University of Houston

Department of Electrical
and Computer Engineering

Optimization of Integrated Power Systems with Hydrogen-Based Infrastructure: Strategic Operation, Planning and Benefits Analysis

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July 19, 2024

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Chapter 1
Introduction

Challenges in Renewable Grids

Characteristics of Renewable Energy:
- Uncertainty
- Intermittency

In renewables dominated grids:
- Large transmission capacity is required to transfer renewable energy to the load areas[1].
- Energy storages are required to compensate the renewable generation[2].

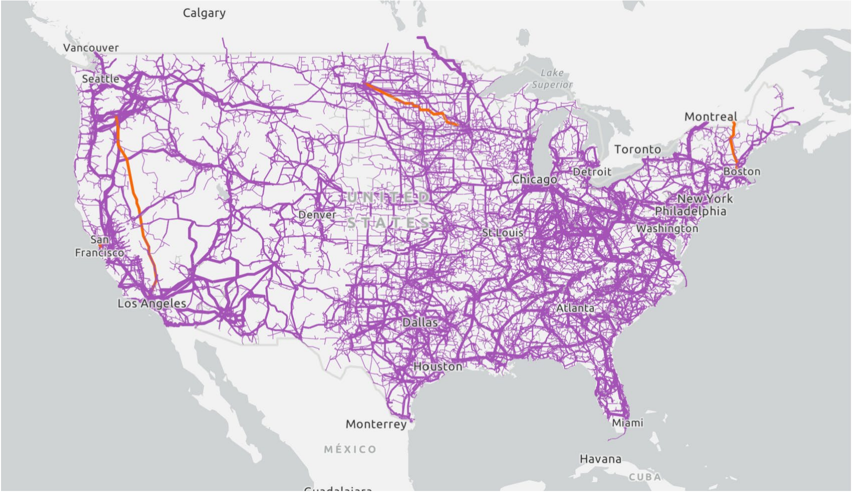


Fig. Transmission Network in United States

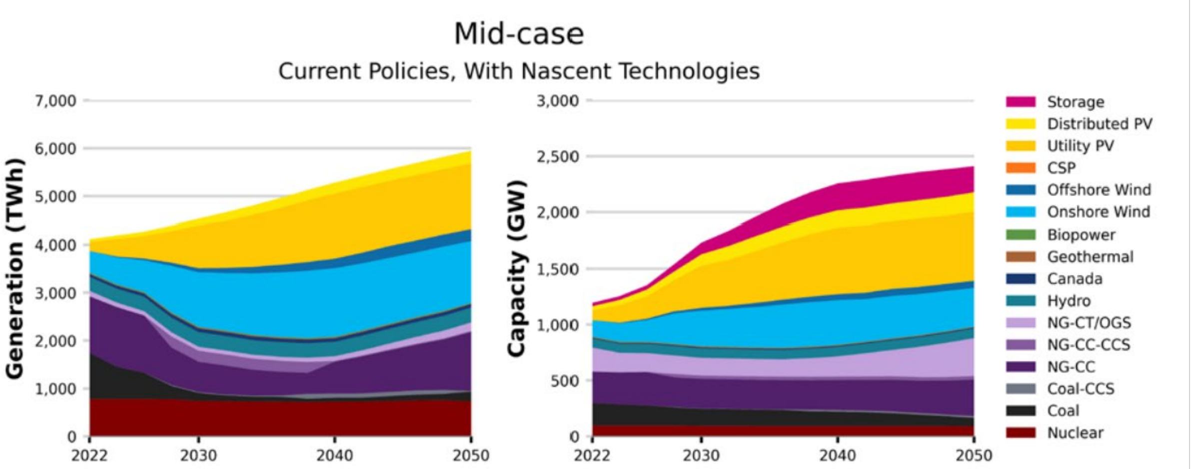


Fig. NREL U.S. Electricity Sector Outlook

Hydrogen storage and transportation can be utilized to enhance the grid ability for energy transmission and storage.

Figure Source: EIA map:
https://atlas.eia.gov/apps/895faaf79d744f2ab3b72f8bd5778e68/explore

[1] Khunitia, Swasti R., et al. "Time-horizons in the planning and operation of transmission networks: an overview." *IET Generation, Transmission & Distribution*

[2] T. Włodek, M. Łaciak, K. Kurowska and Ł. Węgrzyn. "Thermodynamic analysis of hydrogen pipeline transportation – selected aspects," AGH Drilling, Oil, Gas, 2016.

New Trend: Hydrogen in U.S. Power Grids

The Department of Energy (DOE) plans to provide $7 billion for seven regional hydrogen hubs:

- Houston hydrogen Hub: $1.2 billion investment; Use both natural gas with carbon capture and renewables-powered electrolysis.
- Midwest hydrogen hub: $ 1 billion investment; Promote hydrogen use in steel and glass production, power generation, etc.
- California hydrogen expansion: $1.2 billion investment; Scale up production facilities, distribution networks, and refueling stations.

Fig. Existing hydrogen infrastructure in the Gulf Coast region

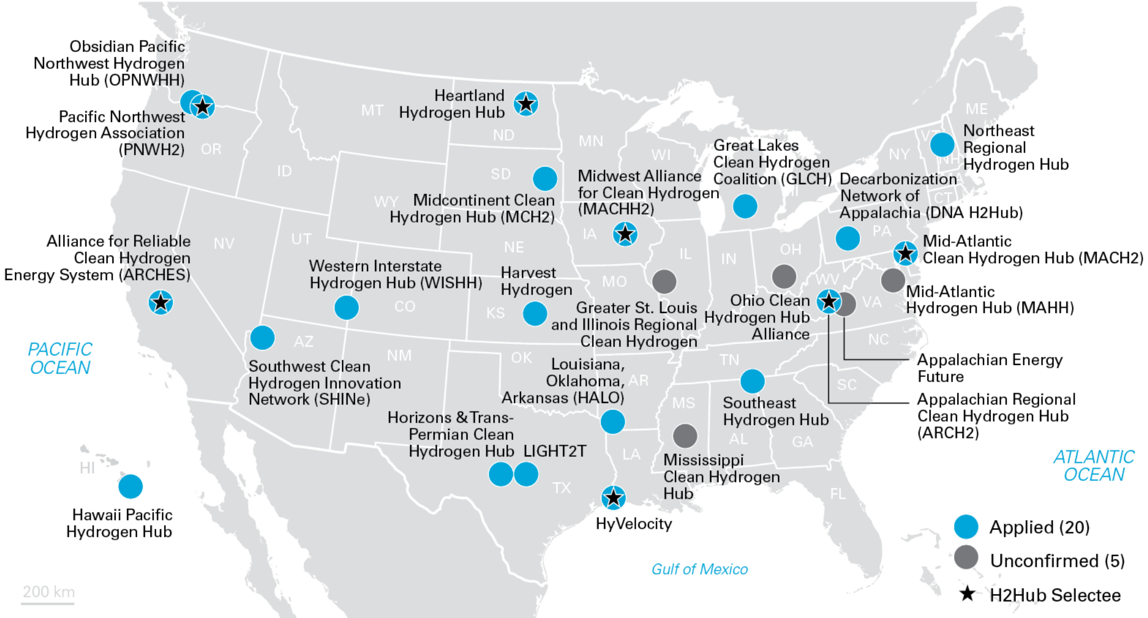


Fig. Map of applicants and proposed hydrogen hubs in U.S.

Figure Source: https://rbnenergy.com/gulf-coast-highway-part-2-the-houston-areas-case-for-becoming-a-doe-backed-hydrogen-hub; https://www.whitecase.com/insight-alert/hydrogen-hub-projects-awarded-7-billion-us-department-energy

Hydrogen Integration with Renewable Grids

Energy Transmission:

Point to point energy transmission in the renewable grids can be realized or enhanced by hydrogen transportation.

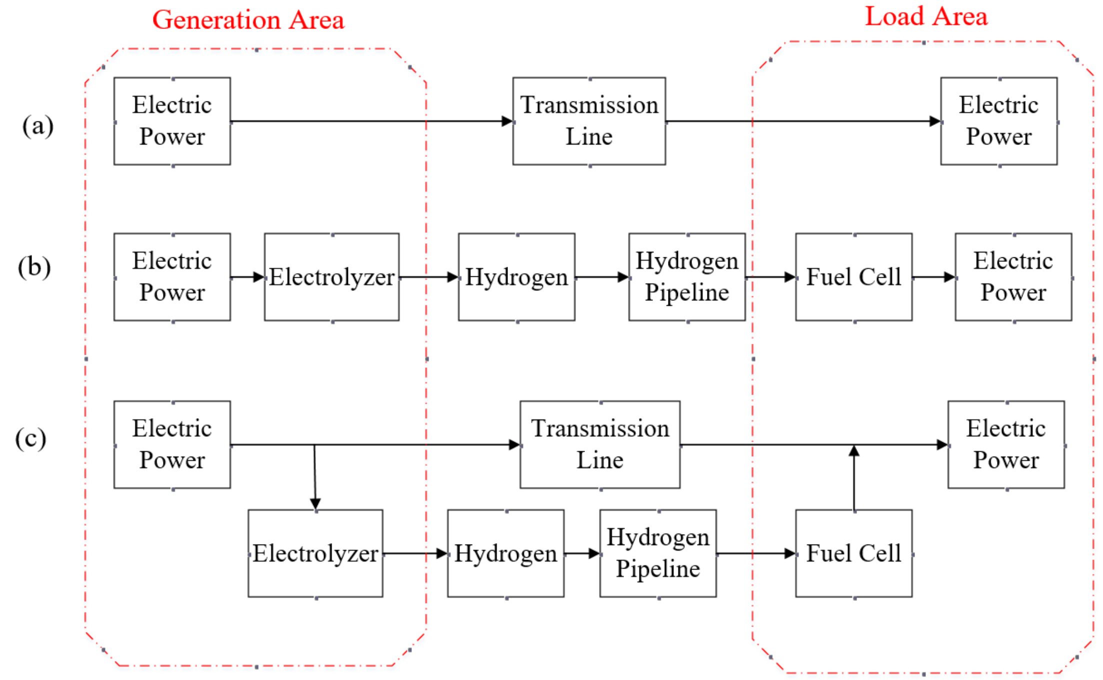


Fig. Different Transmission Configurations: (a) Electrical Transmission (b) Hydrogen Transportation (c) Hybrid Energy Transmission.

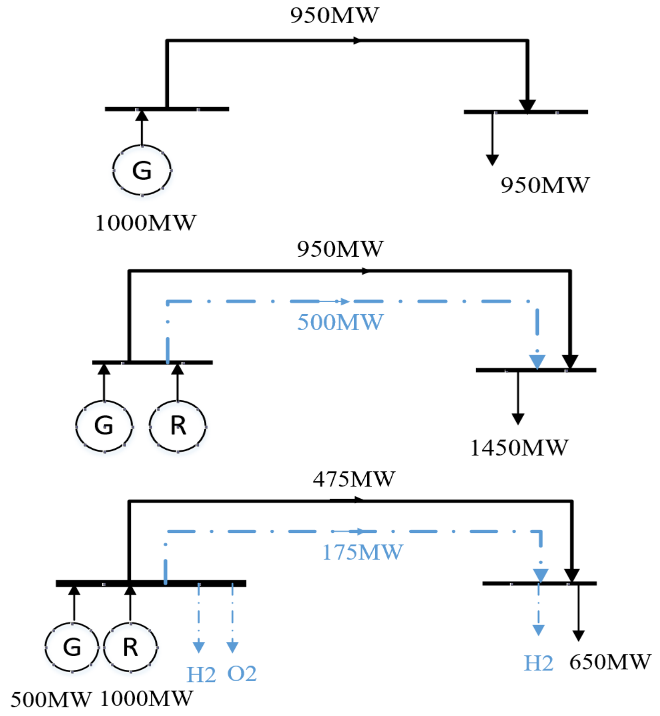


Fig. Example of enhance point to point energy transmission with hydrogen facilities.

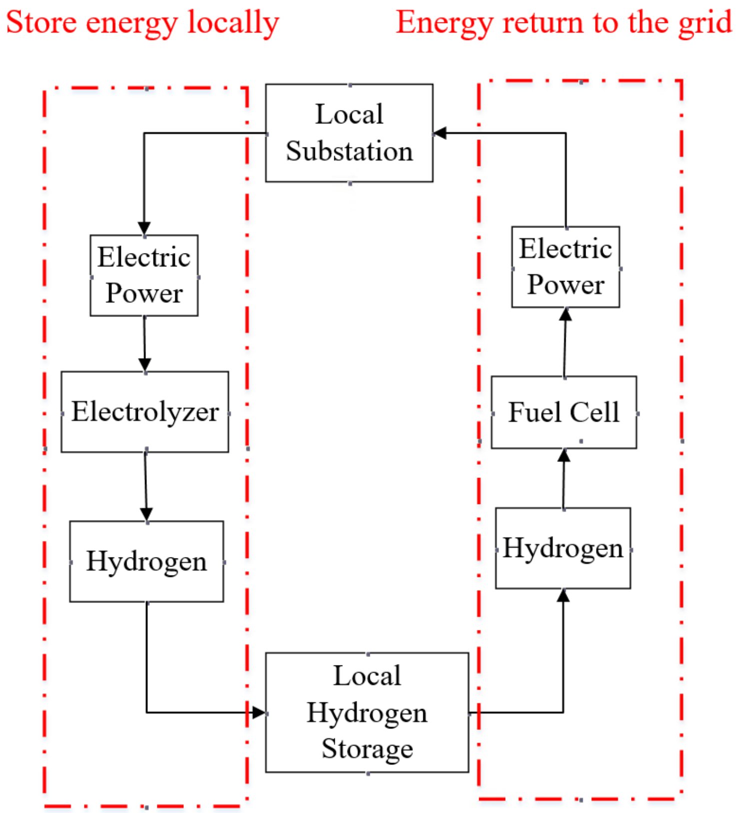
Figures Source: Jin Lu and Xingpeng Li, "Power and Hydrogen Hybrid Transmission for Renewable Energy Systems: An Integrated Expansion Planning Strategy", *Renewable Energy* (under review).

Hydrogen Integration with Electrical Grids

Hydrogen Energy Storage:

Electrical energy can be converted and stored locally to form hydrogen energy hubs.

- Position energy hub close to renewable sources: direct storage of energy, reducing the need for long-distance energy transmission


Store energy locally

Energy return to the grid

Local Substation

Electric Power

Electrolyzer

Hydrogen

Local Hydrogen Storage

Hydrogen

Fuel Cell

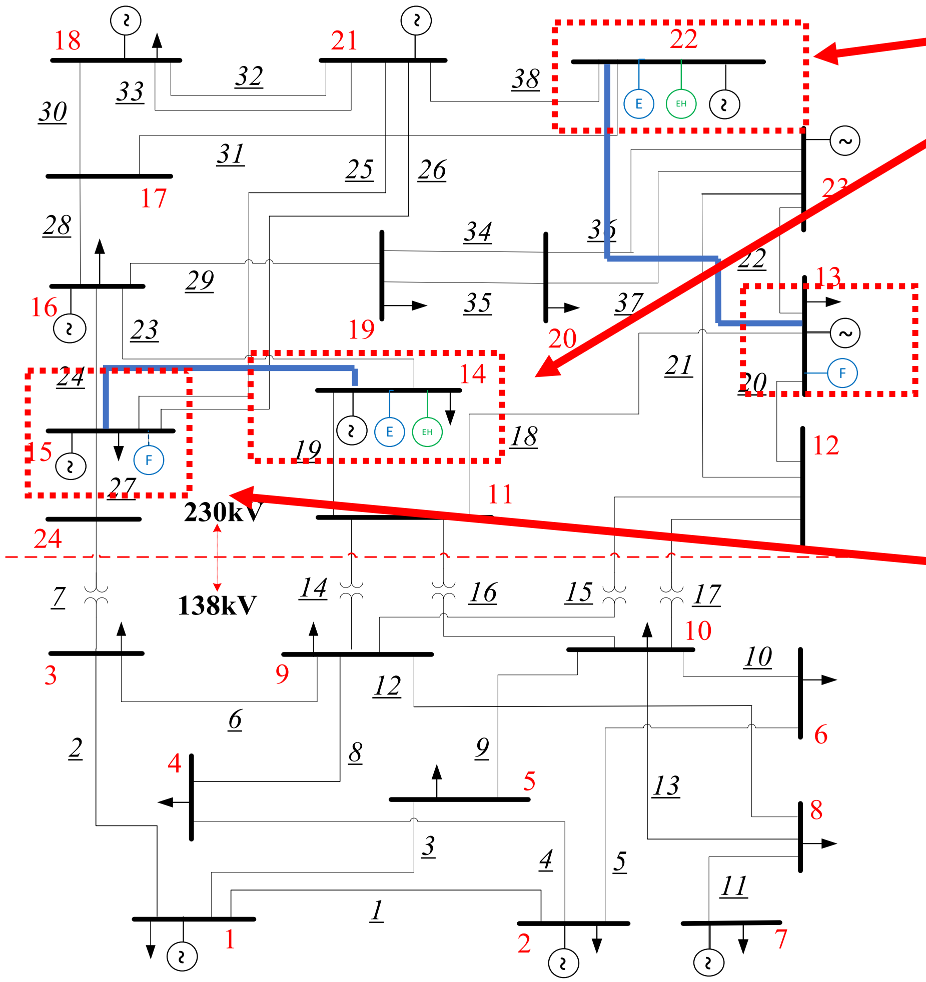
Electric Power

Fig. Local energy exchange using the energy hub / hydrogen hub.

Figure Source: 'Additional $150 million for regional hydrogen hubs'. https://www.energymagazine.com.au/additional-150-million-for-regional-hydrogen-hubs/

Hydrogen Integration with Electrical Grids

Example: Hydrogen transportation and hubs integrated to IEEE 24-bus System



Wind Farm locations.

- The two energy hubs are also located here.
- The terminals (electrolyzer) of hydrogen transportation.

The fuel cells are located on the terminal end of the hydrogen pipelines, where substations with peak loads locate.

n	Branch Index
N	Bus Index
E/F	Electrolyzers/Fuel Cell for Hydrogen Transportation Integration
EH	Energy hubs

Figure Source: Jin Lu and Xingpeng Li, “The Benefits of Hydrogen Energy Transmission and Conversion Systems to the Renewable Power Grids: Day-ahead Unit Commitment”, *54th North American Power Symposium*, Salt Lake City, UT, USA, Oct. 2022.

Contributions and Organization

Daily Operation of Hybrid Grids

- The unit commitment with both hydrogen and electrical constraints
- The optimal grid coordination with hydrogen transportation and energy hubs.

Scheduling of Seasonal Hydrogen Storage

- Determine the annual scheduling of salt caverns.
- The linearized hydrogen inventory equation for seasonal storage

Power System Test Case for Hydrogen Studies

- Facility locations based on footprint of Texas
- Spatio-temporal correlated renewable production and dynamic line rating profiles.

Planning and Expansion of Hybrid Transmission Network

- Consider capital and maintenance costs of hydrogen facilities
- Multi-scenarios for future periods
- Invests in hydrogen facilities

Enhancing Power System Restoration with Fuel Cells

- Consider fuel cells as black start resources
- Restore high quality skeleton network with less restoration time
- Restoration performance comparison

Conclusions & Future Work

Chapter 2
Daily Operation of Hybrid Grids

Security-Constrained Unit Commitment

In power systems, loads typically have daily patterns.

- System operators schedule generators day ahead to meet forecasted demand.

Security Constrained Unit Commitment (SCUC) – Mixed-integer LP problem

- Determine the generator on/off status, output power.
- Find the most economic solution, while maintaining system reliability.

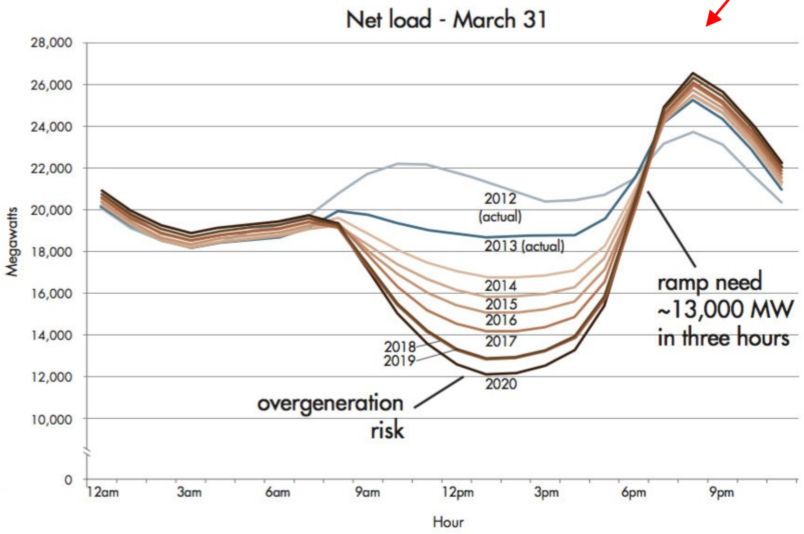
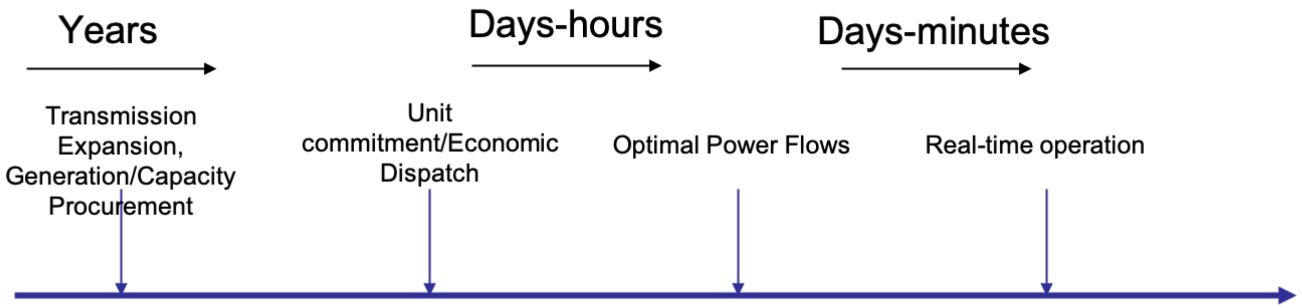


Fig. Daily load demands in CAISO.



Years

Transmission Expansion, Generation/Capacity Procurement

Days-hours

Unit commitment/Economic Dispatch

Optimal Power Flows

Days-minutes

Real-time operation

Fig. Timeline for power system operation and planning.

Figure Source: “California ISO duck curve” https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf
Figure Source: “Power Systems Planning - Methods and Applications.” https://how-to.aimms.com/Articles/510/Energy_modelling.html

Security-Constrained Unit Commitment

Security Constrained Unit Commitment (SCUC) considers:

- Transmission constraints such as power flow, nodal power balance, etc.
- Generation constraints such as maximum generation capacity, ramping rate, reserve, etc.

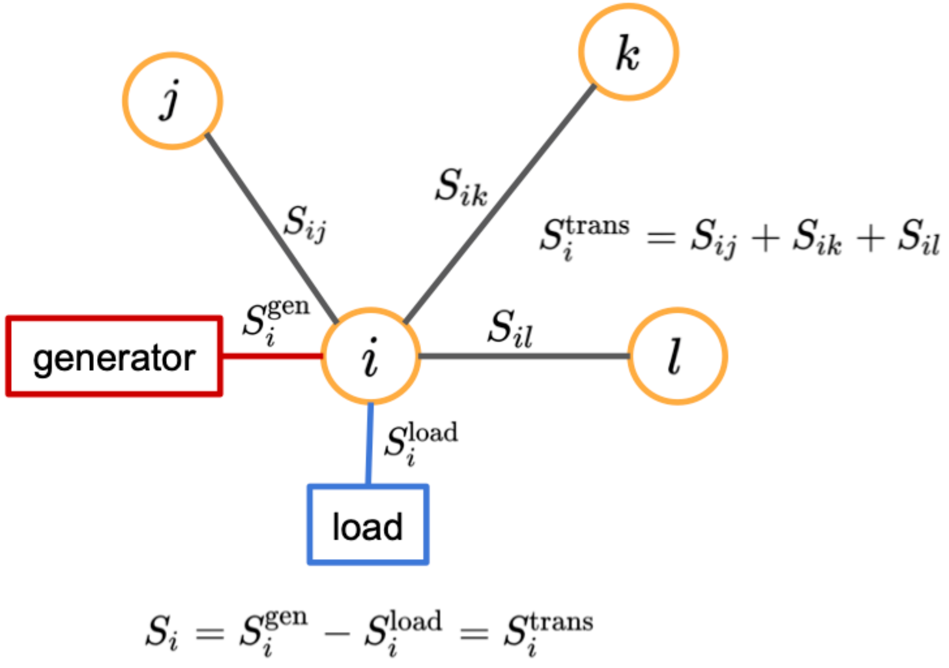


Fig. Power balance of a bus connected to three adjacent buses.

Figure Source: “A Gentle Introduction to Power Flow” https://invenia.github.io/blog/2020/12/04/pf-intro/

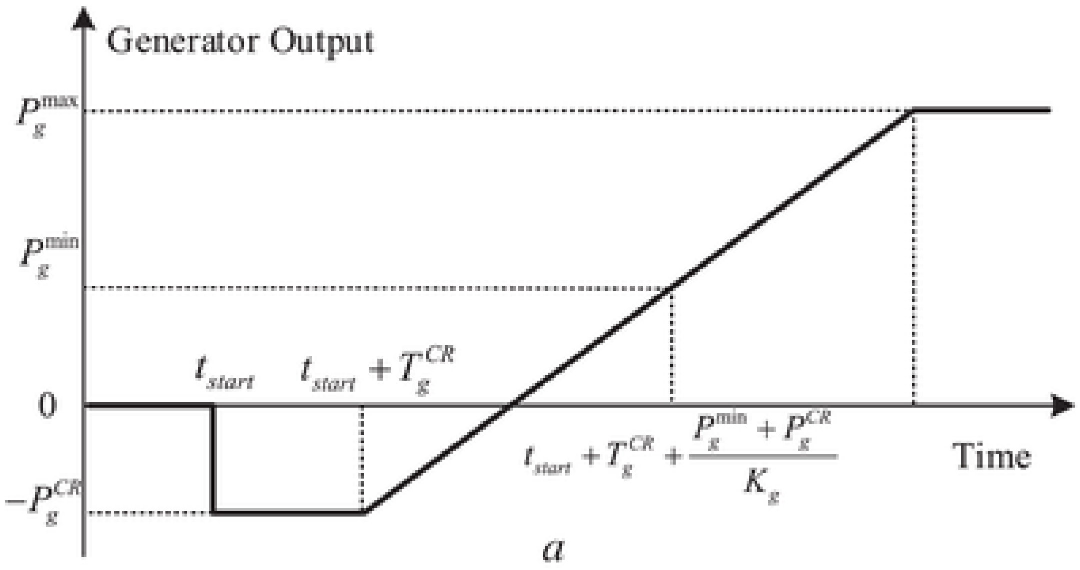


Fig. Typical generator start-up curve.

Figure Source: Y. Bian, Z. Bie, and G. Li, “Proactive repair crew deployment to improve transmission system resilience against Hurricanes,” IET Generation, Transmission & Distribution, vol. 15, no. 5, pp. 870–882, 2020.

Operation Models for Hybrid Grids

Operations for hybrid electric-hydrogen energy grids:

- The amount of hydrogen imported or exported for the **hydrogen storage** for each time period.
- The working power / pressure of **compressors** for hydrogen pipelines.
- On/off status of **fuel cells** and **electrolyzers**.

SCUC for hybrid grids

- Determine operations for both electrical and hydrogen facilities.
- Consider the physical constraints related to hydrogen facilities.

*SCUC: daily scheduling of generator commitment

Operation Models for Hybrid Grids

We developed two SCUC models, which are customized for grids integrated with hydrogen facilities:

- Hybrid energy transmission -- Energy transmission between locations
- Energy hub -- Local energy storage

Constraints for hydrogen facilities:

- The power limits for electrolyzers and fuel cells
- The efficiency of electrolyzers and fuel cells
- Hydrogen flow equation
- Etc.

Constraints differs based on the hydrogen integration methods

*SCUC: daily scheduling of generator commitment

Operation Models for Hybrid Grids

For hydrogen transportation-integrated grids:

The hydrogen stored in the pipeline:

$$E_t = E_{t-1} + \sum_{e \in E} \eta_e P_{et} - \sum_{f \in F} P_{ft}/\eta_f \, , \qquad \forall t$$

The hydrogen storage limit for hydrogen pipeline: $0 \leq E_t \leq E^{max}, \forall t$

For energy hubs-integrated grids:

The hydrogen stored in each energy hub are calculated separately:

$$E_{nt} = E_{n,t-1} + \sum_{e \in E(n)} \eta_e P_{et} - \sum_{f \in F(n)} P_{ft}/\eta_f \quad \forall n \in N^H, t$$

The hydrogen energy storage limit at each energy hub:

$$0 \leq E_{nt} \leq E_{nt}^{max}, \qquad \forall n \in N^H, t$$

Model of Hydrogen Facilities

The key points for incorporating hydrogen facilities in SCUC:

- The electricity consumed or generated at the electrolyzers and fuel cell locations.
- The hydrogen stored in the hydrogen pipelines / energy hubs must be modeled.
  - Give optimal electrical-hydrogen conversion schedule, for each hydrogen pipeline and hub per time interval.

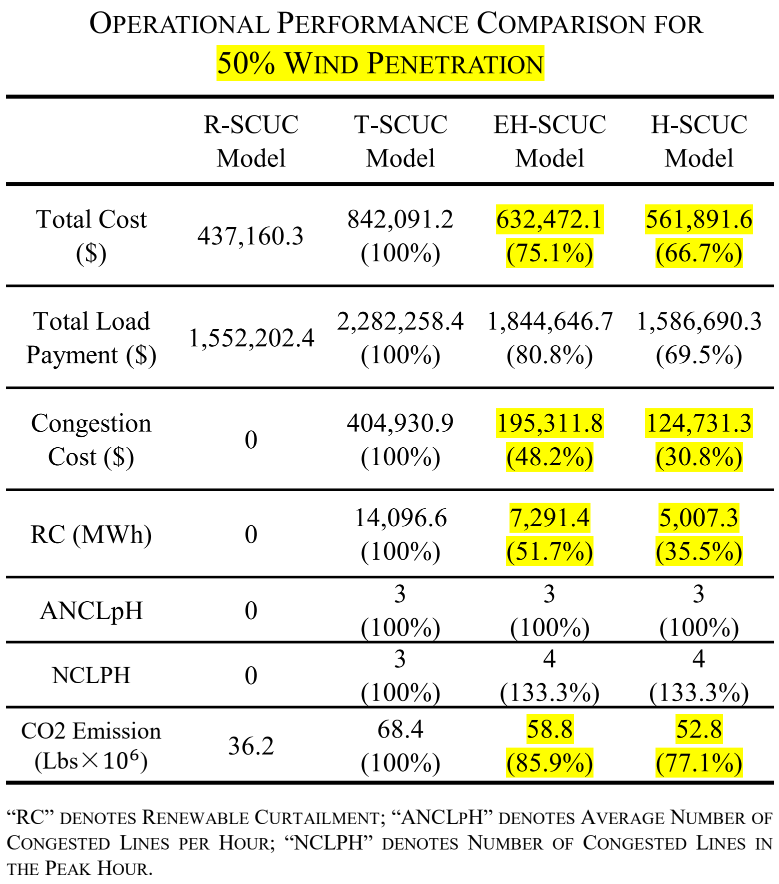
Four SCUC models for simulations:

- H-SCUC: Hydrogen transportation-integrated grids
- EH-SCUC: Energy hubs-integrated grids
- T-SCUC: Traditional model with no hydrogen integration
- R-SCUC: Assumes no network congestions

*SCUC: daily scheduling of generator commitment

Benefit Analysis for Daily Operation

The SCUC models are conducted on the IEEE 24-bus system for various wind penetration scenarios.



OPERATIONAL PERFORMANCE COMPARISON FOR 50% WIND PENETRATION

	R-SCUC Model	T-SCUC Model	EH-SCUC Model	H-SCUC Model
Total Cost ($)	437,160.3	842,091.2 (100%)	632,472.1 (75.1%)	561,891.6 (66.7%)
Total Load Payment ($)	1,552,202.4	2,282,258.4 (100%)	1,844,646.7 (80.8%)	1,586,690.3 (69.5%)
Congestion Cost ($)	0	404,930.9 (100%)	195,311.8 (48.2%)	124,731.3 (30.8%)
RC (MWh)	0	14,096.6 (100%)	7,291.4 (51.7%)	5,007.3 (35.5%)
ANCLpH	0	3 (100%)	3 (100%)	3 (100%)
NCLPH	0	3 (100%)	4 (133.3%)	4 (133.3%)
CO2 Emission (Lbs × 10^6)	36.2	68.4 (100%)	58.8 (85.9%)	52.8 (77.1%)

"RC" DENOTES RENEWABLE CURTAILMENT; "ANCLPH" DENOTES AVERAGE NUMBER OF CONGESTED LINES PER HOUR; "NCLPH" DENOTES NUMBER OF CONGESTED LINES IN THE PEAK HOUR.

When wind penetration level is lower than 10%, the performance of EH-SCUC/H-SCUC and T-SCUC is similar.

At 50% wind penetration level, the SCUCs for hybrid grids can bring more benefits:

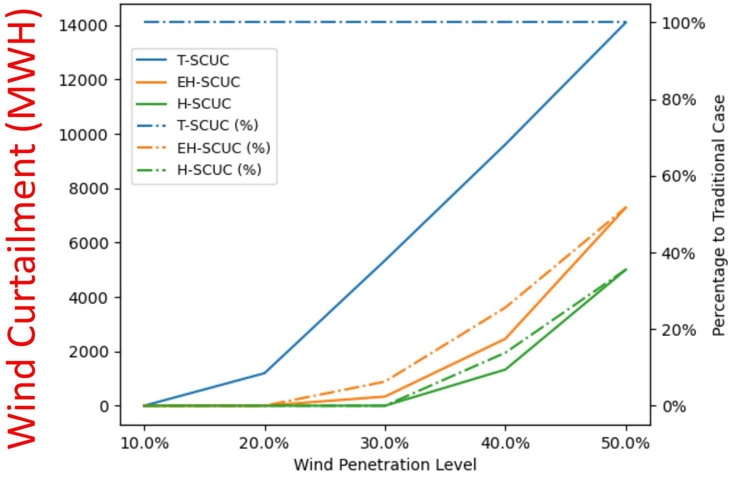
- The cost reduction is 25-35%. Specifically, the congestion cost reduced by 50%-70%.
- Renewable curtailment reduced by 50%-70%.
- CO2 emission reduced by 40%-50%.

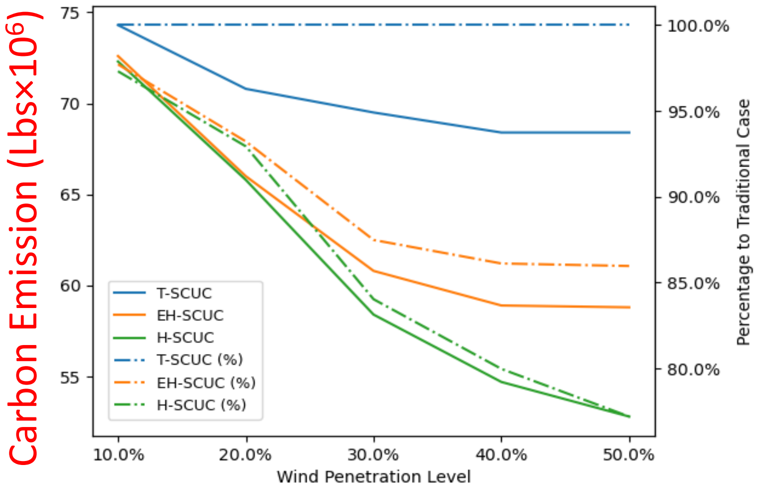
Generator costs data: X. Li, A. S. Korad, and P. Balasubramanian, "Sensitivity Factors based Transmission Network Topology Control for Violation Relief," in IET Generation, Transmission & Distribution, July 2020.

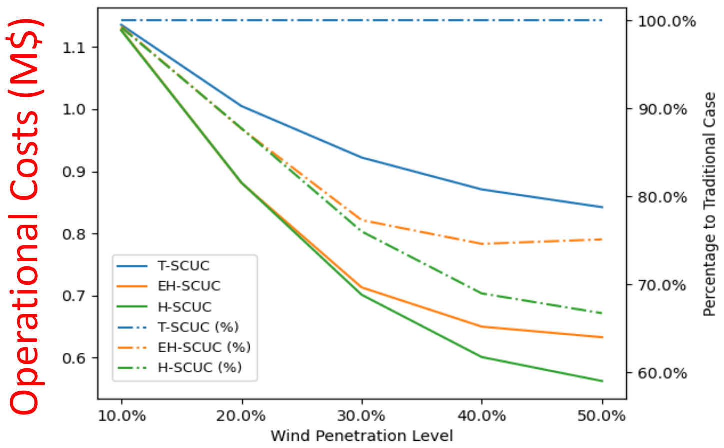
CO2 Emission data: C. Grigg et al., "The IEEE Reliability Test System-1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee," in IEEE Transactions on Power Systems, vol. 14, no. 3, pp. 1010-1020, Aug. 1999.

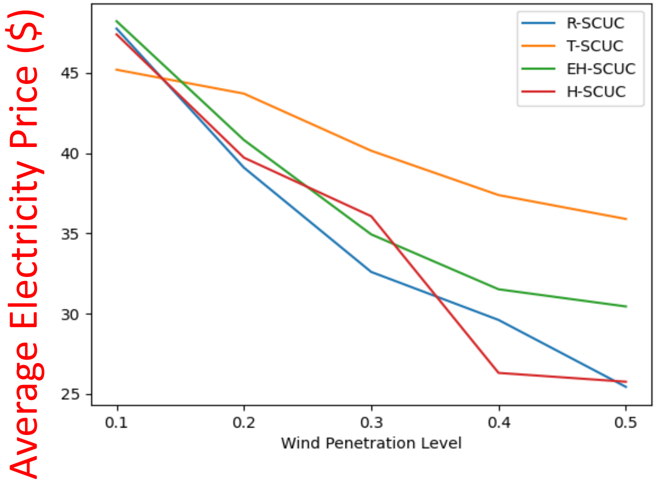
Benefit Analysis for Daily Operation

The H-SCUC/EH-SCUC can reduce the wind curtailment, carbon emission, operational costs, and electricity prices, especially when renewable penetration is high.









Site Selection for Fuel Cells (Hydrogen Pipeline Terminal)

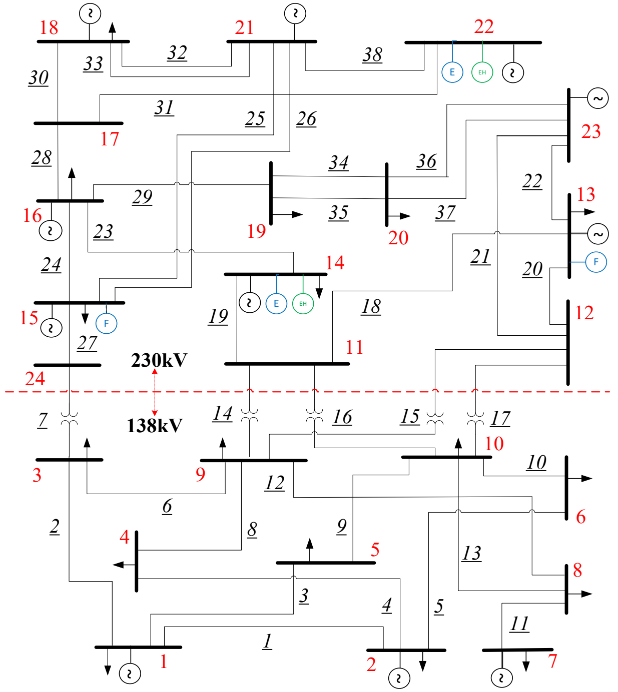
We further study the suitable locations for fuel cells, which is on the terminal end of the hydrogen pipeline, to generate electricity.

Three types of locations are studied:

(i) Fuel cells are located at the high-loaded buses.

(ii) Fuel cells are located at the center of load area.

(iii) Fuel cells are located at the bridges between generation area and load area.



Notes: IEEE 24-bus consists two voltage areas: 138kV area and 230kV area. Most generators located in the 230kV area. More loads located in the 138kV area.

For site selection (i), Bus 13 and Bus 15 are selected where peak loads are over 200 MWh.

For site selection (ii), Bus 4 and Bus 5 are selected.

For site selection (ii), Bus 9 and Bus 10.

Site Selection for Fuel Cells (Hydrogen Pipeline Terminal)

Different fuel cell site selections can result in 10.1% various in wind curtailment, and 2.7% various in total costs.

- The fuel cells locates in the center load or bridge area can have more benefits.

Wind Curtailment of Different Fuel Cell Site Selection Cases under Different Wind Penetration Levels

	10% Wind (MWh)	20% Wind (MWh)	30% Wind (MWh)	40% Wind (MWh)	50% Wind (MWh)
EH-coupled Case (Benchmark)	0	0	335.8 (100%)	2544.5 (100%)	7291.4 (100%)
Site Selection 1	0.0	0.0	0.0	1331.8 (52.3%)	5007.3 (68.6%)
Site Selection 2	0.0	0.0	0.0	1332.7 (52.3%)	4270.8 (58.5%)
Site Selection 3	0.0	0.0	0.0	1339.1 (52.6%)	4303.2 (59.0%)

Total Cost of Different Fuel Cell Site Selection Cases

	10% Wind	20% Wind	30% Wind	40% Wind	50% Wind
EH-coupled Case (Benchmark)	\$1.128M (100%)	\$0.882M (100%)	\$0.712M (100%)	\$0.651M (100%)	\$0.632M (100%)
Site Selection 1	\$1.126M (99.8%)	\$0.881M (99.9%)	\$0.700M (98.3%)	\$0.600M (92.0%)	\$0.561M (88.8%)
Site Selection 2	\$1.126M (99.8%)	\$0.880M (99.8%)	\$0.699M (98.1%)	\$0.597M (91.6%)	\$0.549M (86.8%)
Site Selection 3	\$1.126M (99.8%)	\$0.881M (99.8%)	\$0.700M (98.2%)	\$0.594M (91.1%)	\$0.544M (86.1%)

Contributions

We developed the daily operation models for hybrid grids integrated with: (i) hydrogen transportation (H-SCUC); (ii) energy hubs (EH-SCUC)

The developed models enable the coordination of both hydrogen and electrical facilities in the daily operation.

The models enable precise and numerical benefit analysis of the hydrogen integration on the daily basis.

Publication:

Jin Lu and Xingpeng Li, “The Benefits of Hydrogen Energy Transmission and Conversion Systems to the Renewable Power Grids: Day-ahead Unit Commitment”, *54th North American Power Symposium*, Oct. 2022.

Chapter 3

Scheduling of Seasonal Hydrogen Storage

Salt Caverns for Seasonal Storage

Why long-term energy storage can benefit the renewable grids?

- The renewable productions and loads have various patterns for different seasons.

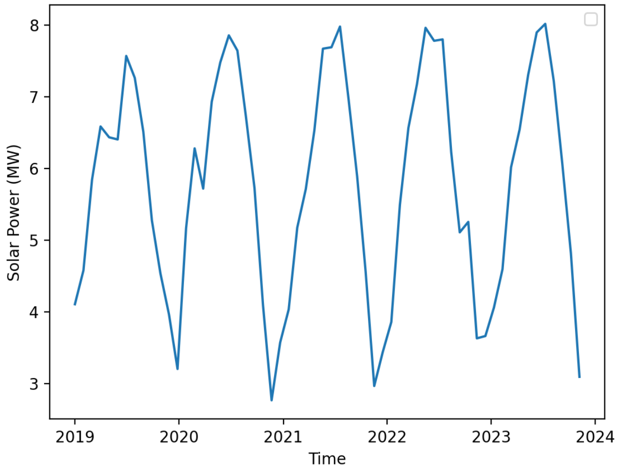


Fig. Monthly Averaged Solar Production at a Solar Plant.

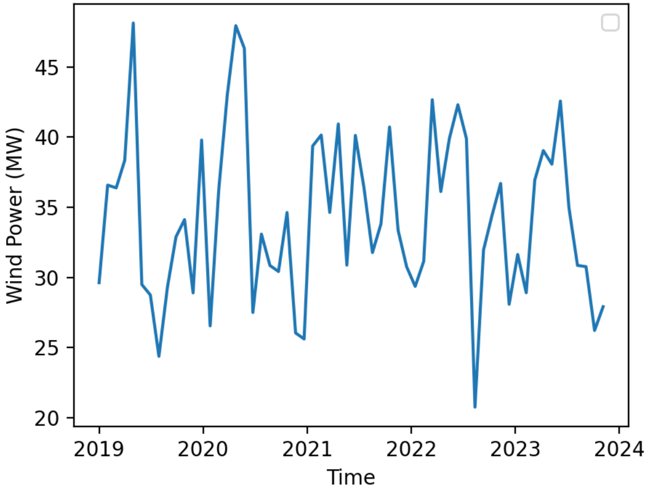


Fig. Monthly Averaged Wind Production at a Wind Plant.

The seasonal storage can provide the long-term temporal flexibility for the renewable production and loads balance.

Figure Source: Jin Lu and Xingpeng Li, “Transmission Planning for Climate-impacted Renewable Energy Grid: Data Preparation, Model Improvement, and Evaluation”, *Journal of Modern Power Systems and Clean Energy* (Accepted).

Salt Caverns for Seasonal Storage

How to utilize the seasonal hydrogen storage?

We developed annual scheduling model (ASM):

- Schedule the hydrogen import or export from the salt cavern for the entire year.
- Determine the operating points of fuel cells and electrolyzers for salt cavern-based hydrogen energy storage system.

(Similar to the energy hub, the full cells and electrolyzers are used for electrical-hydrogen conversion between the salt caverns and electrical grids.)

Salt Caverns

A form of underground storage, have been identified as a potentially efficient and economical option for storing large volumes of hydrogen.

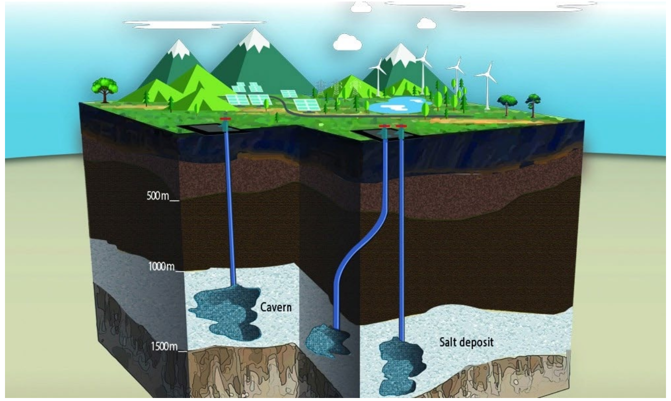


Figure Source: “Why Salt Is This Power Plant’s Most Valuable Asset” https://www.smithsonianmag.com/innovation/salt-power-plant-most-valuable-180964307/ ; “Underground natural gas storage in salt caverns and the challenge of hydrate formation” https://as-schneider.blog/2021/12/09/natural-gas-storage-in-salt-caverns-and-the-challenge-of-hydrate-formation/

Linearized Hydrogen Inventory Equation

Goal: Minimize the total cost over the year, while maintaining the grid reliability when coordinating electrical and hydrogen facilities.

To determine the hydrogen import/export from the salt cavern:

- The amount of hydrogen should be modeled for each hour, day and season.

Our developed annual scheduling model (ASM) is designed as a mixed-integer linear programming (MILP) problem.

  - Get the solution in limited time, while considering lots of constraints

Thus, we developed the linearized hydrogen inventory equation.

Linearized Hydrogen Inventory Equation

The equation can calculate the hydrogen E_{nqtd} stored at bus n at time interval t for day d in Quarter q.

$$E_{nqtd} = \boxed{E^{0}_{n,q}} + \boxed{\sum_{t' \in T^D} \left(\sum_{e \in E(n)} \eta_e P_{eqt'} - \sum_{f \in F(n)} P_{fqt'}/\eta_f \right) * (d-1)} + \boxed{\sum_{t'' \in T^P(t)} \left(\sum_{e \in E(n)} \eta_e P_{eqt''} - \sum_{f \in F(n)} P_{fqt''}/\eta_f \right)}$$

$$\forall g, q, t, d$$

Initial Hydrogen Stored at the Start of the Quarter

Total hydrogen energy generated or consumed in previous days of the quarter

Accumulated hydrogen energy generated or consumed in previous hours of the day

T^D -- Set of time periods in a day for previous daily stored hydrogen calculation.
$T^P(t)$ -- Set of time periods in a day before period t.

Scheduling Model for Hydrogen Storage

The intra-day electrical-hydrogen energy exchange constraints are included in the typical daily operation of annual scheduling model (ASM).

- The fluctuation of the renewables such as solar power can be mitigated.

The cross-season electrical-hydrogen exchange can be captured using the linearized hydrogen inventory equation in ASM.

Other considerations formulated in ASM:

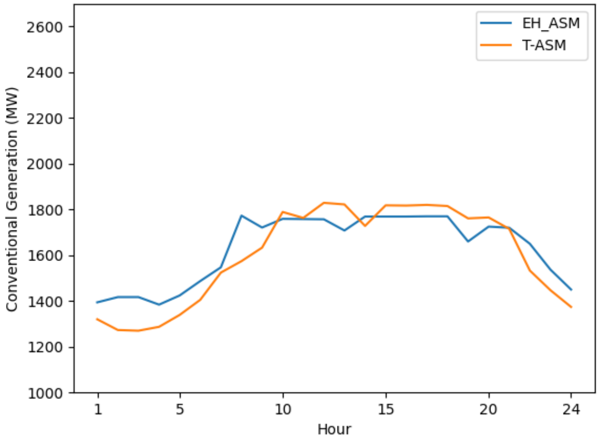
- The amount of hydrogen inventory has consistency between seasons.
- We assume the inventory of hydrogen is the same at the beginning and end of the year.

Scheduling Model for Hydrogen Storage

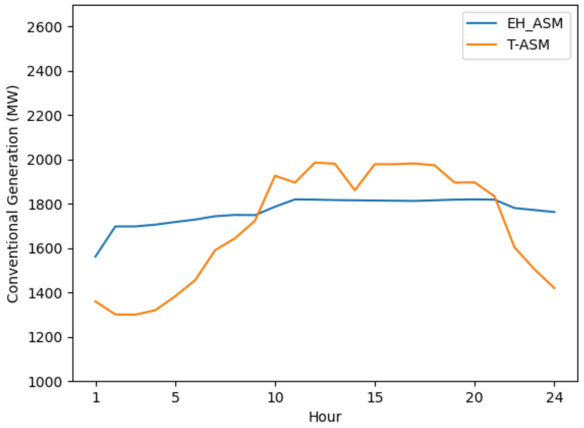
Multi-scenarios of daily operations for different seasons are considered in the ASM.

- Each scenario has different loads, available renewable generation, dynamic line ratings.
- The models contains physical constraints for each scenario.

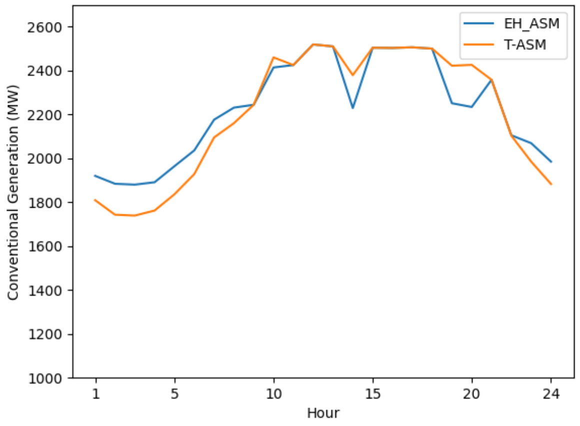
- Our developed ASM with hydrogen storage (EH-ASM) reduces the output of thermal generators compared with traditional operation strategy (T-ASM).



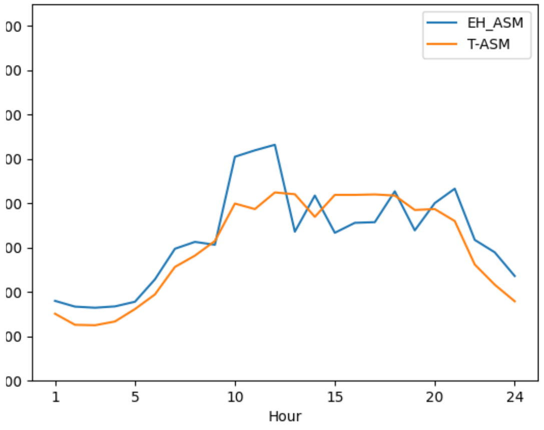
Quarter I



Quarter II



Quarter III



Quarter IV

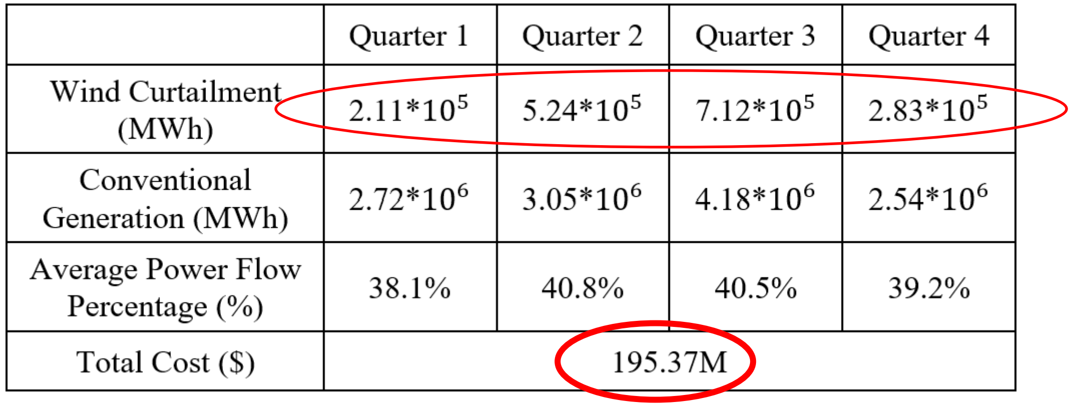
The thermal generation reduced substantially in Quarter II.

*ASM: Annual hydrogen storage scheduling model

Annual Benefit Analysis of Seasonal Hydrogen Storage

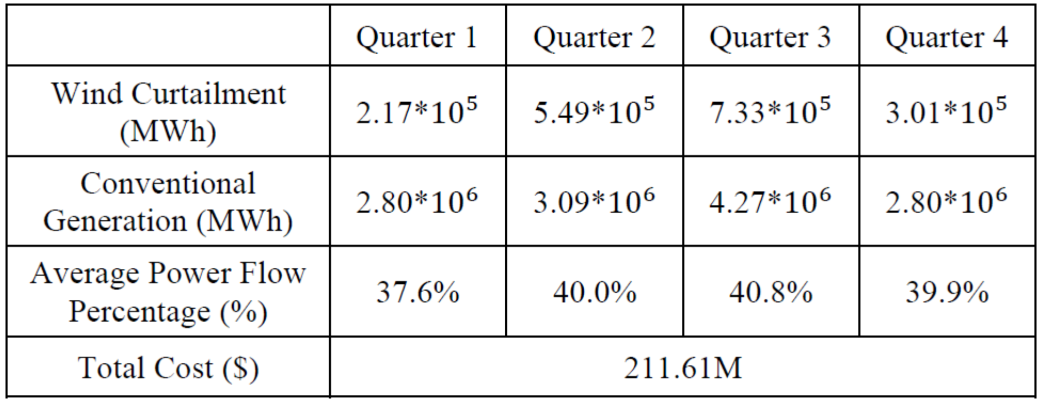
The round-trip efficiency of electrical-hydrogen exchange is about 37%[1,2,3].
The simulations for 37% round-trip efficiency at 50% wind penetration level are conducted:

EH-ASM Simulation Results at 50% Wind Penetration Level



	Quarter 1	Quarter 2	Quarter 3	Quarter 4
Wind Curtailment (MWh)	$2.11*10^5$	$5.24*10^5$	$7.12*10^5$	$2.83*10^5$
Conventional Generation (MWh)	$2.72*10^6$	$3.05*10^6$	$4.18*10^6$	$2.54*10^6$
Average Power Flow Percentage (%)	38.1%	40.8%	40.5%	39.2%
Total Cost ($)	195.37M			

T-ASM Simulation Results at 50% Wind Penetration Level



	Quarter 1	Quarter 2	Quarter 3	Quarter 4
Wind Curtailment (MWh)	$2.17*10^5$	$5.49*10^5$	$7.33*10^5$	$3.01*10^5$
Conventional Generation (MWh)	$2.80*10^6$	$3.09*10^6$	$4.27*10^6$	$2.80*10^6$
Average Power Flow Percentage (%)	37.6%	40.0%	40.8%	39.9%
Total Cost ($)	211.61M			

- The total cost reduction with developed EH-ASM is 7.6% as compared to the benchmark T-ASM.

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[1] IRENA, “Hydrogen from Renewable Power: Technology Outlook for the Energy Transition,” 2018.
[2] Hydrogen and Fuel Cell Technologies Office, “Hydrogen Storage,” Energy.gov.
[3] M. A. Semeraro, “Renewable energy transport via hydrogen pipelines and HVDC transmission lines,” Energy Strategy Reviews, vol. 35, 2021.

*EH-ASM: Annual hydrogen storage scheduling with energy hub

Contribution

We developed an annual scheduling model (ASM) which can schedule the optimal daily hydrogen exchange operations for different seasons of the whole year.

We developed the linearized hydrogen inventory equation, which can be utilized in other linear programming strategies for seasonal hydrogen storage applications.

The developed EH-ASM can reduce the total annual costs by 7.67%, at common hydrogen conversion efficiency (37% round-trip).

Publication:

Jin Lu and Xingpeng Li, “Annual Benefit Analysis of Integrating the Seasonal Hydrogen Storage into the Renewable Power Grids”, *IEEE PES General Meeting*, Orlando, Florida, USA, Jul. 2023.

Chapter 4

Power System Test Case for Hydrogen Studies

Test Case Requirement for Hydrogen Studies

Detailed technical parameters on generation and transmission facilities.

- To achieve accurate numerical results in simulation-based studies of hydrogen integration.

Renewable-enriched system with **spatio-temporal correlated profiles**.

- Hydrogen facilities are crucial for addressing issues caused by high penetration of renewables.
- High-resolution and realistic renewable production profiles are essential for this purpose.

Accurate **grid prospection** and future profiles creation.

- Accurate future scenarios of the power system must be built to ensure correct and reliable assumptions for the future application of hydrogen.

Texas 123-bus backbone transmission System

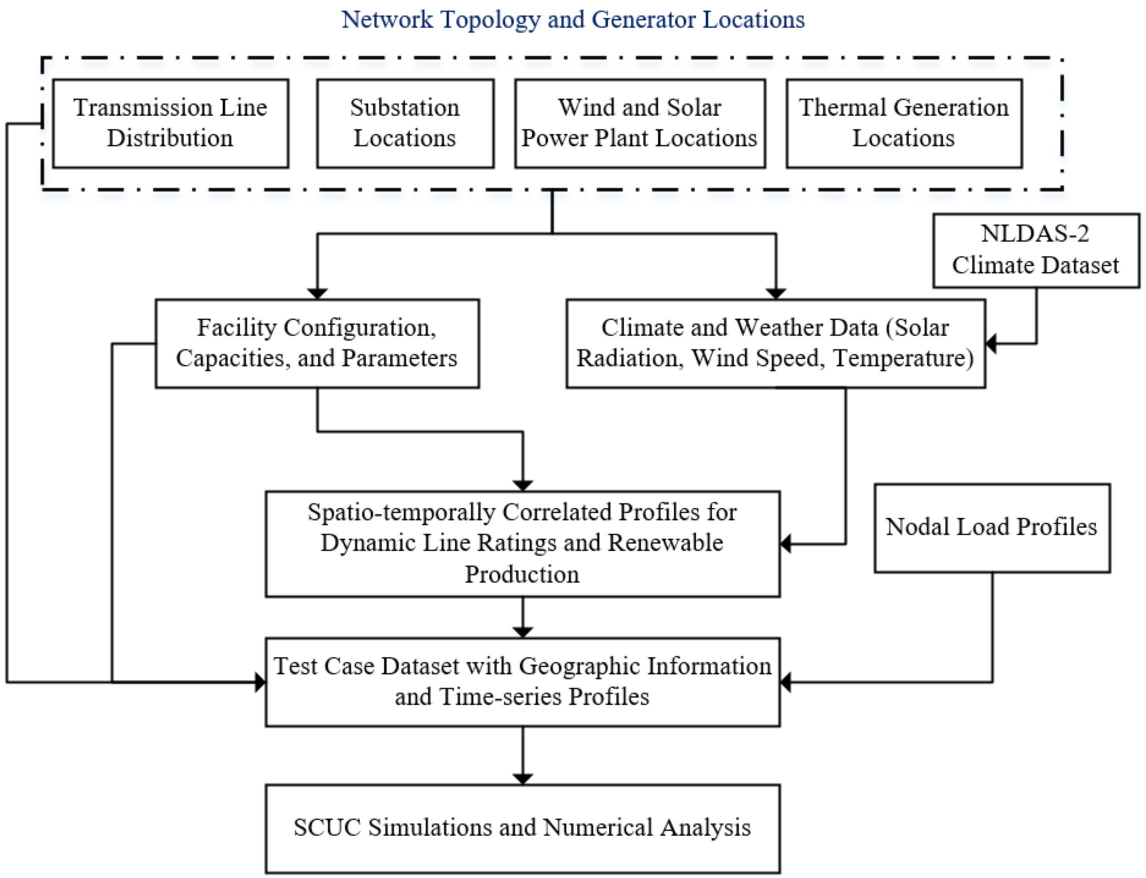
We created the Texas 123-bus backbone transmission (TX-123BT) test case.

- Based on the footprint of Texas, providing locations of substations, renewable power plants etc.
- Spatio-temporal correlated profiles for solar & wind production, dynamic line ratings.
- Current and future profiles, as well as representative profiles for scenario-based simulations.

Fig. Texas 123-bus transmission network topology.

Figure Source: Jin Lu, Xingpeng Li, Hongyi Li, Taher Chegini, Carlos Gamarra, Y. C. Ethan Yang, Margaret Cook, and Gavin Dillingham, “A Synthetic Texas Power System with Time-Series High-Resolution Weather-Dependent Spatio-Temporally Correlated Grid Profiles”, IEEE Transactions on Power Systems (under review).

System Design Workflow and Profile Scenarios


Network Topology and Generator Locations

Transmission Line Distribution

Substation Locations

Wind and Solar Power Plant Locations

Thermal Generation Locations

NLDAS-2 Climate Dataset

Facility Configuration, Capacities, and Parameters

Climate and Weather Data (Solar Radiation, Wind Speed, Temperature)

Spatio-temporally Correlated Profiles for Dynamic Line Ratings and Renewable Production

Nodal Load Profiles

Test Case Dataset with Geographic Information and Time-series Profiles

SCUC Simulations and Numerical Analysis

Fig. Texas 123-bus backbone transmission (TX-123BT) test case creation workflow.

Develop weather-dependent profiles based on facility configurations and weather data

- Hourly profiles for 2017-2021 created utilizing historical weather data from North American Land Data Assimilation System Phase 2 (NLDAS-2).
- 3-Hour resolution profiles for 2020-2050 created utilizing weather data from Coupled Model Intercomparison Project Phase 6 (CIMP6).
- SCUC simulations for validation.

Figure Source: Jin Lu, Xingpeng Li, Hongyi Li, Taher Chegini, Carlos Gamarra, Y. C. Ethan Yang, Margaret Cook, and Gavin Dillingham, “A Synthetic Texas Power System with Time-Series High-Resolution Weather-Dependent Spatio-Temporally Correlated Grid Profiles”, IEEE Transactions on Power Systems (under review).

Infrastructure Details and Profiles Creation

- Generation fuel mix; Capacity and locations of different type of power plants.
- Thermal generator start-up and operation costs; Ramping rate, start-up and shutdown time.
- Dynamic Line rating calculation using IEEE Std 738-2012.

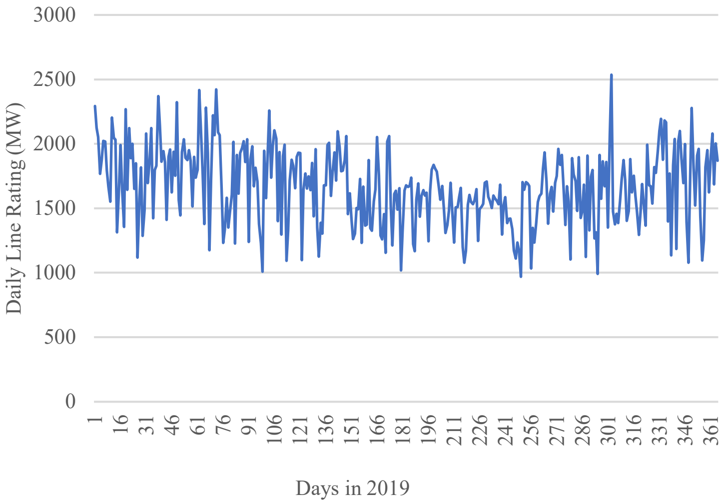


Fig. The daily thermal ratings of line 15 during the year 2019

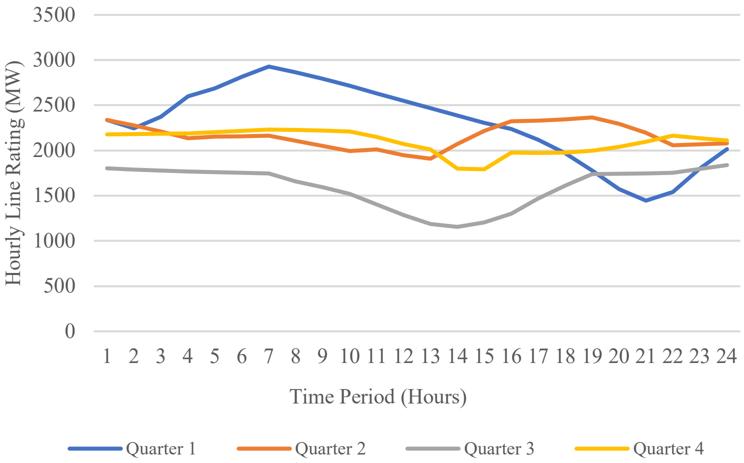


Fig. Hourly ratings of line 15 in four typical days for different quarters.

Infrastructure Details and Profiles Creation

<u>Weather-dependent renewable production model:</u>

- Wind turbine production equation; Wind speed estimation using log profiles.
- Least square method for more accurate wind power plant profile creation.
- Solar production: Five-parameter single diode equivalent circuit; Maximum power point equation.

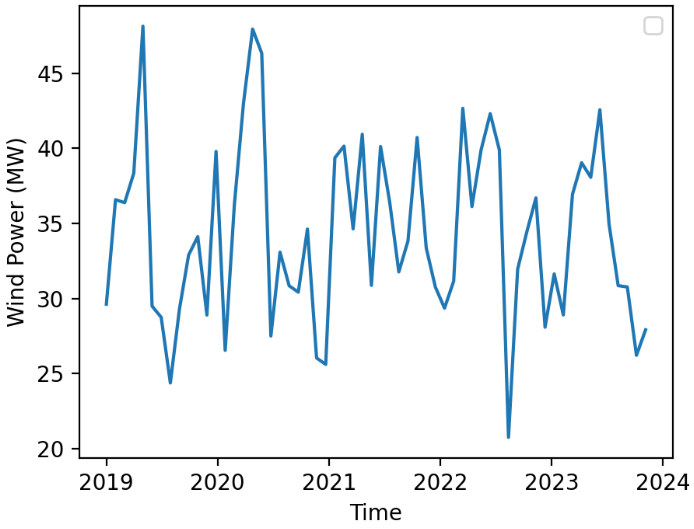


Fig. Monthly Averaged Wind Production at Wind Plant 72.

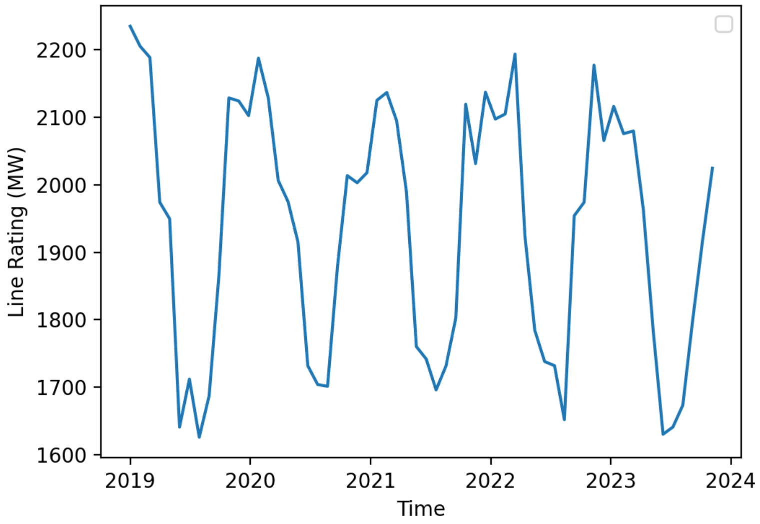


Fig. Plot of the Averaged Dynamic Line Rating at Line 1.

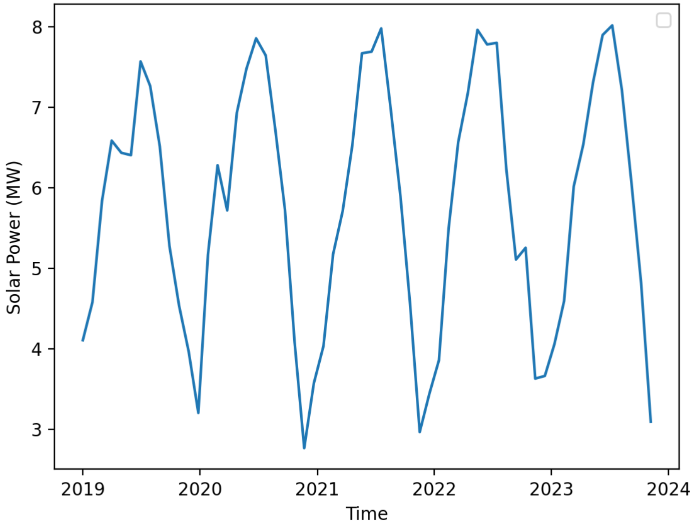


Fig. Monthly Averaged Solar Production at Solar Plant 66.

*Climate data from NLDAS-2 and CIMP-6 are extracted and validated for profile creation.

Hydrogen Profiles and Initial Studies

Hydrogen Hub Profiles

- Two hydrogen hubs are deployed close to areas of renewable production.

HETCS Profiles

- Two HETCS lines extending from the renewable resource areas located in the northeast of Texas to the cities in the southwest.

Table. Daily Operation Costs of TX-123BT with Various Hydrogen Integration in Different Quarters (M$)

Quarter	No Hydrogen Case	HB Case	HT Case
Quarter I	16.748	16.728	16.722
Quarter II	7.528	7.508	7.537
Quarter III	22.714	19.546	19.506
Quarter IV	11.267	11.240	11.229

* TX-123BT: Texas 123-bus backbone transmission test case

Hydrogen Profiles and Initial Studies

Advantages of the High Temporal Resolution TX-123BT Profiles:

The costs associated with daily operations can reduced when using

- DLR profiles instead of daily line rating profiles
- Hourly renewable production profiles

Table. Comparison of Daily Operation Costs (M$) for Hydrogen Studies Utilizing TX-123BT DLR Profiles

Quarter	HB with HLRP	HB without HLRP	HT with HLRP	HT without HLRP
Quarter I	16.728	17.483	16.722	17.536
Quarter II	7.508	8.838	7.537	8.028
Quarter III	19.546	22.502	19.506	21.824
Quarter IV	11.240	11.723	11.229	11.729

*HLRP represents hourly line rating profiles

Table. Comparison of Daily Operation Costs (M$) for Hydrogen Studies Utilizing TX-123BT Weather-Dependent Renewable Production Profiles

Quarter	HB Case with WRP	HB Case without WRP	HT Case with WRP	HT Case without WRP
Quarter I	16.728	20.888	16.722	20.887
Quarter II	7.508	12.832	7.537	12.830
Quarter III	19.546	19.546	19.506	19.506
Quarter IV	11.240	15.399	11.229	15.466

*WRP represents weather-dependent renewable production profiles

*An exception is noted in Quarter III, where loads are high and most renewable energy sources are utilized. In such situations, the hourly renewable production becomes less significant.

Contribution

The power system test case with spatio-temporal future profiles are created to accelerate the hydrogen integration studies.

The Dataset is published and publicly available, including files on geographic information system (GIS).

The test case has been used by Sandia National Laboratories, and studied by researchers in Princeton University etc.

Publication:

[1] Jin Lu, Xingpeng Li, Hongyi Li, Taher Chegini, Carlos Gamarra, Y. C. Ethan Yang, Margaret Cook, and Gavin Dillingham, "A Synthetic Texas Power System with Time-Series High-Resolution Weather-Dependent Spatio-Temporally Correlated Grid Profiles", *IEEE Transactions on Power Systems* (under review).
[2] Jonathan Yang, Mingjian Tuo, Jin Lu, and Xingpeng Li, "Analysis of Weather and Time Features in Machine Learning-aided ERCOT Load Forecasting", *IEEE Texas Power and Energy Conference*, College Station, TX, Feb. 2024.
[3] Ali Ghaffari1, Fengwei Hung, Y. C. Ethan Yang, Jin Lu, Xingpeng Li, "The development of a coupled agent-based generation expansion planning tool with a power dispatch model", *Energy and Climate Change* (under review).

Chapter 5

Planning and Expansion of Hybrid Energy Transmission Network

Offshore Energy Transmission Configurations

U.S. national goal: deploying 30 GW offshore wind capacity by 2030[1].

Traditional offshore energy transmission:

- Underwater cables (HVDC lines) transmits the electricity back to mainland.
- The cables connected to onshore substations, where electricity is distributed into the bulk grid.

Clustered Farms and Shared Infrastructure:

- Nearby wind farms use a shared transmission system to reduce costs.
- A central hub collects electricity from multiple farms before transmitting to shore.

We investigated three different offshore hybrid energy transmission configurations

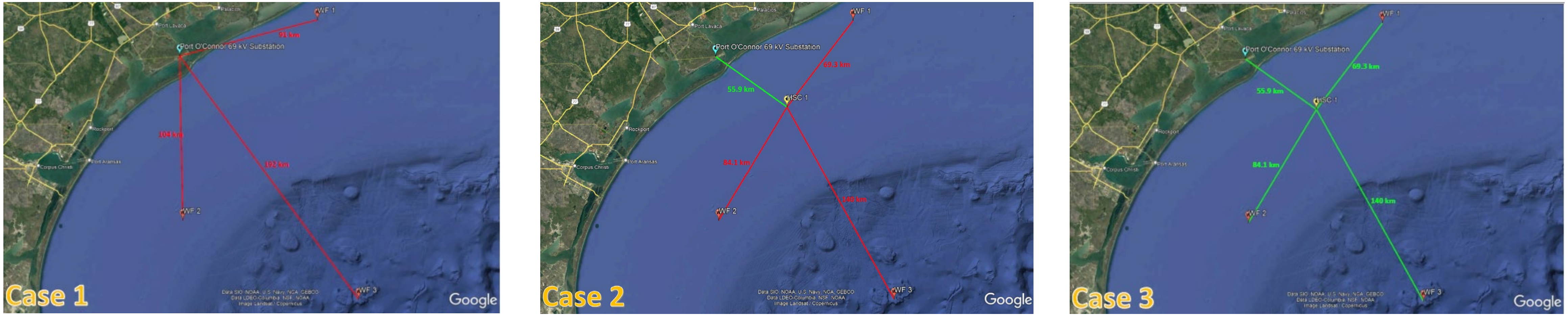


Fig. Three Different Transmission Configurations for Offshore Wind Farms

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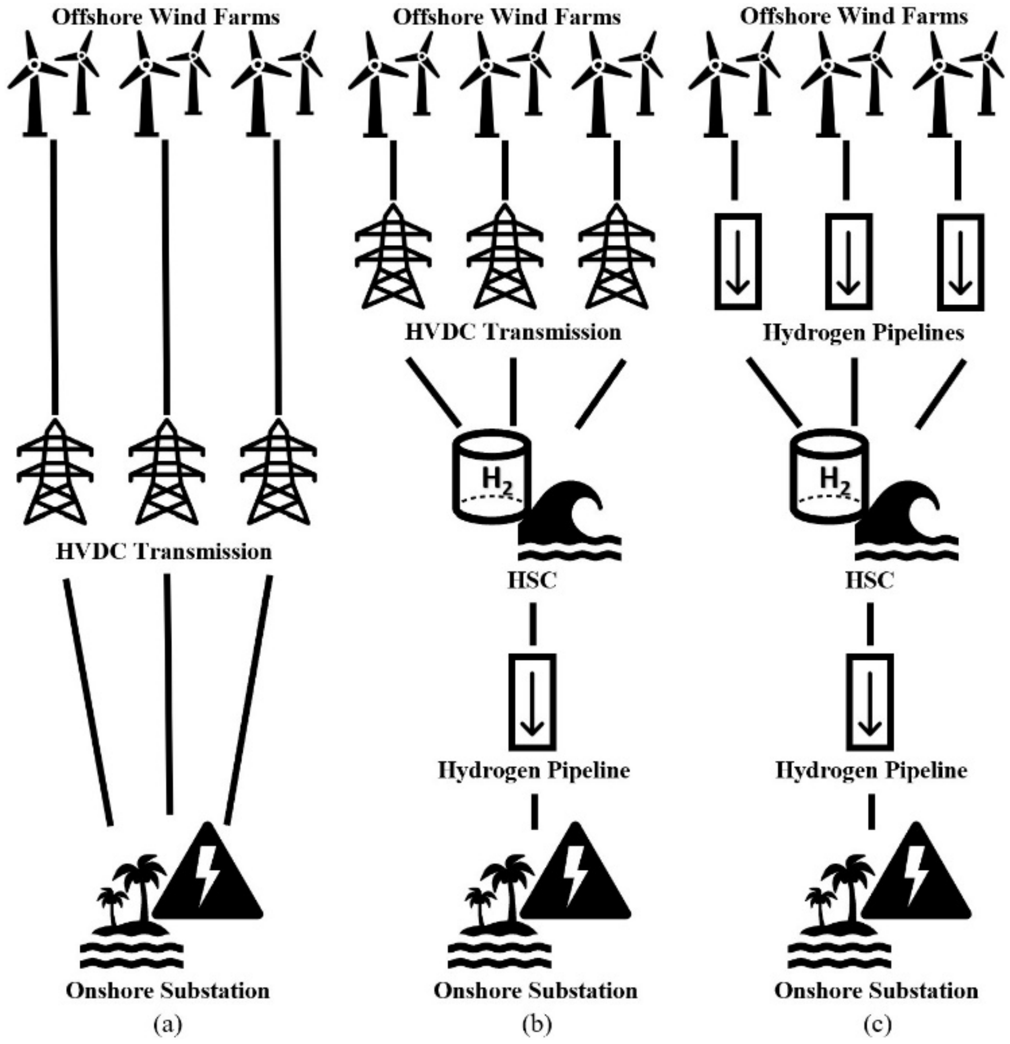
[1] "DOE Releases Strategy to Accelerate and Expand Domestic Offshore Wind Deployment" https://www.energy.gov/articles/doe-releases-strategy-accelerate-and-expand-domestic-offshore-wind-deployment

Figure Source: Jesus Silva-Rodriguez, Jin Lu and Xingpeng Li, "Cost-Benefit Analysis and Comparisons for Different Offshore Wind Energy Transmission Systems", *Offshore Technology Conference*, Houston, TX, USA, May 2023.

Offshore Hybrid Transmission Configurations



a) <u>HVDC configuration</u>: direct point-to-point HVDC transmission from each wind farm location to an onshore substation.

b) <u>Hybrid configuration</u>: point-to-point HVDC transmission from each wind farm location to a hydrogen super center (HSC), then power transmission via high pressure hydrogen pipelines (HPHP) from the HSC to the onshore substation.

c) <u>Hydrogen pipelines (HP) configuration</u>: hydrogen generation at each wind farm location and transmission via low pressure hydrogen pipelines (LPHP) to the offshore HSC, then all hydrogen collectively transmitted via HPHP from the HSC to the onshore substation.

Figure Source: Jesus Silva-Rodriguez, Jin Lu and Xingpeng Li, "Cost-Benefit Analysis and Comparisons for Different Offshore Wind Energy Transmission Systems", *Offshore Technology Conference*, Houston, TX, USA, May 2023.

Planning Models for Offshore Hybrid Transmission

We developed the planning models for the three offshore transmission configurations separately.

Sizing problem

- Determine the number of HVDC lines or hydrogen pipelines to be invested.
- For the entire planning span, the models will maximize the total revenue
  - The revenue for energy delivered to onshore substation.
  - The transmission facility capital cost.

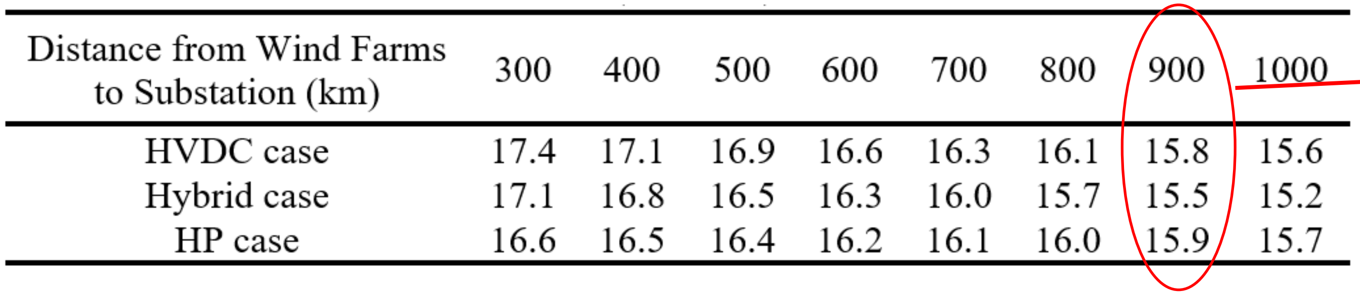
Considered constraints: HVDC line flow equation, hydrogen conversion constraints, hydrogen flow equation, hydrogen storage constraints, fuel cells and electrolyzers power ratings.

Sensitivity Analysis on Distance and Capacity

We explore the performance of different configurations for various scenarios:

- Distances between wind farms
- Wind farm capacities

The Total Revenue (Billion $) vs. Distances between Wind Farms.



Distance from Wind Farms to Substation (km)	300	400	500	600	700	800	900	1000
HVDC case	17.4	17.1	16.9	16.6	16.3	16.1	15.8	15.6
Hybrid case	17.1	16.8	16.5	16.3	16.0	15.7	15.5	15.2
HP case	16.6	16.5	16.4	16.2	16.1	16.0	15.9	15.7

When the distances are longer than 900km, the hydrogen pipelines should be utilized.

The Total Revenue (Billion $) vs. Wind Farm Capacity.

Each Wind Farm Capacity (MW)	360	720	1,080	1,440	1,800
HVDC case	7.7	17.2	24.9	34.4	43.8
Hybrid case	7.5	16.8	23.1	28.2	33.3
HP case	7.8	16.5	24.6	29.4	33.5

When the wind farm capacities are lower than 360MW, the hydrogen pipelines should be utilized.

Transmission Expansion Planning in Bulk Power System

Power systems need to expand to accommodate the rising demands.

The transmission expansion planning (TEP) typically looks several decades ahead due to:

- The long construction time of transmission lines
- The necessity to account for long-term shifts in grid load and generation.

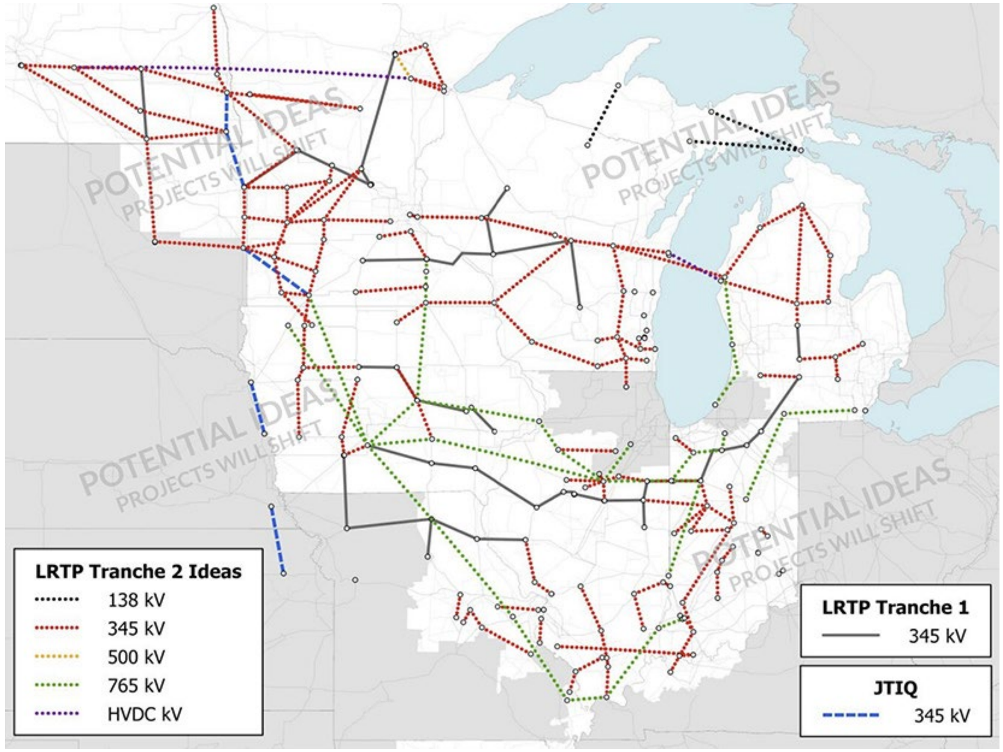


Fig. MISO's Tranche 2 Transmission Planning.

Figure Source: MISO Tranche 2 Transmission Planning Map: https://www.rtoinsider.com/31197-conceptual-tx-planning-map-troubles-miso-members/

Hybrid Transmission Network Expansion Model

For point-to-point energy transmission:

Our developed expansion strategy can utilize the electrical transmission lines, hydrogen pipelines, and the hybrid transmission with both.

From the grid perspective:

Our expansion strategy will investment different point-to-point transmission configuration to different areas in the grid and minimize the system total costs.

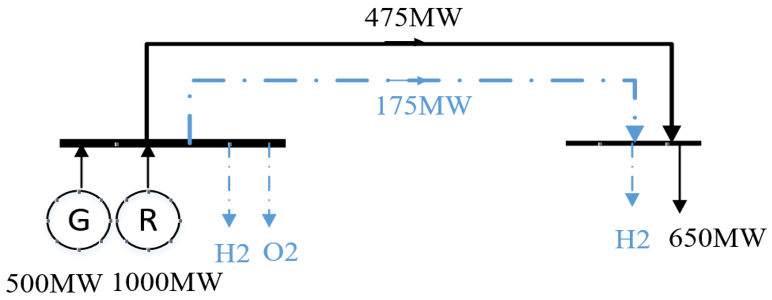


Fig. An example of point-to-point hybrid transmission.

Hybrid Transmission Network Expansion Model

Total Costs:

- The system-wide generation costs
- Capital and maintenance costs
    - electrical transmission lines, hydrogen pipelines, electrolyzers, fuel cells.

$$\min \boxed{C^{NL} + C^{G} + C^{H}} + \boxed{M * \sum_{n\in N, t\in T, d\in D^{T}, p\in P} p^{SD}_{b,t,d,p}}$$

Penalties for load sheddings:

- The grid cannot serve all the loads in all future scenarios.
- Without this term, the optimize problem will be infeasible to solve.
- A big number M is used to ensure the load sheddings are avoided unless the safety constraints cannot be satisfied.

Hybrid Transmission Network Expansion Model

For candidate transmission lines and hydrogen pipelines, their constraints will not be effective until they are constructed.

$$-M*\left(1-u^{NL}_{k,p}\right) \le \boxed{p^{NL}_{k,t,d,p} - \frac{\theta^{F}_{k,t,d,p}-\theta^{T}_{k,t,d,p}}{x^{NL}_{k}}} \le M*\left(1-u^{NL}_{k,p}\right),$$

Big-M method (M is a large number)

The power flow term.

Binary decision variables indicating whether the line will be constructed.

Hydrogen Transmission Investments Analysis

TEP-H: developed expansion strategy considering hydrogen transmission investments

TEP-T: traditional transmission expansion strategy, only consider electrical transmission line investment.

The Transmission Investments by TEP-T and TEP-H.

TEP Model	TEP-T	TEP-H
Number of Hydrogen Pipeline	N/A	1
Hydrogen Investments (M$)	N/A	2,050
Transmission Line Number	11	8
Transmission Investments (M$)	4,285	3,433
Generation Costs (M$)	469,680	465,453
Total Costs (M$)	473,965	470,936

The TEP simulations are conducted on our created TX-123BT test case.

Reduce 3 transmission line investments by increasing one hydrogen pipeline.

The total costs (including capital and maintenance costs of hybrid system) reduced 3,029M$.

Hydrogen Transmission Investments Analysis

The Hydrogen Investment for Various cost reduction with 60% renewable penetration level.

Hydrogen Facilities Cost Reduction	Number of Hydrogen Pipelines	Total Hydrogen Investment (Million $)
0%	2	4,127
20%	2	3,301
40%	2	2,476
60%	3	2,514
80%	3	1,257

When hydrogen facilities costs reduced by 60%, the TEP-H suggests to invest additional pipeline to the grid.

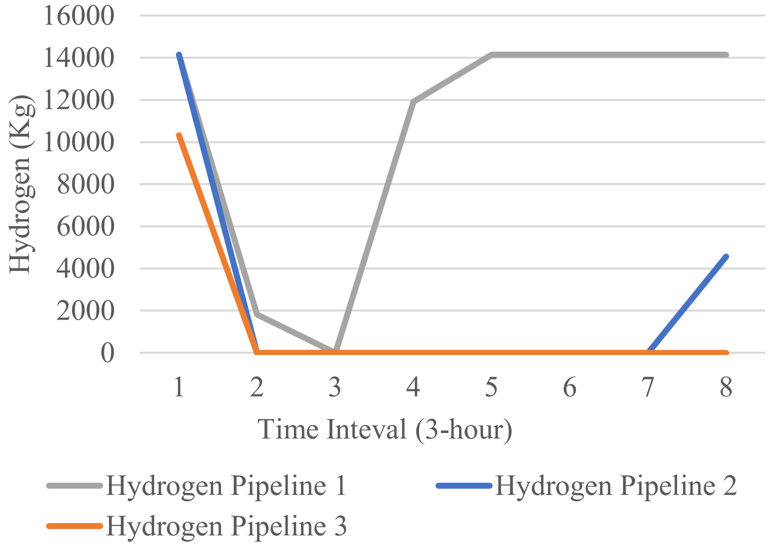


Fig. Daily Operation of Hydrogen Pipelines in Quarter I, 2046-2050.

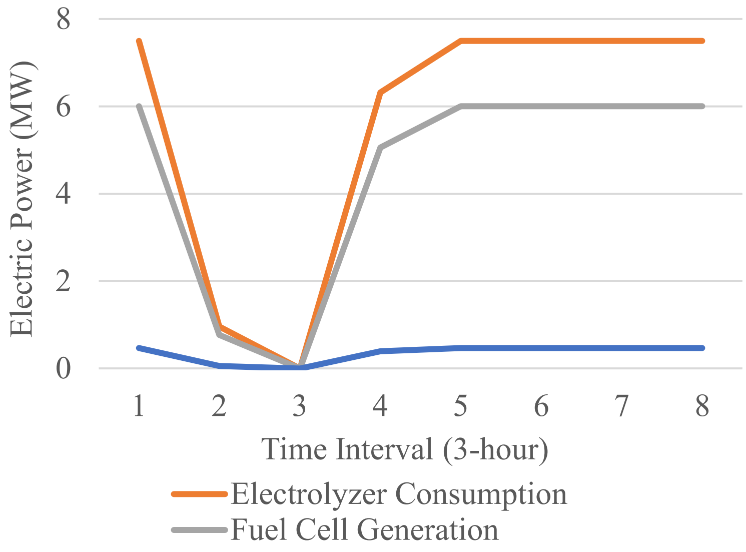


Fig. Daily Operation of Fuel Cells, Electrolyzers and Compressors in Quarter I, 2046-2050.

Contributions

- Developed the sizing model for offshore hybrid transmission system and study future applicability of hydrogen configurations.
- Developed the very first planning model consider both operation costs of the grid and capital costs for electrical and hydrogen transmission.
- TEP-H can reduce electrical transmission investments, and thus reduce grid total costs.

Publication:

[1] Jin Lu and Xingpeng Li, "Transmission Planning for Climate-impacted Renewable Energy Grid: Data Preparation, Model Improvement, and Evaluation", Journal of Modern Power Systems and Clean Energy (accepted).

[3] Jin Lu and Xingpeng Li, "Power and Hydrogen Hybrid Transmission for Renewable Energy Systems: An Integrated Expansion Planning Strategy", *Renewable Energy* (under review).

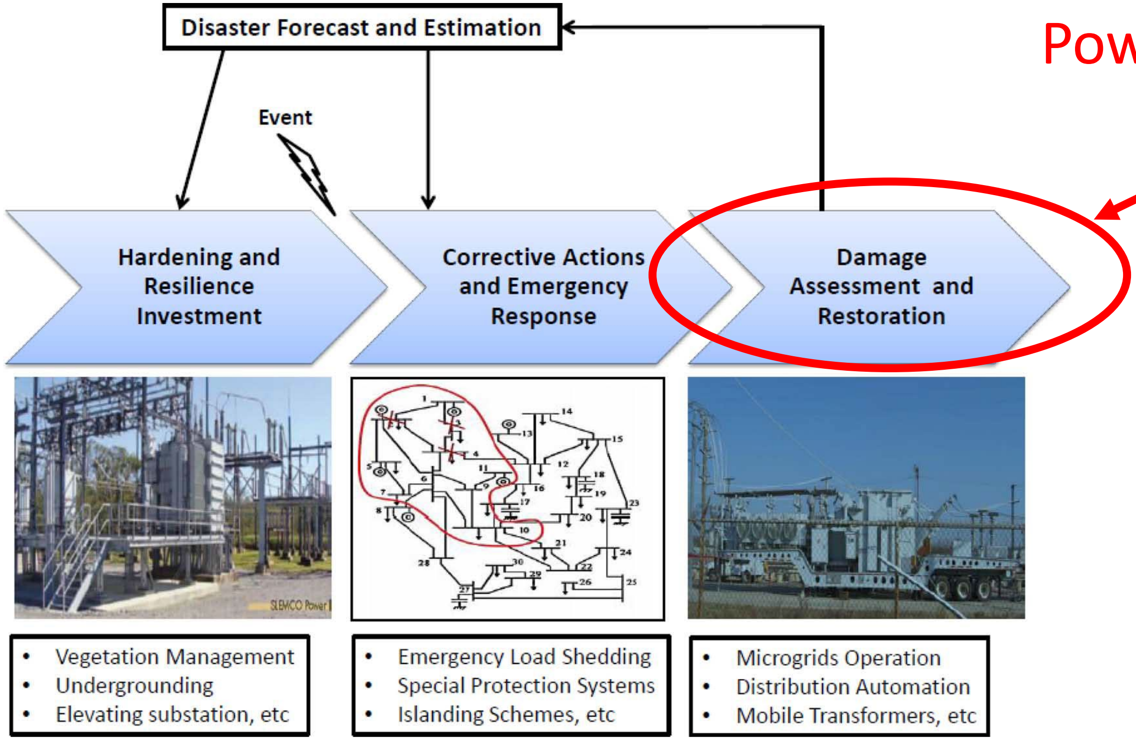
[4] Jesus Silva-Rodriguez*, Jin Lu* and Xingpeng Li, "Cost-Benefit Analysis and Comparisons for Different Offshore Wind Energy Transmission Systems", *Offshore Technology Conference*, Houston, TX, USA, May 2023.

1: Jin Lu and Jesus Silva-Rodriguez contributed equally to this work as co-first authors.

Chapter 6
Enhancing Power System Restoration with Fuel Cells

Grid Resilience Enhancement

- After a partial or complete collapse of the system, power system restoration is needed.
- A faster power system restoration process can enhance the grid resilience.



Disaster Forecast and Estimation

Event

Hardening and Resilience Investment

Corrective Actions and Emergency Response

Damage Assessment and Restoration

- Vegetation Management
- Undergrounding
- Elevating substation, etc

- Emergency Load Shedding
- Special Protection Systems
- Islanding Schemes, etc

- Micrograids Operation
- Distribution Automation
- Mobile Transformers, etc

Power system restoration

Fig. Timeline of the response in electric grid under natural disasters

Figure source: Y. Wang, C. Chen, J. Wang and R. Baldick, "Research on Resilience of Power Systems Under Natural Disasters—A Review," in IEEE Transactions on Power Systems, vol. 31, no. 2, pp. 1604-1613, March 2016.

Integrated Skeleton-Network Reconfiguration (ISNR) Model

Drawbacks of traditional TLR model:

- The skeleton-network and its restoration sequence are found separately.
- The determination of the skeleton-network doesn't consider its restoration time.
- Only use the bus importance to evaluate the network.

Integrated Skeleton-Network Reconfiguration (ISNR) Model:

- Co-optimize the selection of the skeleton-network and its restoration sequence.
- Evaluate the network quality considering both the network importance and distance.

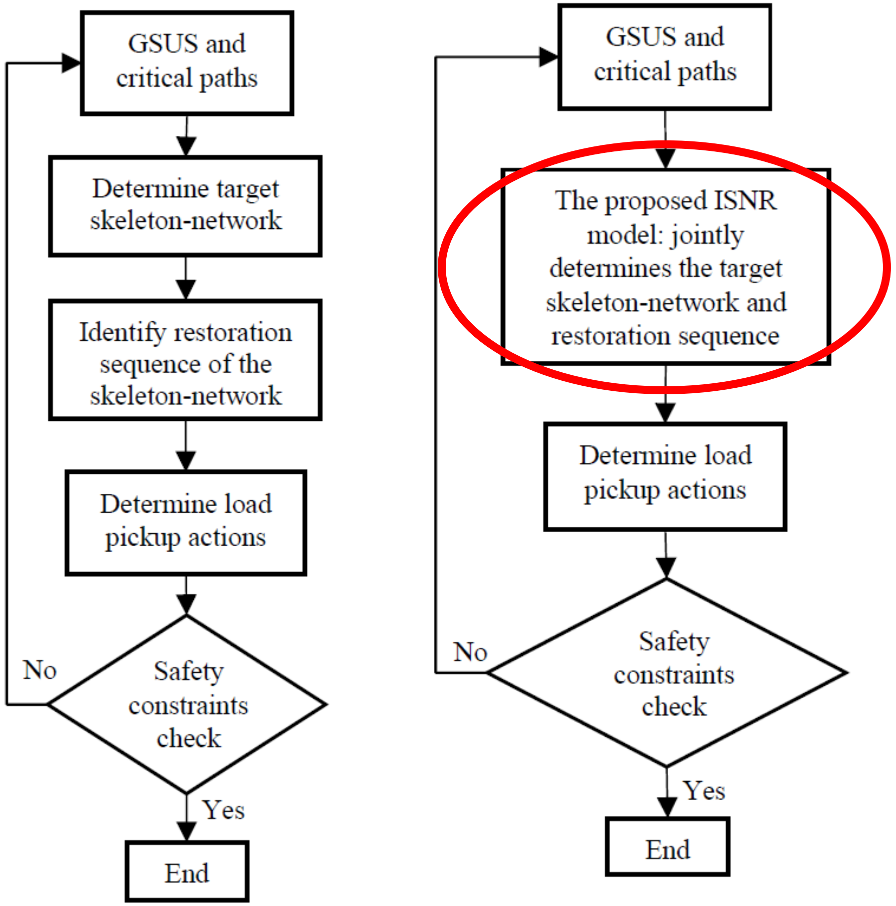


Fig. The scheme of traditional TLR and proposed ISNR strategies.

Black Start Model Utilizing Fuel Cells

Modeling of Fuel Cell as Generation Resources:

- We use binary variables $u_{f,t}^{start}$, $u_{f,t}^{on}$, $u_{f,t}^{max}$ to indicate different operation status of the fuel cell f.
  - When $u_{f,t}^{start}$ is 1, it indicates the fuel cell is starting up.
  - When $u_{f,t}^{on}$ is 1, it indicates the fuel cell is generating power.
  - When $u_{f,t}^{max}$ is 1, it indicates fuel cell is operating at the high end of its range.

The equation that calculate actual power from fuel cells injected into the grid:

- Involves the multiplication of these binary variables.
- To linearize it, three ancillary variables $y_{f,t1,t2}^{start}$, $y_{f,t1,t2}^{on}$, $y_{f,t1,t2}^{max}$ are utilized.

Black Start Model Utilizing Fuel Cells

Modeling of Fuel Cell as Generation Resources:

Other constrains for fuel cells:

- The operation range of the fuel cells.
- The time duration of different operation status.
- Fuel cell location and restoration of related transmission facilities.
- Fuel cell initial status after the blackout.

Model for Comparison – Utilizing Battery Storage:

The model consider battery storage as black start resources:

- Battery state of charge (SOC) constraints.
- Battery discharge time and status constraints.
- Battery location and restoration of related transmission facilities.

Black Start Performance Comparison

Both fuel cells and batteries can <u>significantly facilitate the black start</u>

- Battery and fuel cell have similar performance in many situations.

The performance between battery and fuel cell can be different:

- When energy storage become a binding constraint

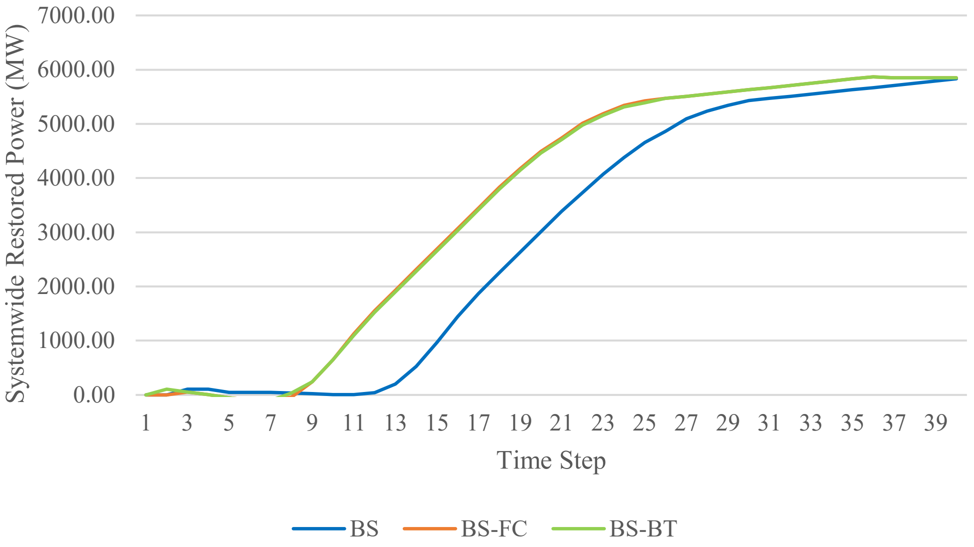


Fig. Systemwide Restored Power During the Black Start.

Table. Generator Startup Time of the Grids with Different Black Start Resources

	Without Fuel Cells and Batteries	Fuel Cells (50MW)	Batteries (50MW)
Generator 2	140 min	40 min	40 min
Generator 3	220 min	120 min	120 min
Generator 4	160 min	60 min	60 min
Generator 5	240 min	140 min	160 min
Generator 6	180 min	80 min	80 min
Generator 7	200 min	100 min	100 min
Generator 8	80 min	140 min	140 min
Generator 9	220 min	120 min	120 min
Generator 10	200 min	100 min	100 min
System Average	182.2 min	100 min	102.2 min

*Simulations conducted on IEEE 39-bus system

Sizing of the Fuel Cells and Batteries

- Larger size of fuel cells and batteries will result in a faster black start.
- However, the performance improvement plateaus when the capacity exceeds a certain value (150MW-200MW).

Table. Generator Start-up Time (min) with Different Fuel Cells Generation Capacity

Fuel Cell Capacity (MW)	100	50	40	30	20	15	10	5
Generator 3	80	120	80	120	120	140	120	120
Generator 5	140	140	140	140	160	160	160	160
Generator 6	80	80	120	80	100	100	100	140
Generator 7	80	100	140	140	140	100	100	140
Generator 8	120	140	140	140	140	140	160	160
System Average	91.1	100	104.4	104.4	108.8	108.8	111.1	115.5

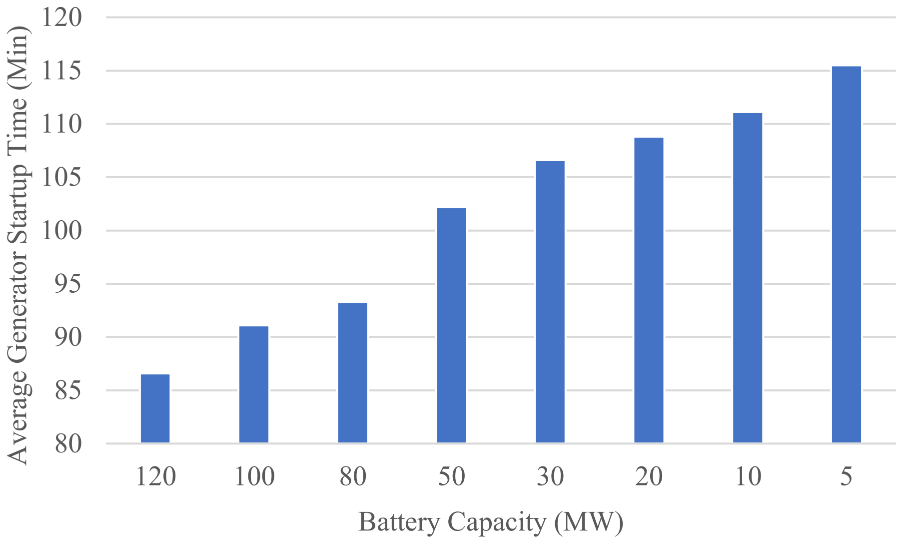


Fig. Average Generator Startup Time for Black Start with Different Battery Capacities.

*Simulations conducted on IEEE 39-bus system

Black Start on TX-123BT

- The developed black start model is scalable for bulk power system.
- The black start is significantly facilitated by fuel cell plants.

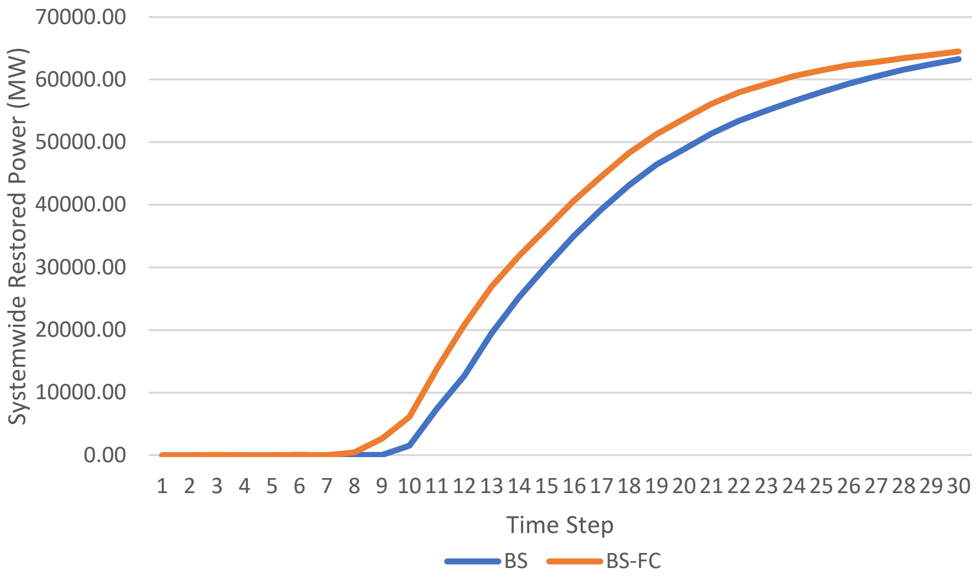


Fig. Systemwide Restored Power During the Black Start on TX-123BT.

Table. Statistical Data for Black Start on TX-123BT

Total Number of Large-Scale Thermal Power Plants	138
Average Time Steps that Generator Start Ramping Up	5.63
Total Restored Power (MW)	69,152
Total Number of Branches	255
Total Number of Buses	123
Total Number of Critical Branch in BS	75
Total Number of Critical Bus in BS	82

* TX-123BT: Texas 123-bus backbone transmission test case

Black Start on TX-123BT

- 75 of total 255 branches are required to restored for black start.
- The critical network includes 7 separate areas, a large and efficient network is necessary for following load pick-up.

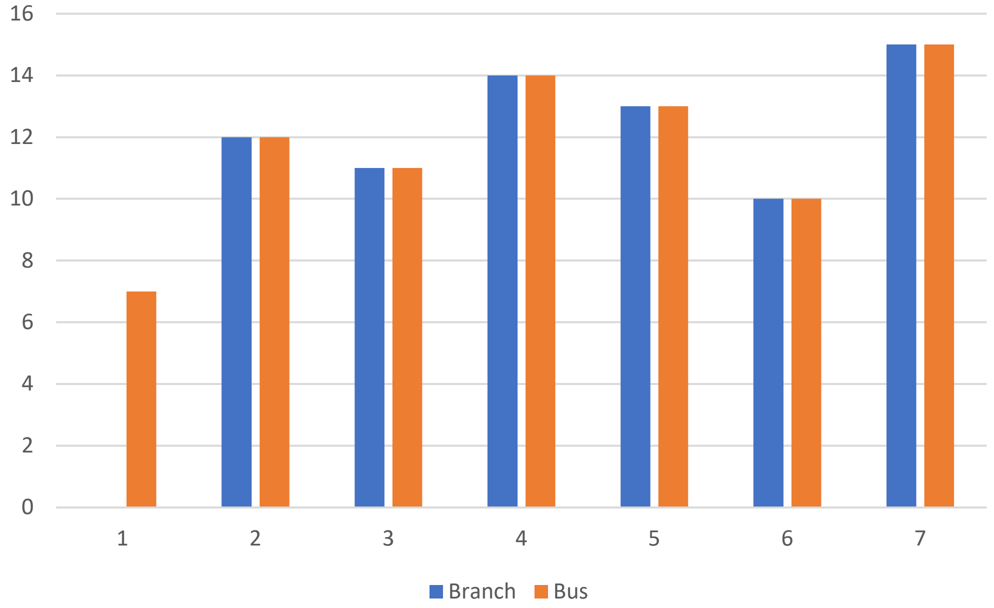


Fig. Number of Restored Critical Branch and Bus during Black Start.

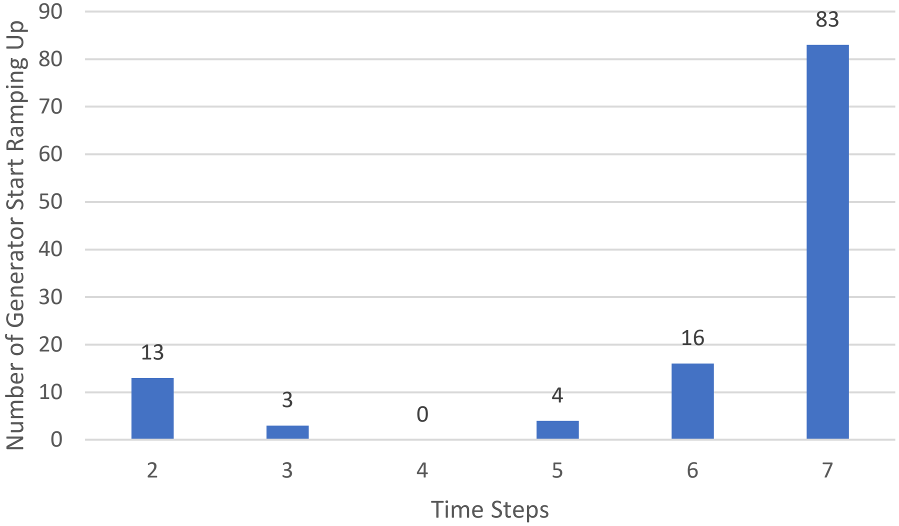


Fig. Number of Generator Start Ramping Up during Black Start.

* TX-123BT: Texas 123-bus backbone transmission test case

Network Reconfiguration Model for ISNR

Delicately combines energization constraints and skeleton network evaluation.

The transmission energization path are modeled:

- The restoration sequence of transmission lines, substations
- Related constraints are linearized by introducing ancillary binary variables

A new skeleton network quality index is proposed:

- Considering both bus importance and network distance
- The network distance for each time interval can be evaluated based on the restored transmission facilities

With new objective function to restore the qualified network as quickly as possible.

*ISNR: Integrated Skeleton-Network Reconfiguration strategy

Network Reconfiguration Performance Comparison

Fuel cell and battery can also facilitate the network reconfiguration greatly.

- The capacity of fuel cells or batteries will have less impact on the network reconfiguration.
- The restoration of transmission facilities does not rely on high generation power.

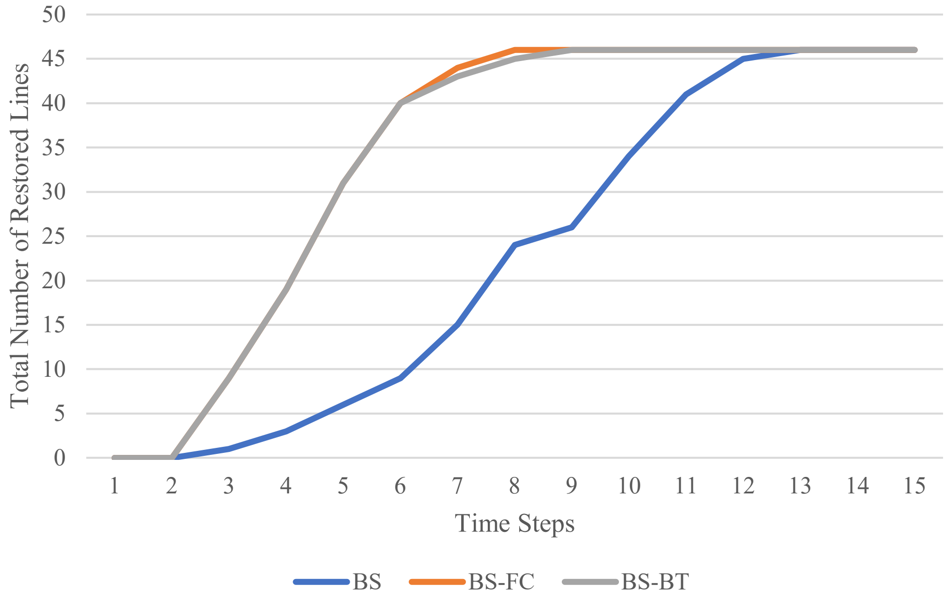


Fig. Total Number of Restored Lines for Grids with Different BS Resources.

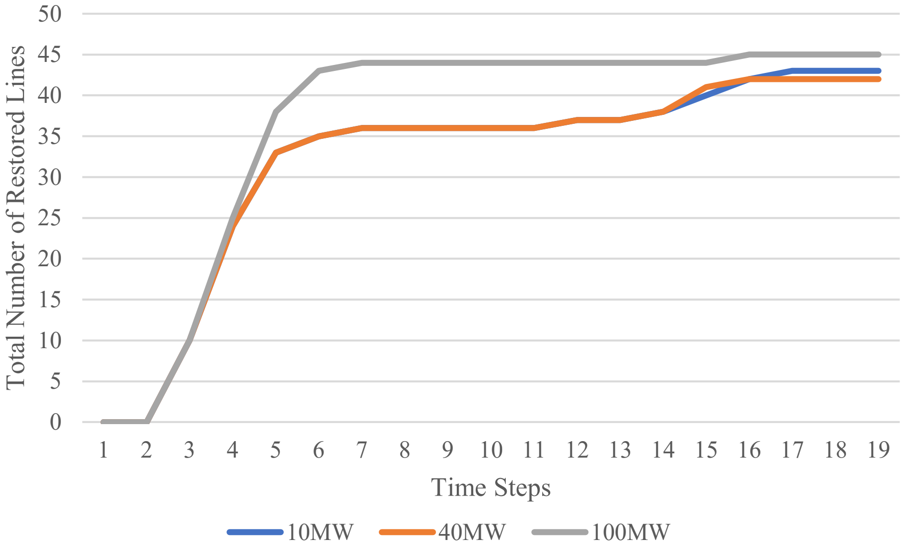


Fig. Total Number of Restored Lines for Grids with Different Fuel Cell Capacities.

Contributions

We proposed the integrated restoration strategy for the renewable grids.

- Delicately combined both the energization constraints and network evaluation.
- Achieve both fast restoration of the network and the quality of the network.

The black start strategies utilizing fuel cells and batteries are developed.

- Both the black start and network reconfiguration are facilitated greatly.

Publication:

Jin Lu and Xingpeng Li, “Optimal Skeleton Network Reconfiguration considering Topological Characteristics and Transmission Path,” 53rd North American Power Symposium, College Station, TX, USA, Nov. 2021.

Jin Lu and Xingpeng Li, “Optimizing Black Start in Power Systems with Fuel Cells and Battery Energy Storage: A Comparative Study,” *IEEE Systems Journal* (in preparation).

Chapter 7
Conclusions & Future Work

Conclusions

- We conducted the pioneer studies on the daily operation, seasonal storage, long-term expansion planning, and restoration of the renewable grids with hydrogen facilities.

- The respective models are developed, which consider the optimal coordination of hydrogen and electrical facilities.

Key Findings:

- The proposed daily operation and seasonal storage strategy can well utilize excess renewable energy for the benefits of future renewable grids.
- The planning model can find hybrid energy transmission solutions which are cost-effective over the long operation periods.
- The restoration strategy can utilize fuel cells as black start resources, greatly facilitate the black start and network reconfiguration process.

Future Work

Developing Strategies for Hydrogen Facilities with Battery Storage:

Electrolyzers require steady power for safe operation. Combining hydrogen facilities with batteries enhances this capability.

Develop Optimal Strategies: Develop planning and operation strategies that leverage the strengths of the co-operation of hydrogen and battery systems.

Application of Advanced Machine Learning for hybrid grids:

TX-123BT Test case provides a valuable platform for ML research with spatio-temporal correlated profiles over long periods.

Develop Predictive Models: Use machine learning to develop models that anticipate hydrogen demand fluctuations and optimize the operation of hydrogen-integrated power systems in real-time.

Publications

1. **Jin Lu** and Xingpeng Li, “Transmission Planning for Climate-impacted Renewable Energy Grid: Data Preparation, Model Improvement, and Evaluation”, *Journal of Modern Power Systems and Clean Energy* (accepted).
2. **Jin Lu** and Xingpeng Li, “Annual Benefit Analysis of Integrating the Seasonal Hydrogen Storage into the Renewable Power Grids”, *IEEE PES General Meeting*, Orlando, Florida, USA, Jul. 2023.
3. **Jin Lu** and Xingpeng Li, “The Benefits of Hydrogen Energy Transmission and Conversion Systems to the Renewable Power Grids: Day-ahead Unit Commitment”, *54th North American Power Symposium*, Salt Lake City, UT, USA, Oct. 2022.
4. **Jin Lu** and Xingpeng Li, “Optimal Skeleton Network Reconfiguration considering Topological Characteristics and Transmission Path,” *53rd North American Power Symposium*, College Station, TX, USA, Nov. 2021.
5. **Jin Lu**, Xingpeng Li, Hongyi Li, Taher Chegini, Carlos Gamarra, Y. C. Ethan Yang, Margaret Cook, and Gavin Dillingham, “A Synthetic Texas Power System with Time-Series High-Resolution Weather-Dependent Spatio-Temporally Correlated Grid Profiles”, *IEEE Transactions on Power Systems* (under review).
6. **Jin Lu** and Xingpeng Li, “Power and Hydrogen Hybrid Transmission for Renewable Energy Systems: An Integrated Expansion Planning Strategy”, *IEEE Systems Journal* (under review).
7. Jesus Silva-Rodriguez*, **Jin Lu*** and Xingpeng Li, “Cost-Benefit Analysis and Comparisons for Different Offshore Wind Energy Transmission Systems”, *Offshore Technology Conference*, Houston, TX, USA, May 2023.
8. Jonathan Yang, Mingjian Tuo, **Jin Lu**, and Xingpeng Li, “Analysis of Weather and Time Features in Machine Learning-aided ERCOT Load Forecasting”, *IEEE Texas Power and Energy Conference,* College Station, TX, Feb. 2024.
9. Ali Ghaffari1, Fengwei Hung, Y. C. Ethan Yang, **Jin Lu**, Xingpeng Li, “The development of a coupled agent-based generation expansion planning tool with a power dispatch model”, *Energy and Climate Change* (under review).
10. **Jin Lu** and Xingpeng Li, “Optimizing Power System Black Start with Fuel Cells and Battery Energy Storage,” *IEEE Systems Journal* (in preparation).

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Thank you!

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