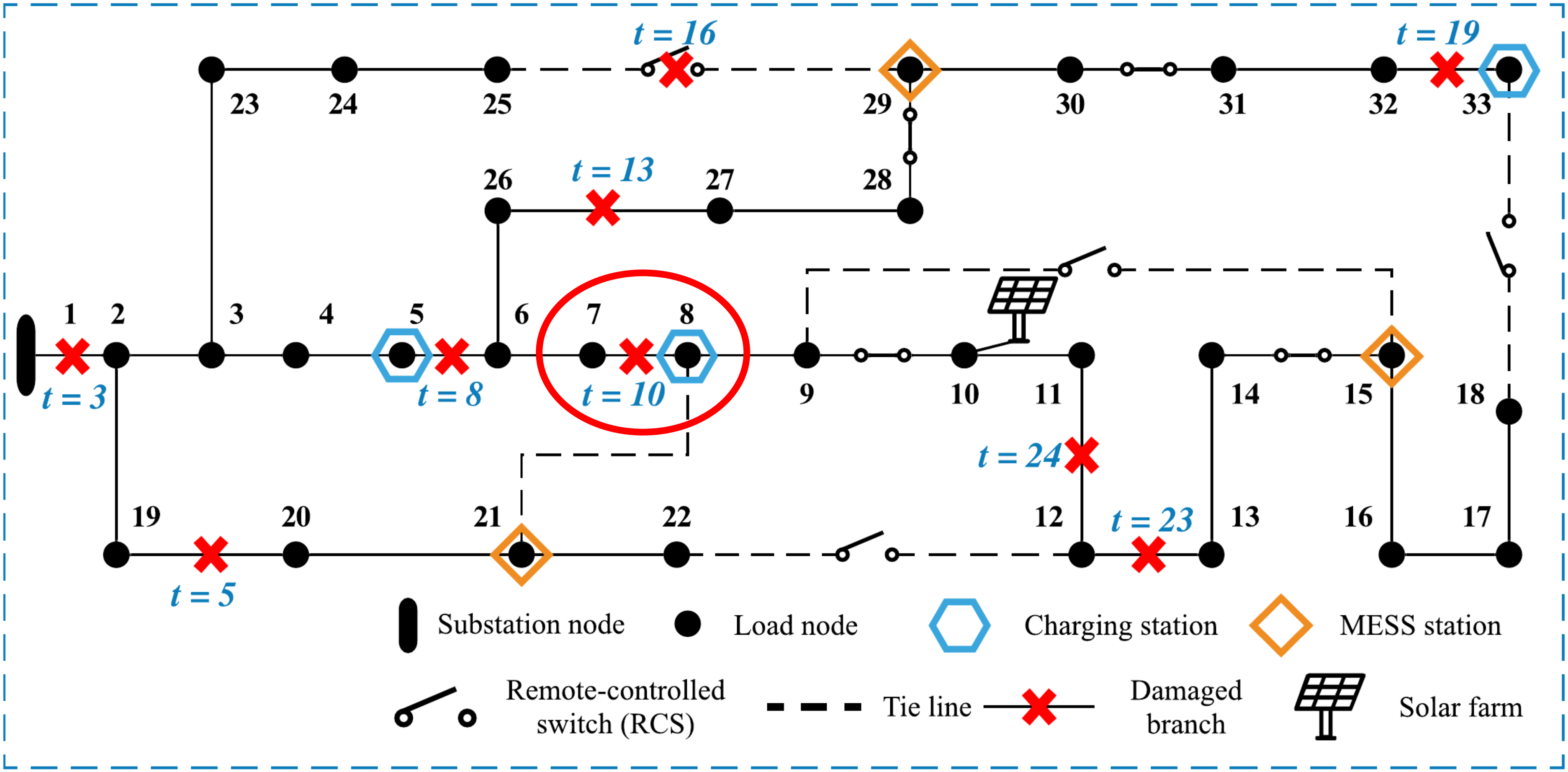
t = 22

❑ Damage Scenario – Case 1



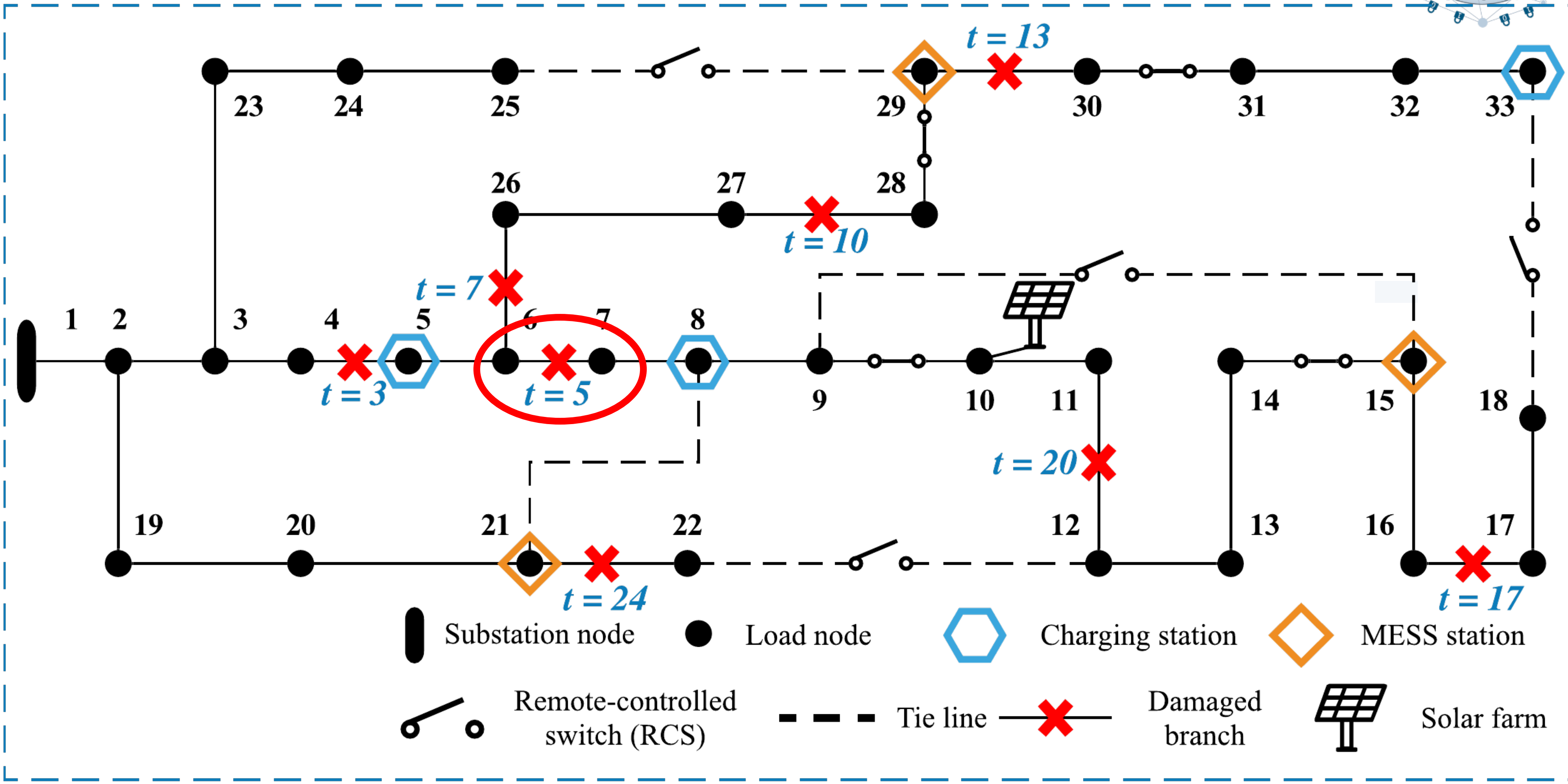
Solar farm reconnected to the main grid **at *t* = 7**

❑ Damage Scenario – Case 2



Solar farm reconnected to the main grid **at *t* = 10**

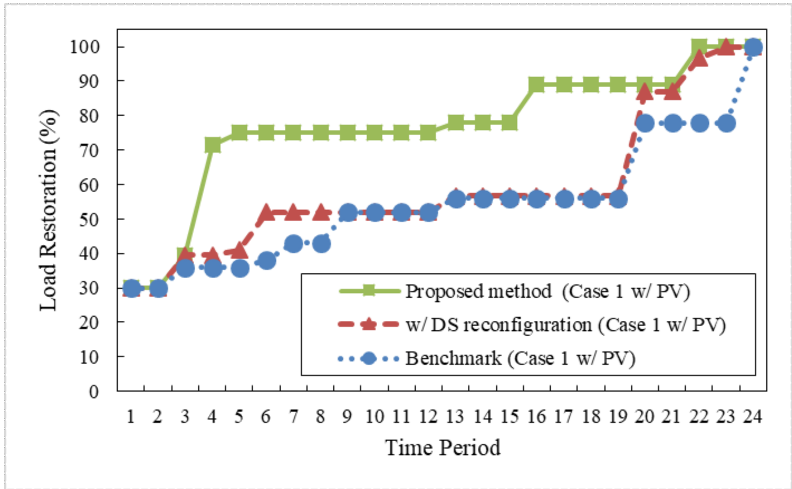
❑ Damage Scenario – Case 3

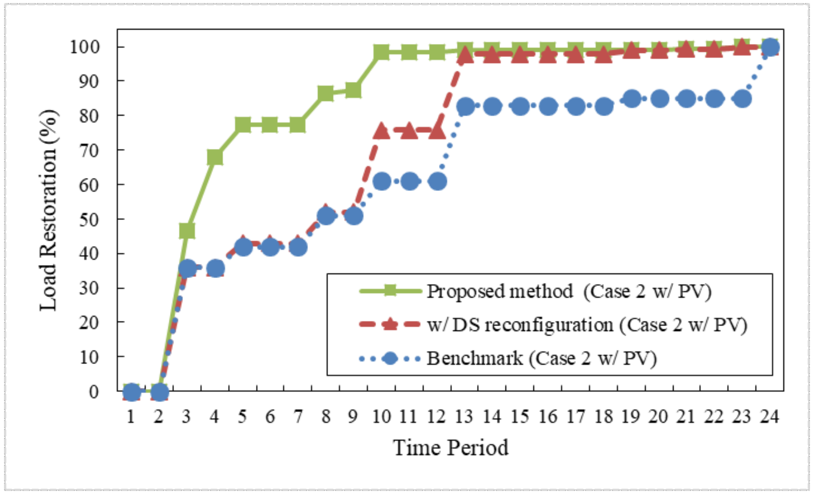


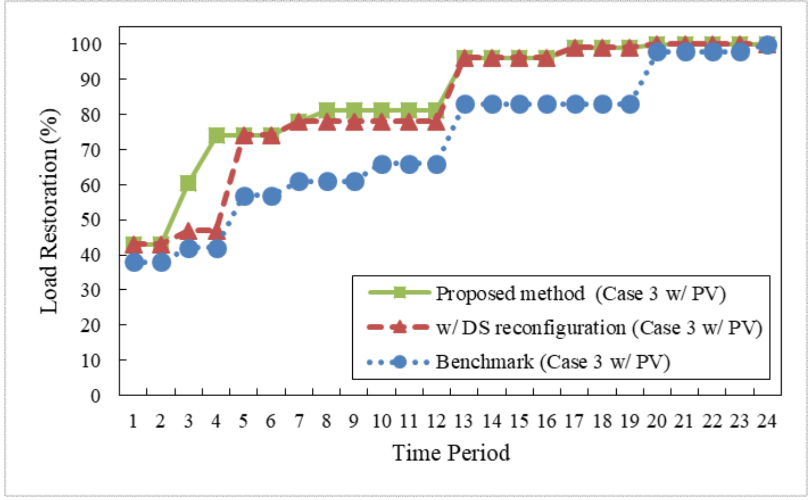
Solar farm reconnected to the main grid **at *t* = 5**

Case Study: MPSs with PV Generation

❑ Numerical Results – Recovery Rate with PV Generation



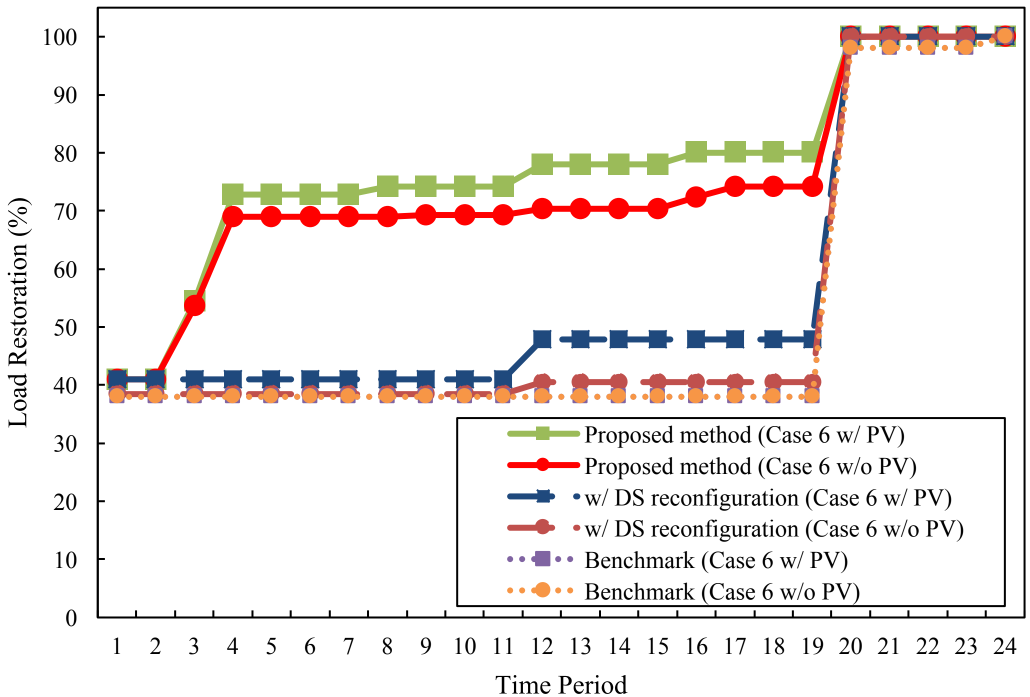




Considering PV generation, resulted in:
Same RCS actions
Same MPSs dispatch strategy

Case Study: MPSs with PV and Repair Strategy

❑ Numerical Results



Time period	Remote-controlled switch (RCS) actions
$t = 1$	close branch 9-15, 12-22, 18-33, 25-29
$t = 7$	open branch 14-15
$t = 18$	open branch 18-33
$t = 20$	close branch 14-15, open branch 9-15, 25-29
$t = 24$	open branch 12-22

RCS actions are the same in both cases w/ and w/o PV generation

---		Time Period												
		1	2	3	4	5	6	7	8	9~13	14	15	16	17~24
MPS	EV 1	node 1	→	node 8				→		node 33				
	MESS 1	node 1	→		node 15			→	node 29		→	node 21	→	node 29
	MEG 1	node 1	→		node 15									

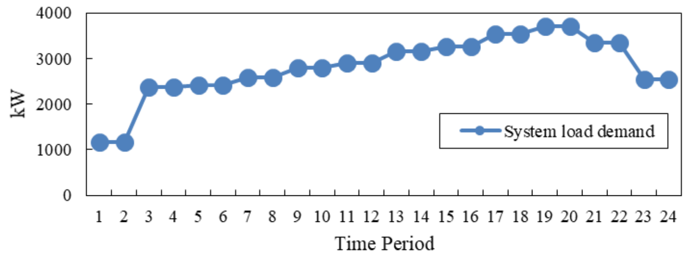
MPS dispatch strategy (case w/o PV generation)

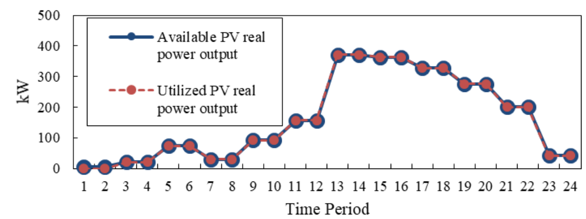
---		Time Period								
		1	2	3	4~5	6	7	8~12	13~14	15~24
MPS	EV 1	node 1	→	node 8		→		node 33	→	node 8
	MESS 1	node 1	→		node 15		→	node 29		
	MEG 1	node 1	→		node 15					

MPS dispatch strategy (case w/ PV generation)

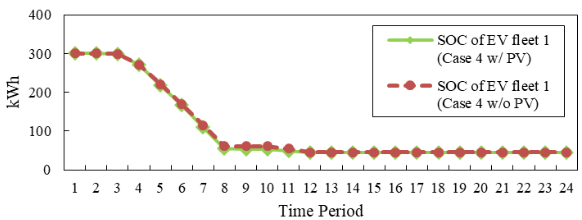
Case Study: MPSs with PV and Repair Strategy

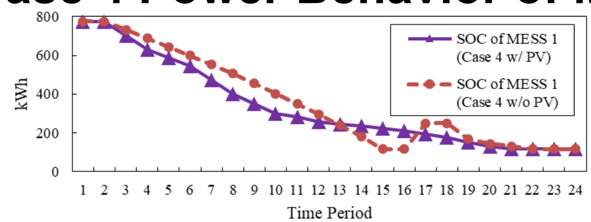
❑ Numerical Results – Output From MPSs

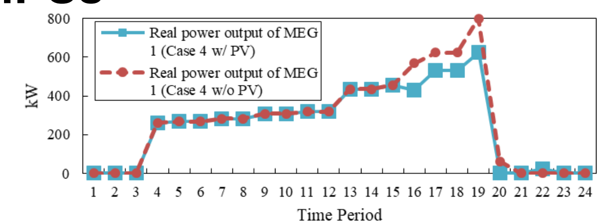




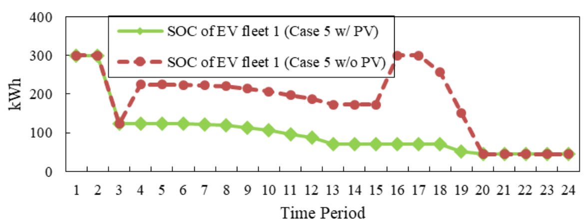
Case 4 Power Behavior of MPSs

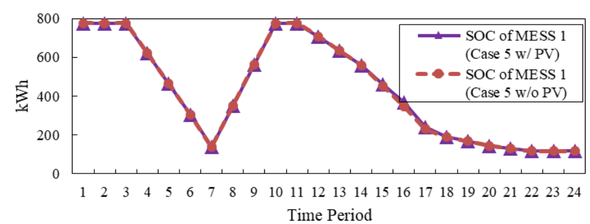


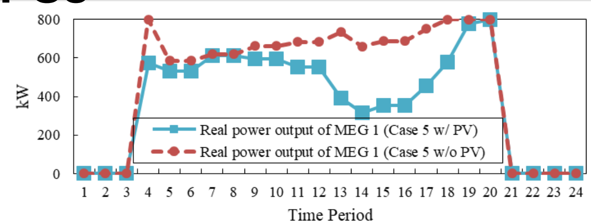




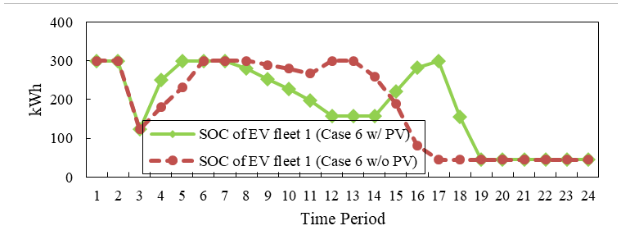
Case 5 Power Behavior of MPSs

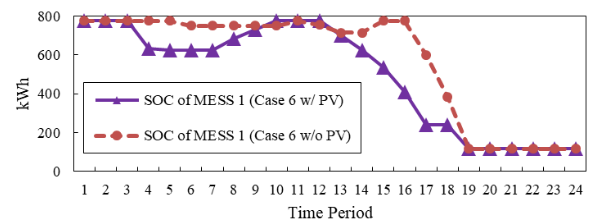


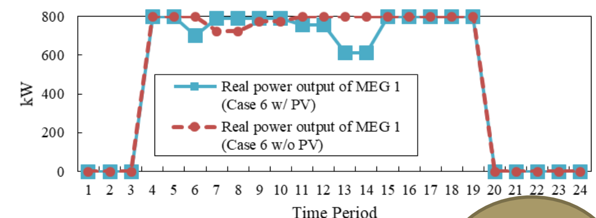




Case 6 Power Behavior of MPSs







Agenda

❑ Conclusion

1. In this research, a model for **deriving mobile power source dispatch strategy** is proposed, it is further extended to **consider PV generation** across the distribution system.
2. The effectiveness of the proposed method is verified in cases with/without PV generation, with different damage scenarios and different repair strategies.
3. The contribution of the proposed method facilitating the restoration is greatly **affected by PV generation**.

Thank You!

If you have any question, please feel free to contact:
mostafa_nazemi@gwu.edu