



Smart Energy Systems Lab

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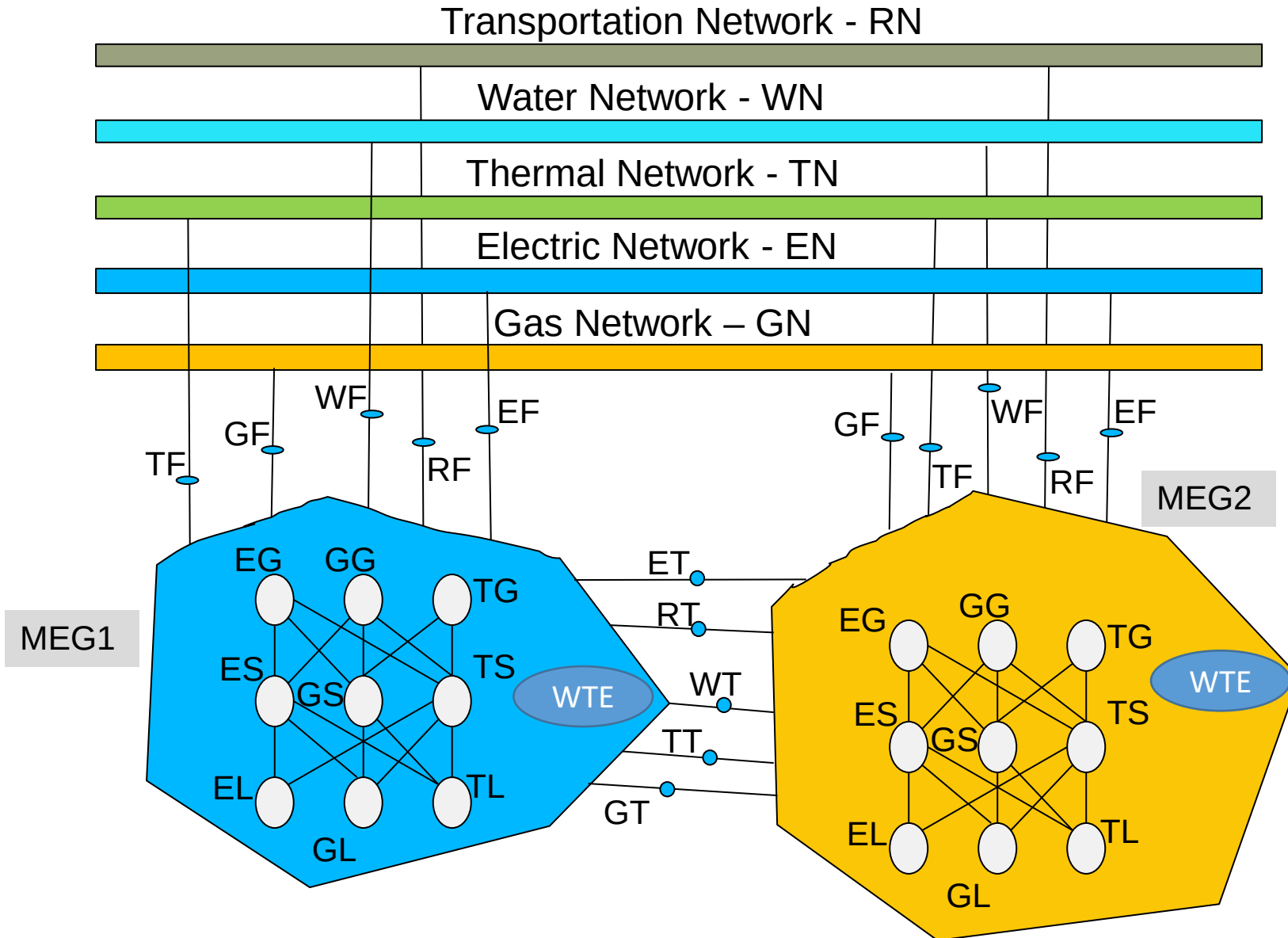
*26th INPRO Dialogue Forum on
Deployment of Nuclear Energy Systems
for Applications Beyond Electricity, 23-28 Aug, 2026*

Resilient Nuclear-Renewable Hybrid Energy Systems and Digital Twin for SMR Deployments

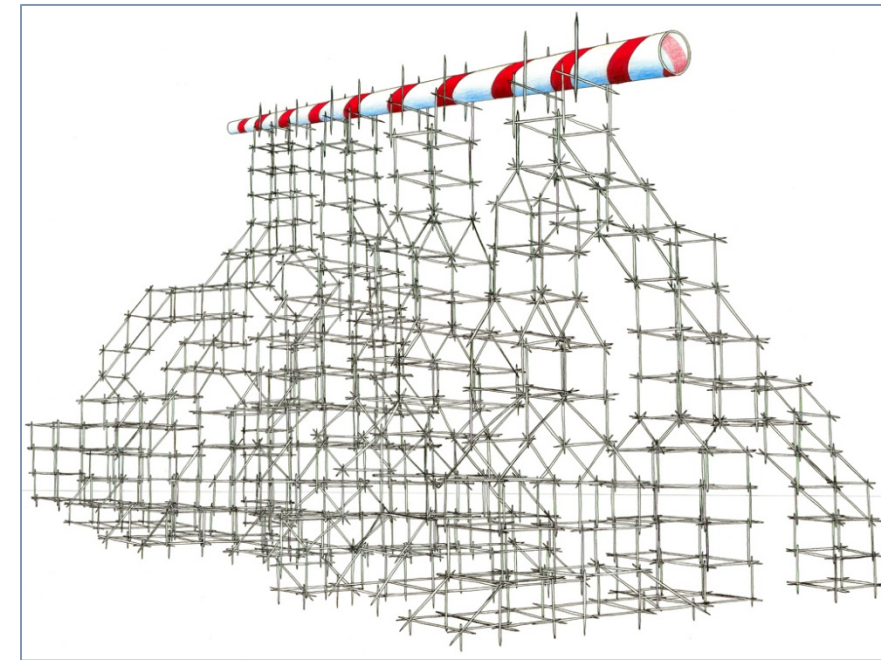
Hossam Gaber (A.Gabbar), Professor (FESNS / FEAS – UOIT), PhD, P.Eng.,
Dr. Hossam Gaber, Ontario Tech University, Canada

Acknowledgement: SESL Team Members, Ontario Tech University, Canada

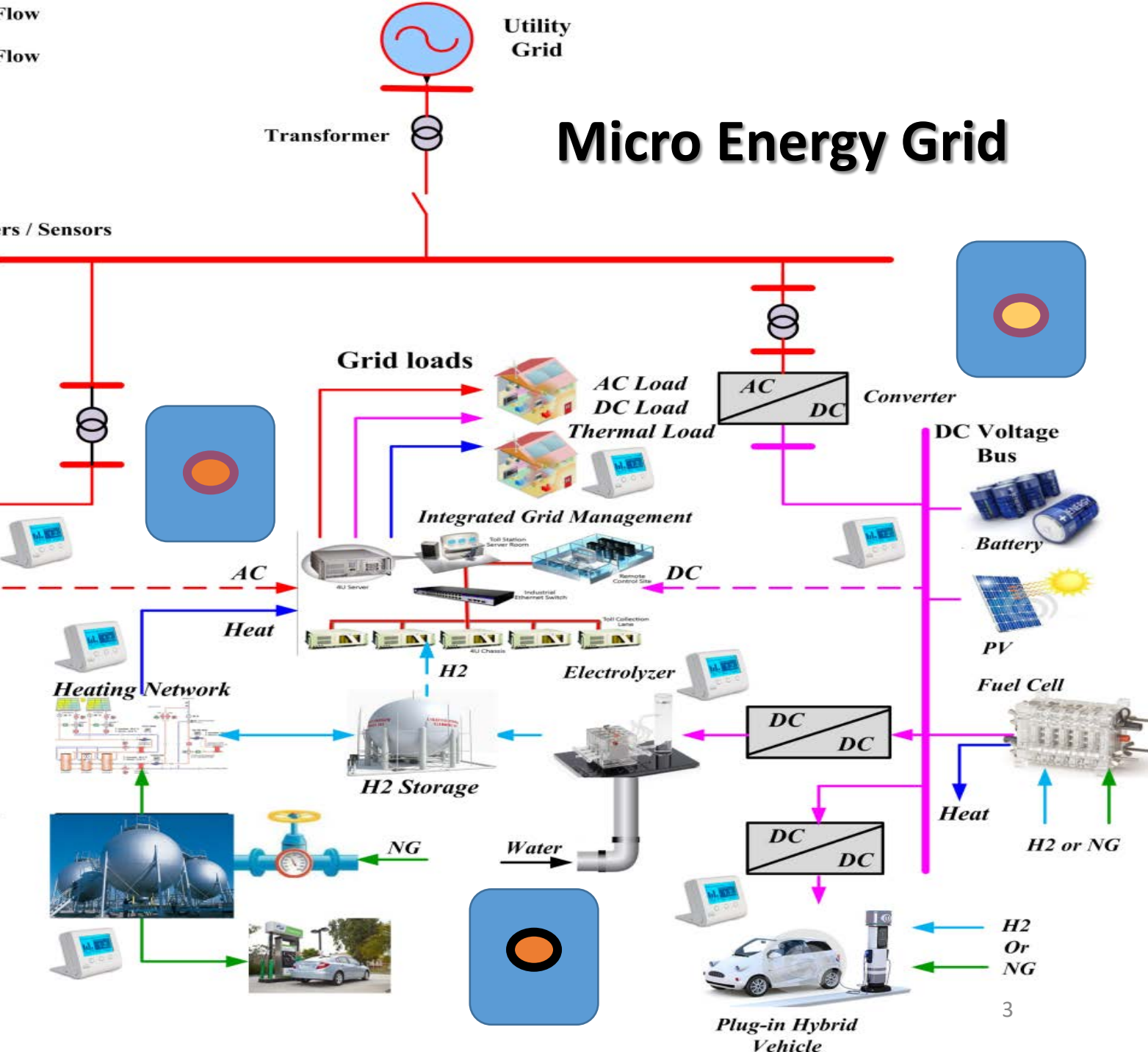
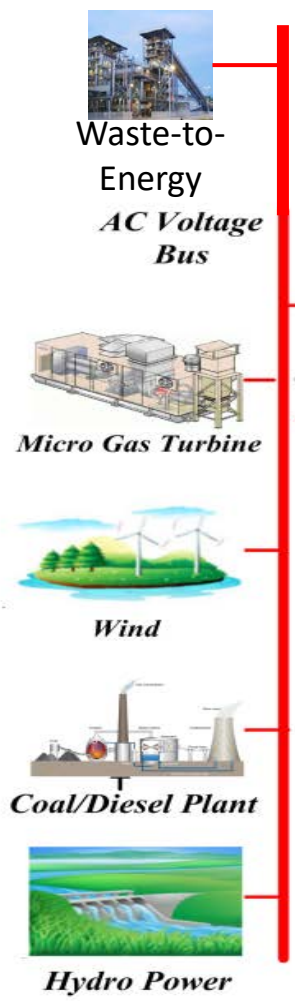
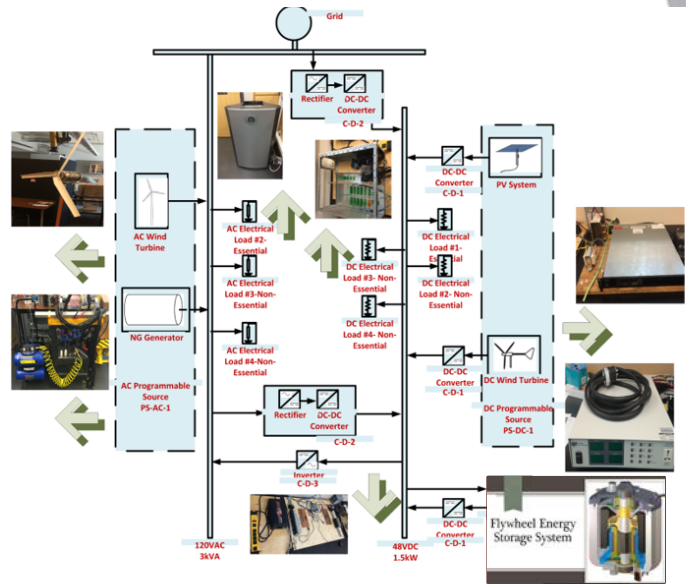
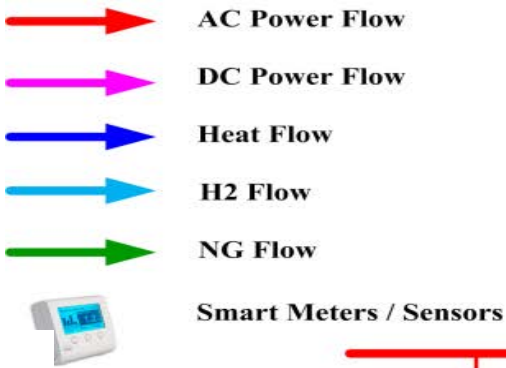
Interconnected Micro Energy Grids



Adaptive Interconnected Micro Energy Grid Superstructure

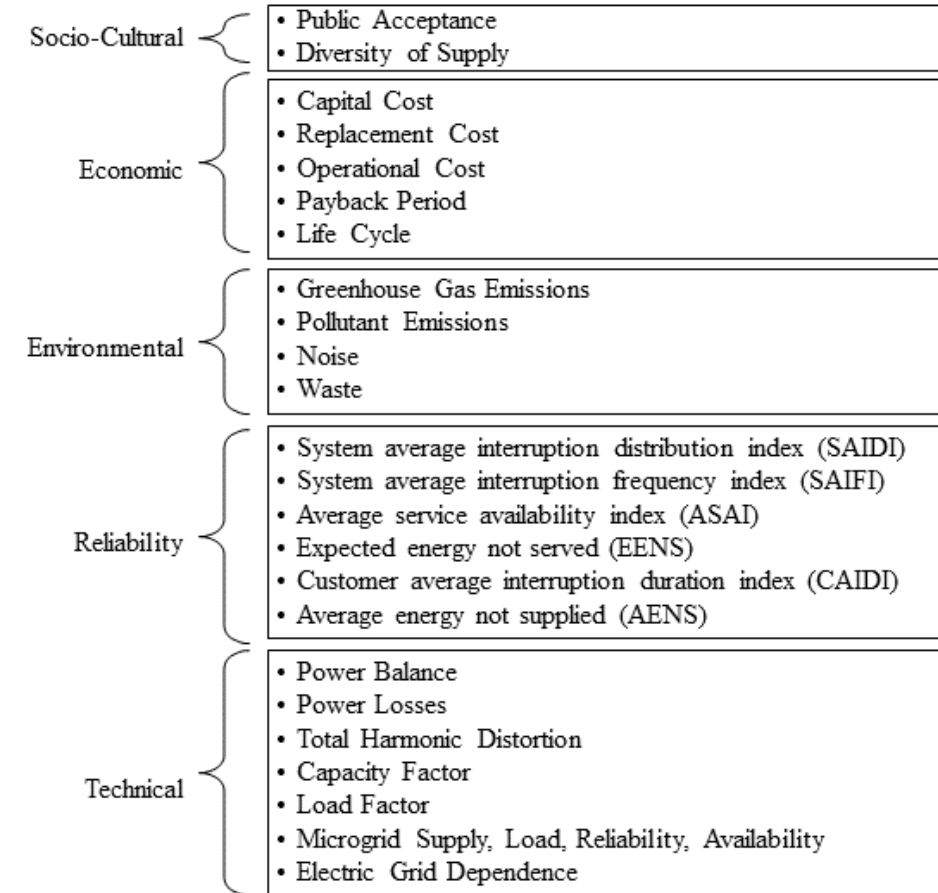
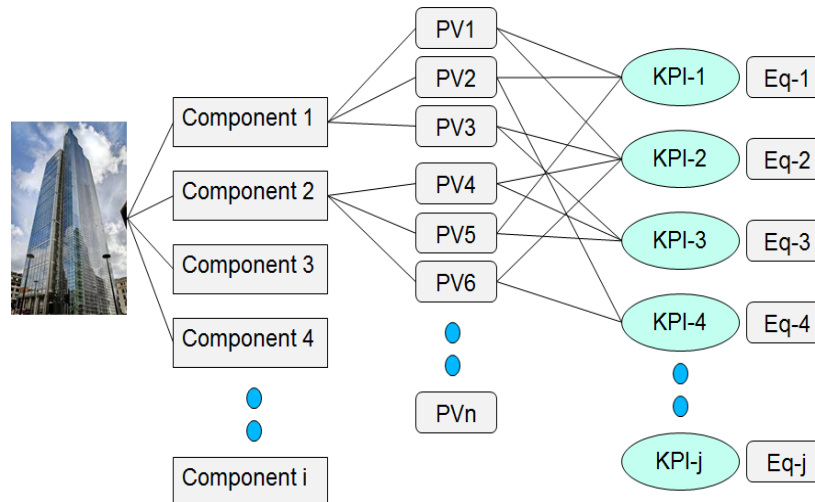


MEG Demonstration at UOIT

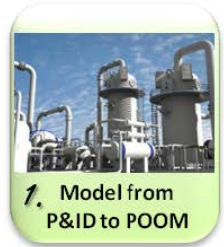


KPI Modeling

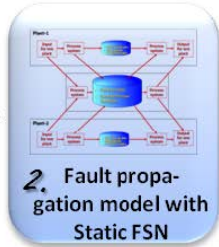
- EWFHT (Generation / Storage / Loads)
- KPI Modeling
 - Resiliency
 - Socio-cultural
 - Economic
 - Environmental
 - Reliability / Safety / Security
 - Technical



Risk-based Energy Systems



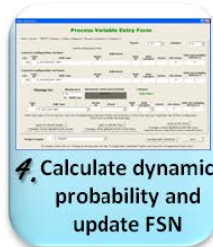
1. Model from P&ID to POOM



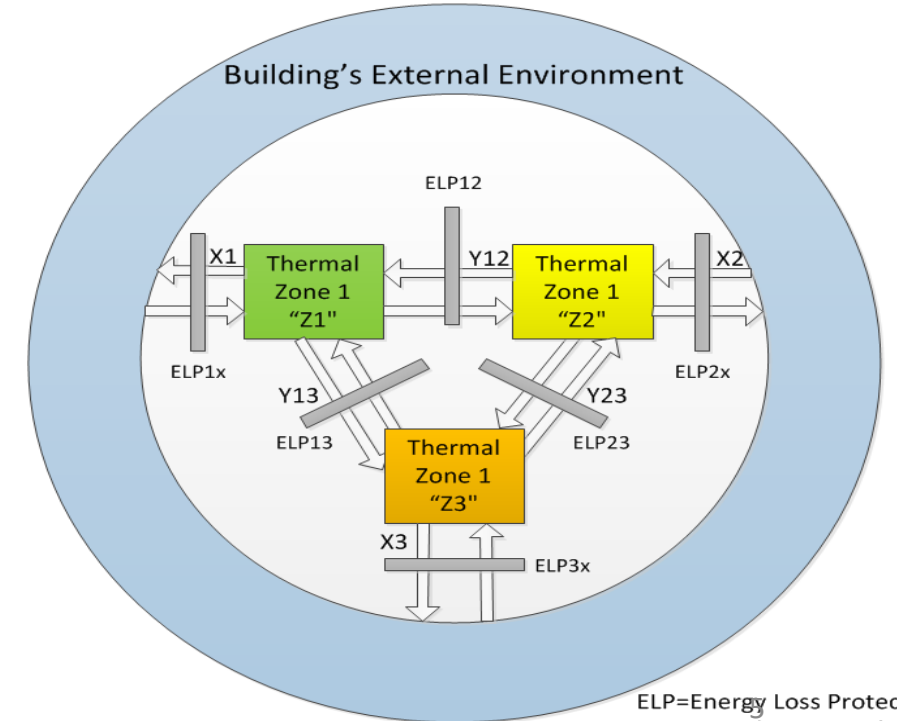
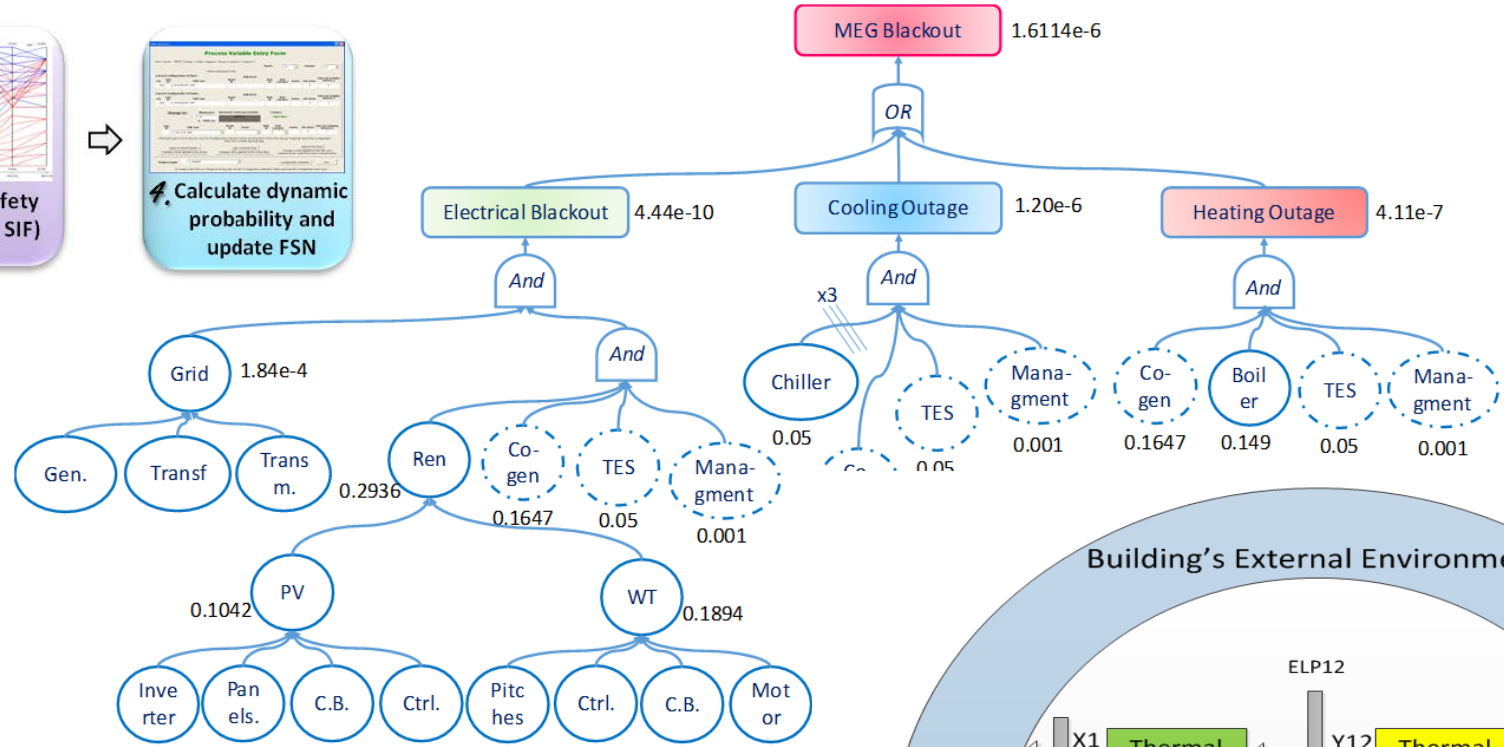
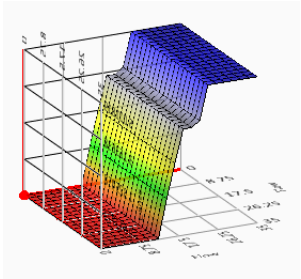
2. Fault propagation model with Static FSN



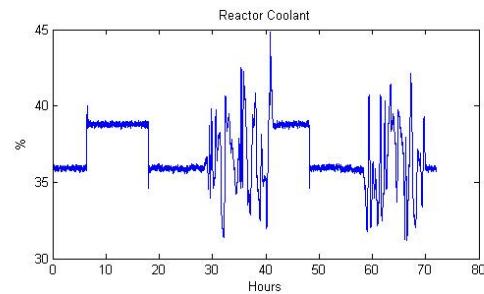
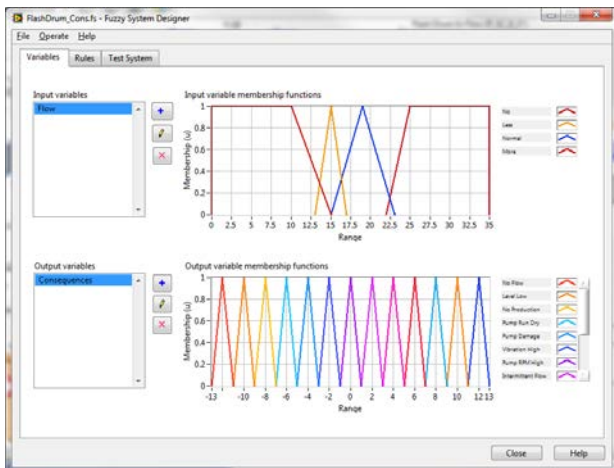
3. Map IPL-Safety to FSN (SIL, SIF)



4. Calculate dynamic probability and update FSN

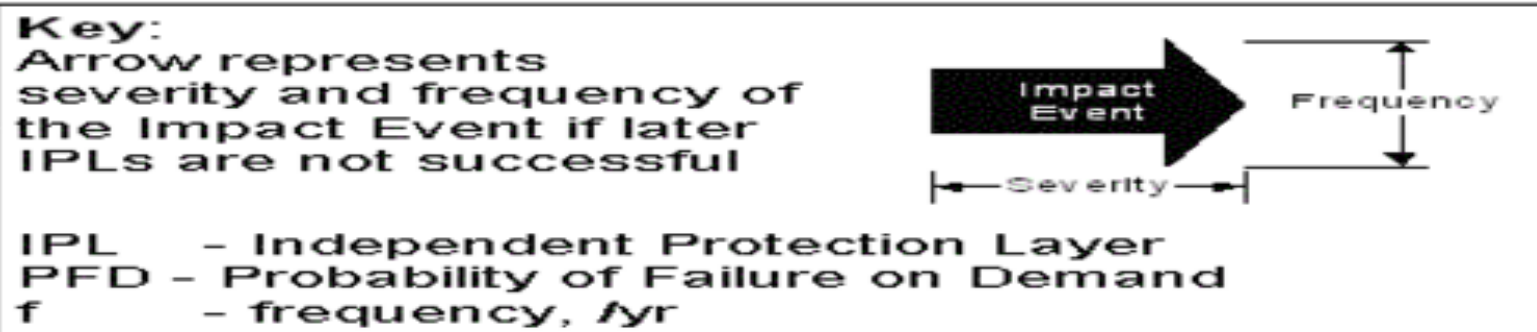
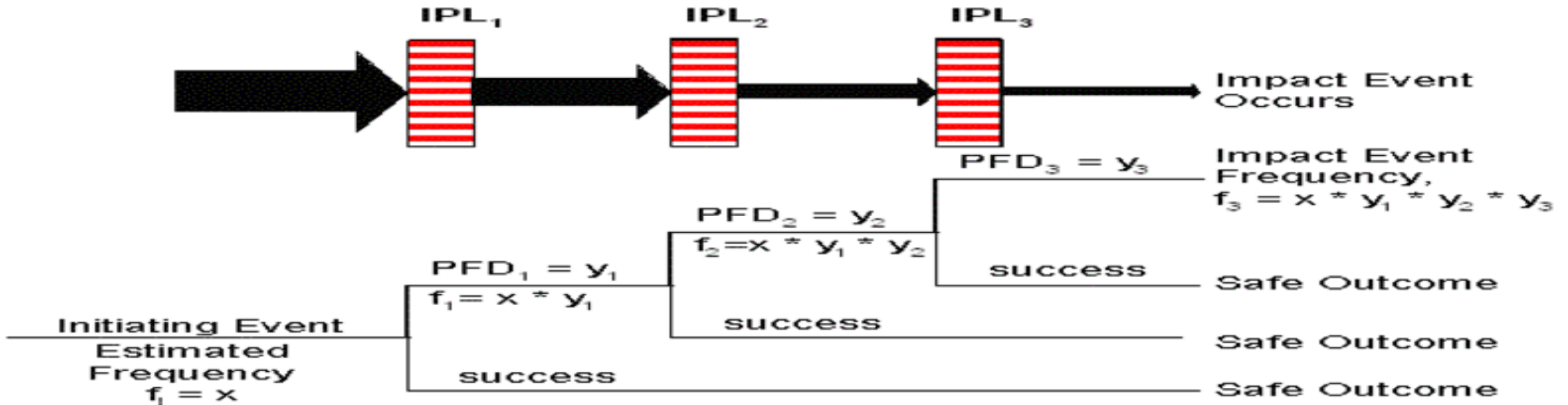


ELP=Energy Loss Protection
Y=Inter-Zonal Energy Exchnge
X=Energy Exchange with external Environment

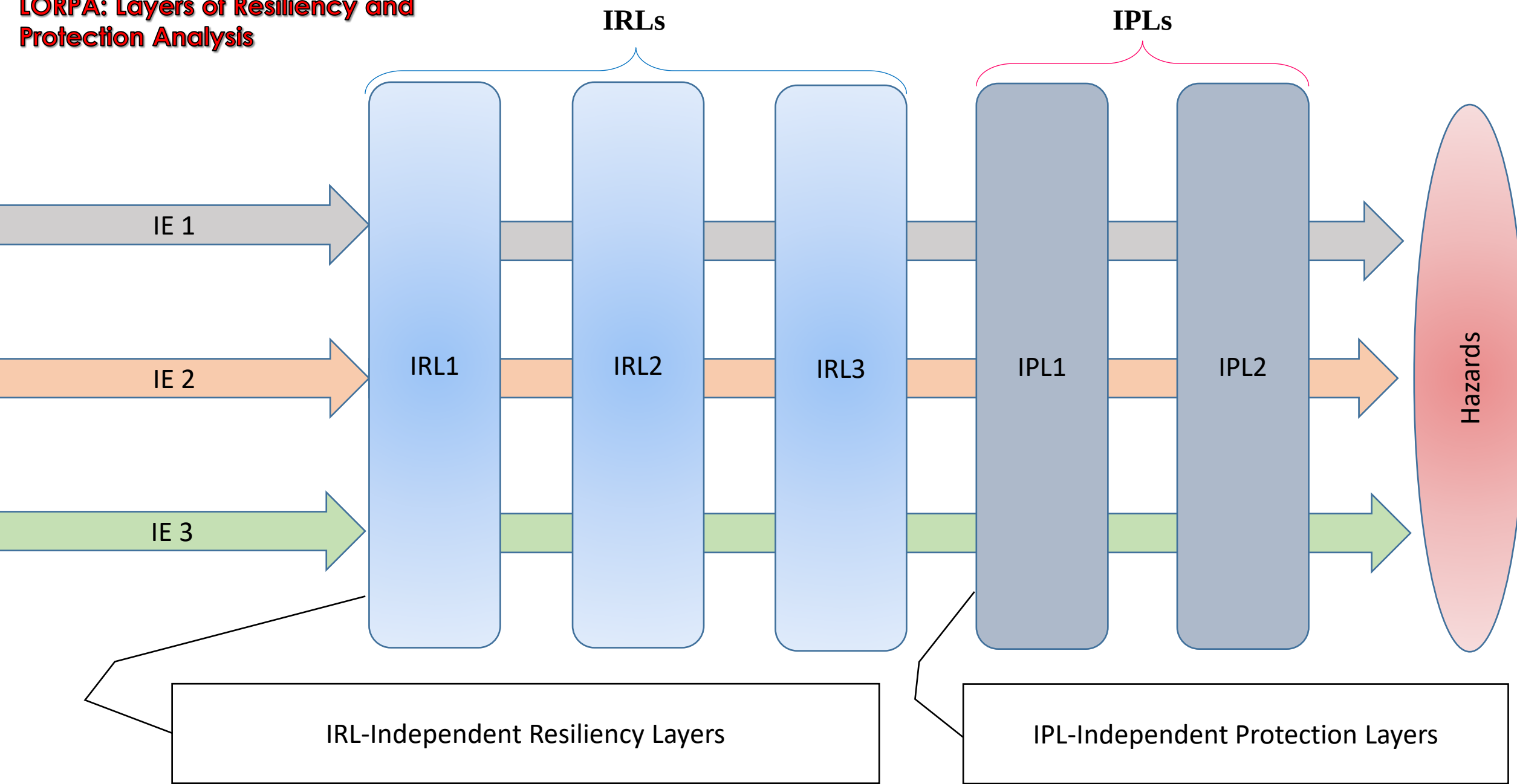


LOPA (Layer of Protection Analysis)

- **LOPA Definition:** is to determine if there are sufficient layers of protection against the consequences of an accident scenario (can the risk be tolerated?).



LORPA: Layers of Resiliency and Protection Analysis

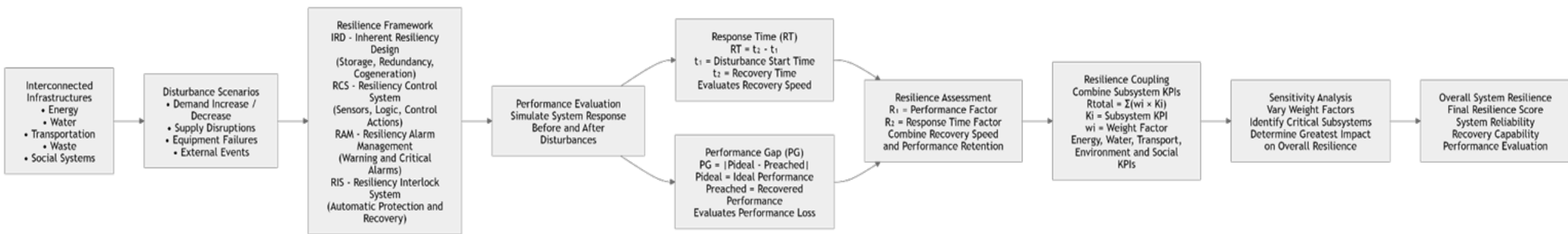


Proposed Resilience Framework

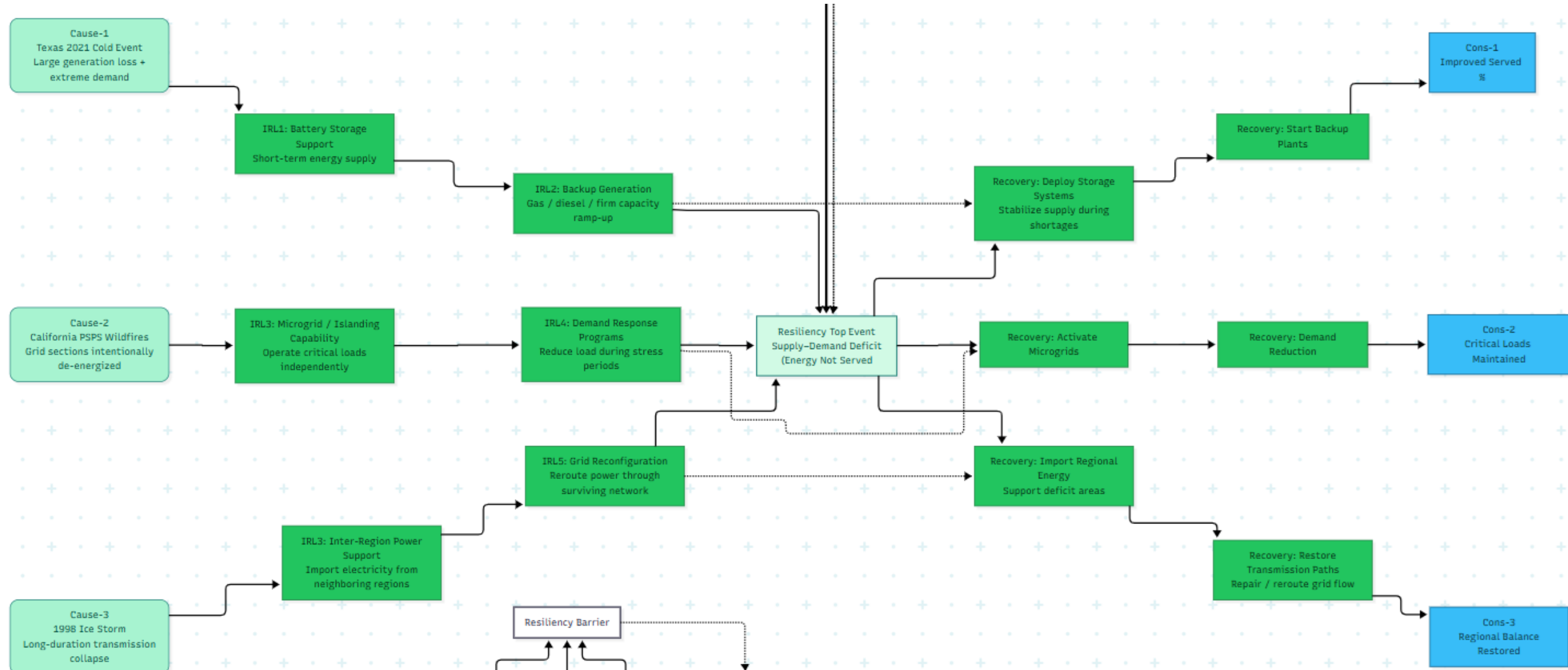
The proposed framework evaluates the ability of interconnected infrastructures to withstand disturbances, maintain critical functionality, and recover efficiently. The framework combines resilience design, monitoring, control, alarm management, and protection mechanisms to improve overall system performance during abnormal operating conditions.

Four Resilience Layers

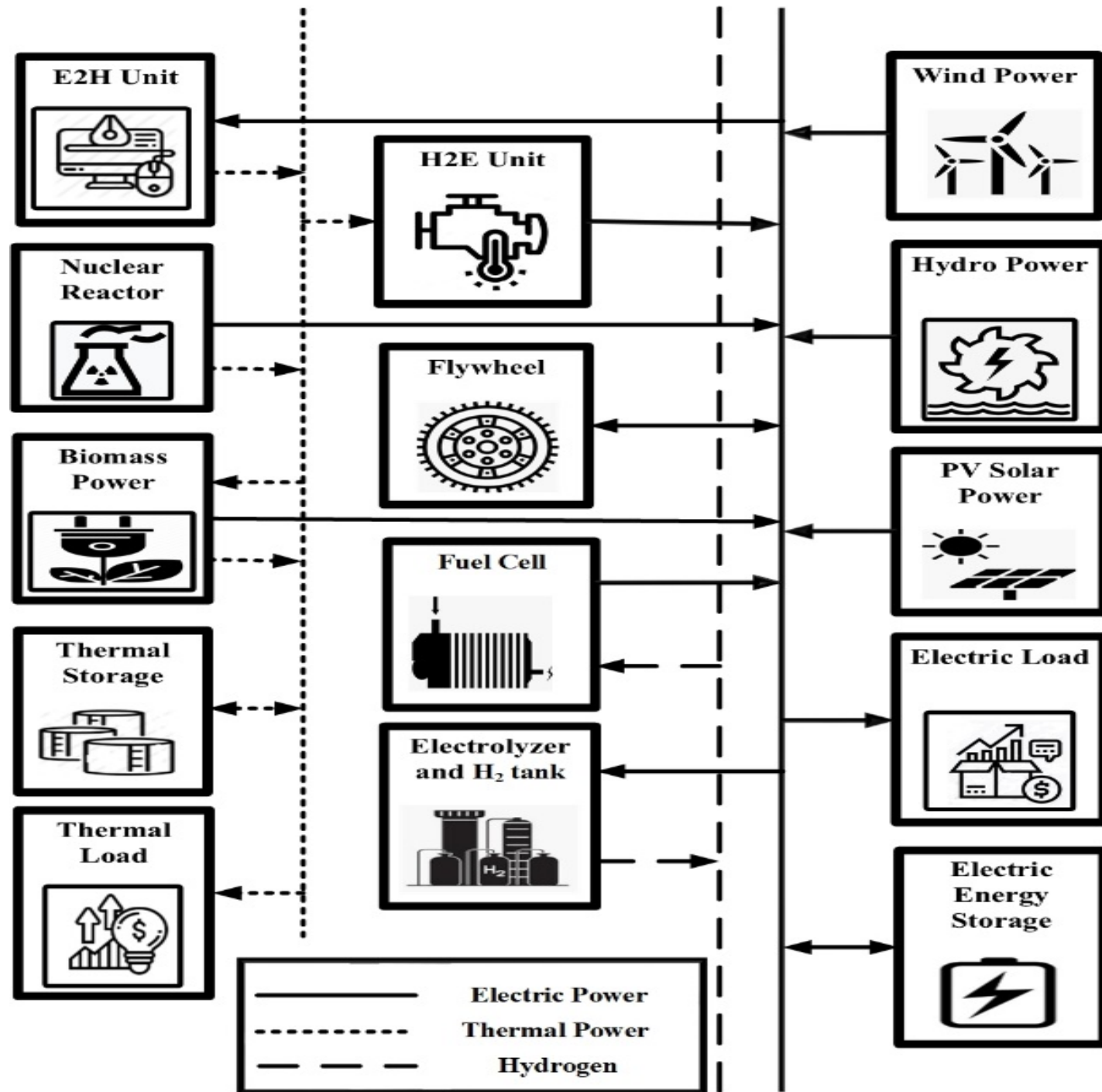
Layers	Function	Role in Resilience
IRD (Inherent Resiliency Design)	Built-in resilience through system design features such as energy storage, redundancy, backup generation, and cogeneration.	Reduces the likelihood of performance degradation and provides the first line of defense against disturbances.
RCS (Resiliency Control System)	Uses sensors, monitoring systems, and control logic to continuously track system conditions and implement corrective actions.	Maintains system operation during disturbances by adjusting supply, storage, and load conditions in real time.
RAM (Resiliency Alarm Management)	Provides resilience alarms, performance warnings, and operator notifications when critical limits are approached.	Improves situational awareness and supports timely decision-making before system performance is significantly affected.
RIS (Resiliency Interlock System)	Automatically activates protection mechanisms, backup resources, and emergency response actions when critical conditions occur.	Prevents major system failures and accelerates recovery when response times are too short for manual intervention.



Double bowtie (IRL)



Nuclear-Renewable Integration Strategies



Nuclear Power Analysis

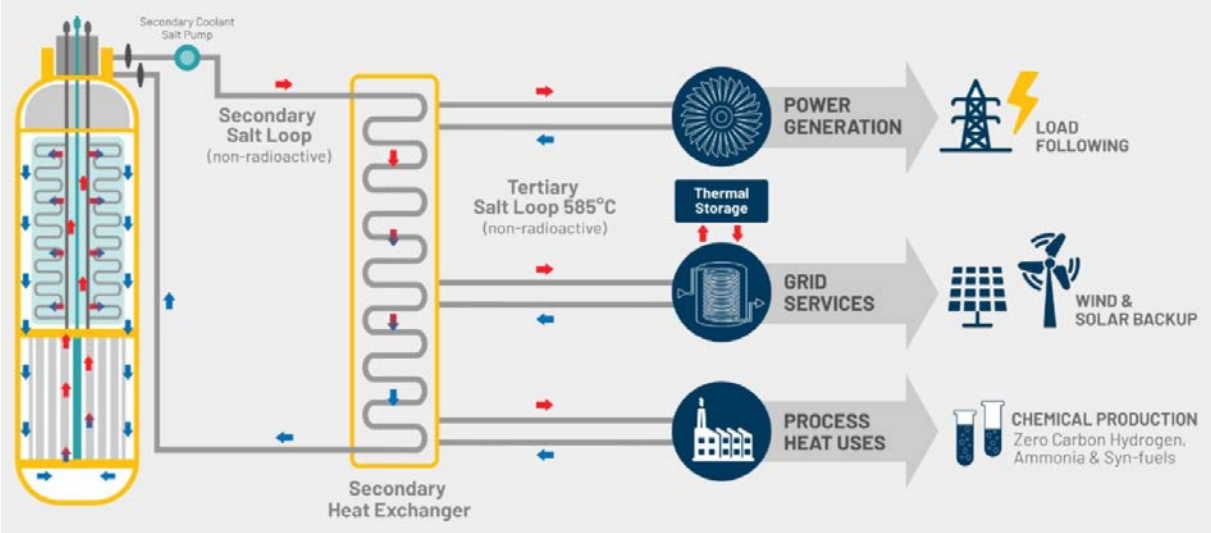
- **Nuclear Reactor Limitations:**
 - New designs (Generation III+ and IV) have load-following capabilities but were not originally designed for it.
 - Each design has its own operational limitations for load-following.

- **Evaluation Challenges:**
 - Existing models and simulators help understand physical effects but are insufficient for real-life conditions.
 - Difficulty in evaluating systems considering grid demand and flexibility for integrating renewable hybrid energy systems.

- **Need for Comprehensive Evaluation:**
 - Assessing the performance of individual components is not enough.
 - Understanding cooperative interactions between different energy sources and load demand is essential.

Acronym	Type	MWe	Load Following (%pm)
BWRX-300	BWR	300	0.50%
NuScale	PWR	710 (6x12)	0.67%
IMSR-400	MSR	194	5.00%
ACR-1000	HWR	1200	0.40%

Source: International Atomic Energy Agency. "Advanced Reactors Information System (ARIS)."

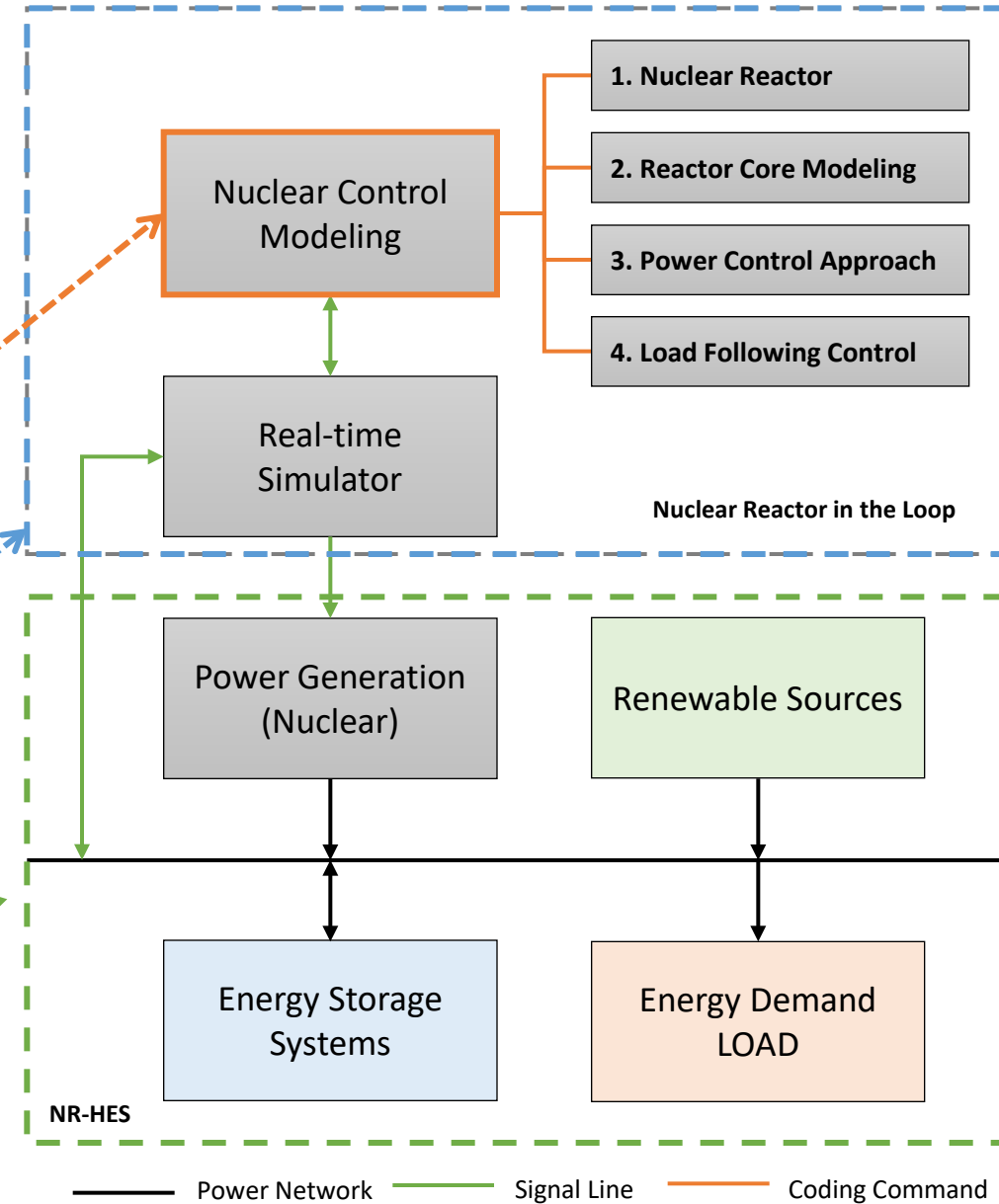
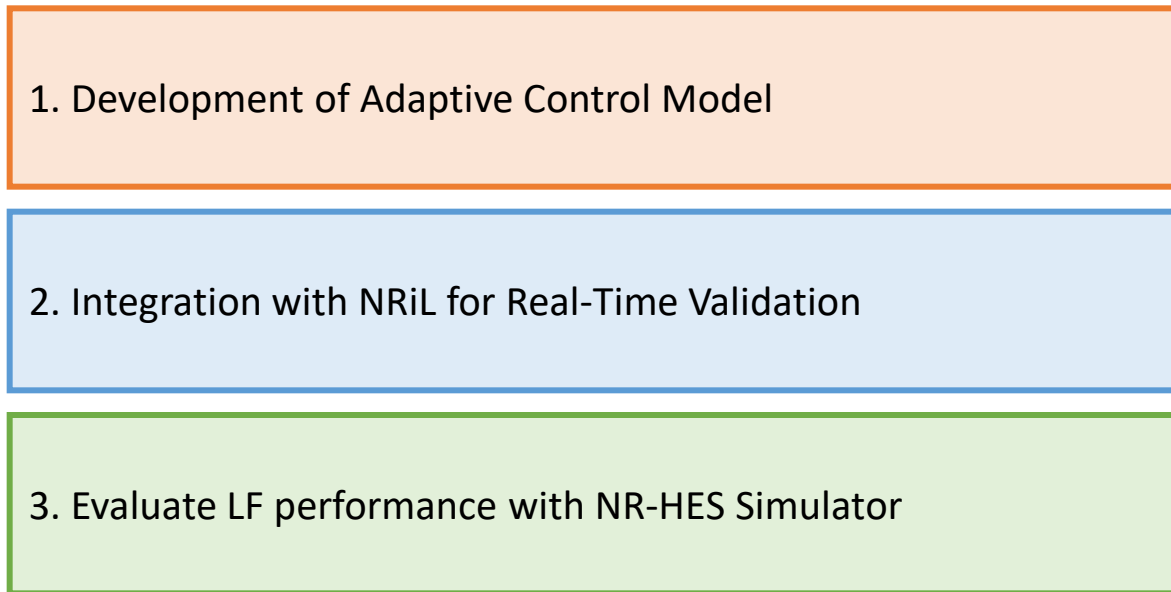


Source: Terrestrial Energy. "Versatile." Terrestrial Energy

Proposed Approach



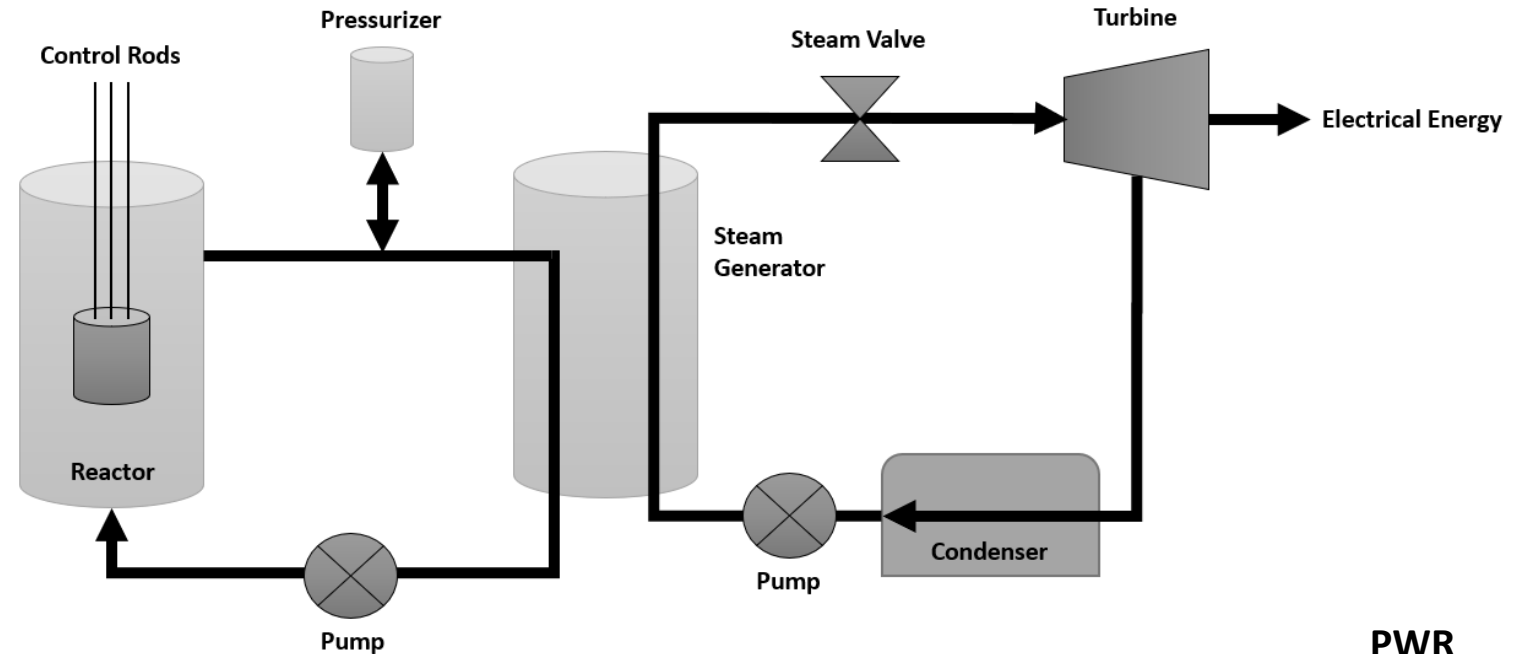
- Contribute to the development and evaluation of Nuclear-Renewable Hybrid Energy Systems (N-RHES) with Load Following capabilities.
- Address the complexities of transitioning to a zero-carbon future by integrating nuclear and renewable energy.
- Employ a three-fold approach:



Development of Adaptive Control Model



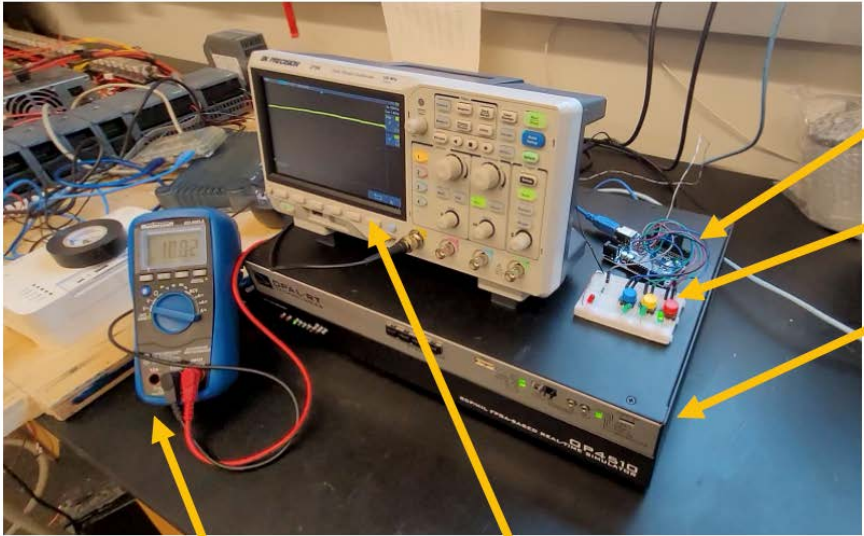
- A nuclear power plant relies on the controlled fission of heavy nuclei to produce heat, which is then used to generate steam. This steam drives turbines connected to generators, producing electricity. The interrelation of the following physical phenomena ensures the efficient and safe production of nuclear power:
- **Fission and Heat Generation**
- **Moderation and Control**
- **Heat Transfer and Steam Production**
- **Mechanical to Electrical Energy Conversion**
- **Cooling and Safety Systems**



Integration with NRiL for Real-Time Validation



- Lab Setup



Multimeter
Measure DC Voltage

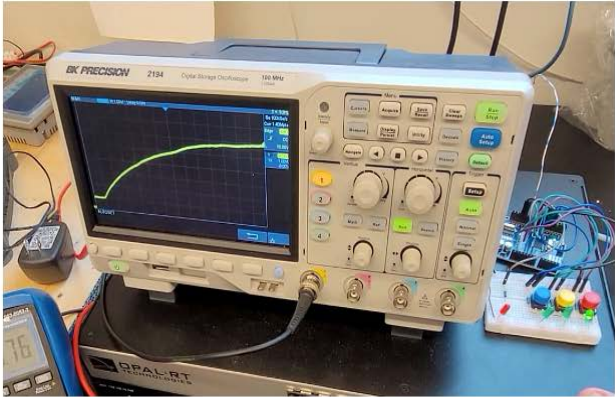
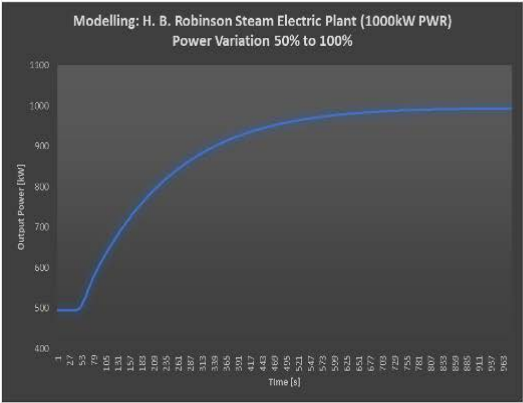
Oscilloscope
Display output power curve

<- Lab Setup

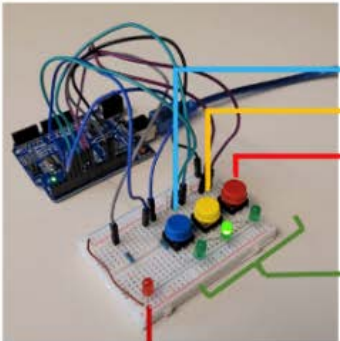
Hardware Integration (Arduino)
Nuclear Reactor Modeling

User Input
Blue button: Set 50% Power Rate
Yellow button: Set 80% Power Rate
Red button: Set 100% Power Rate

OPAL-RT
Real Time Simulator



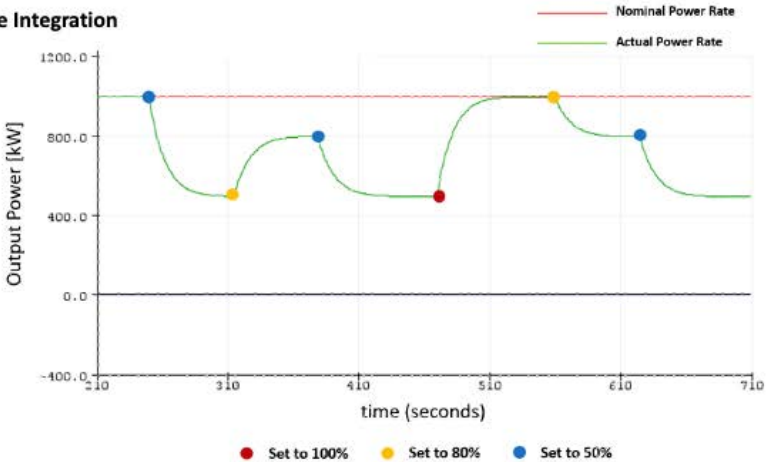
Hardware Integration



- Set the Power Rate at 50%
- Set the Power Rate at 80%
- Set the Power Rate at 100%

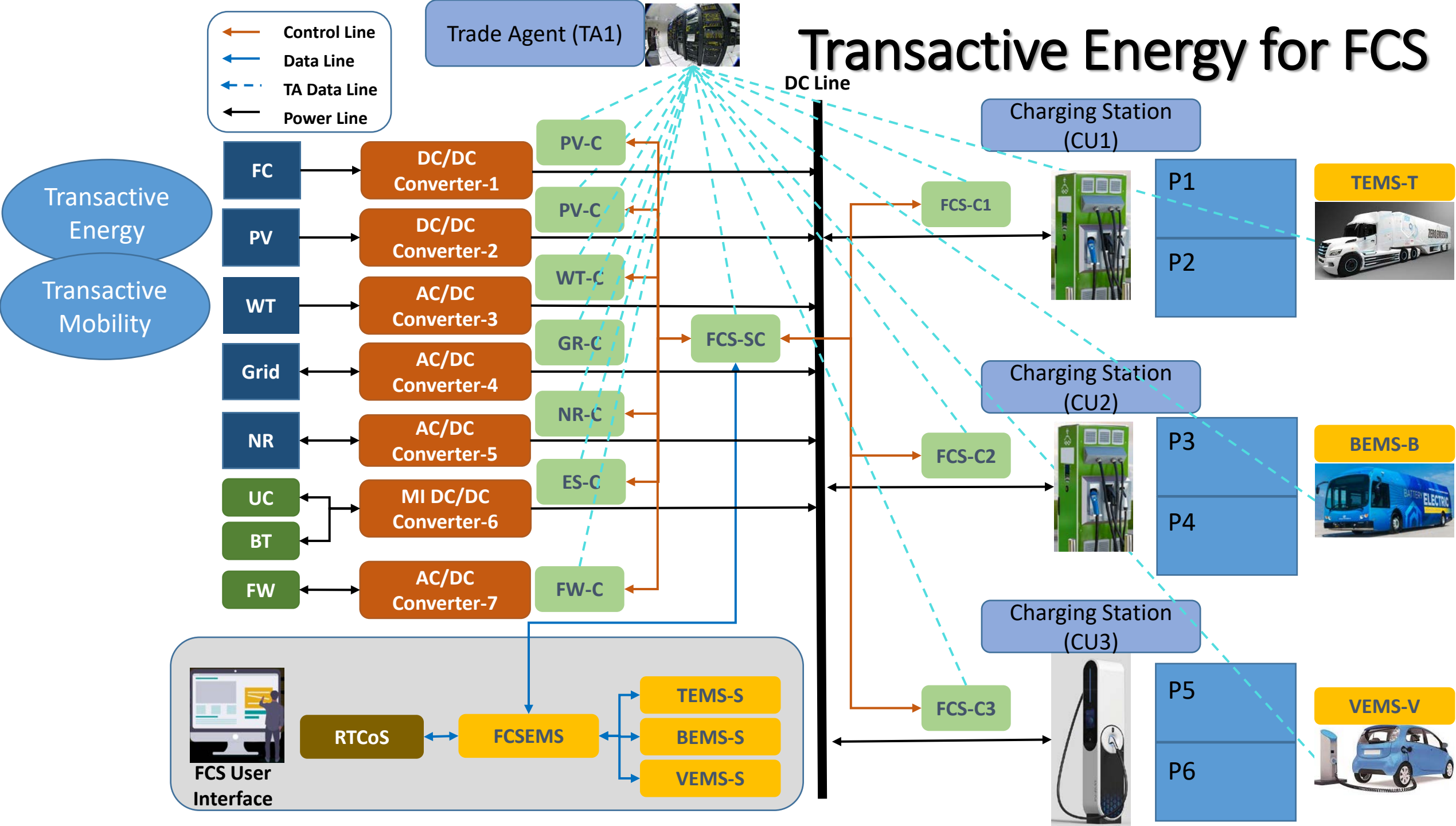
LEDs to indicate which power rate is set

LED to indicate that the Load Following is in process



Design and Simulation of a Nuclear-Renewable Micro Hybrid Energy System for Electric Vehicle Charging Stations

Transactive Energy for FCS



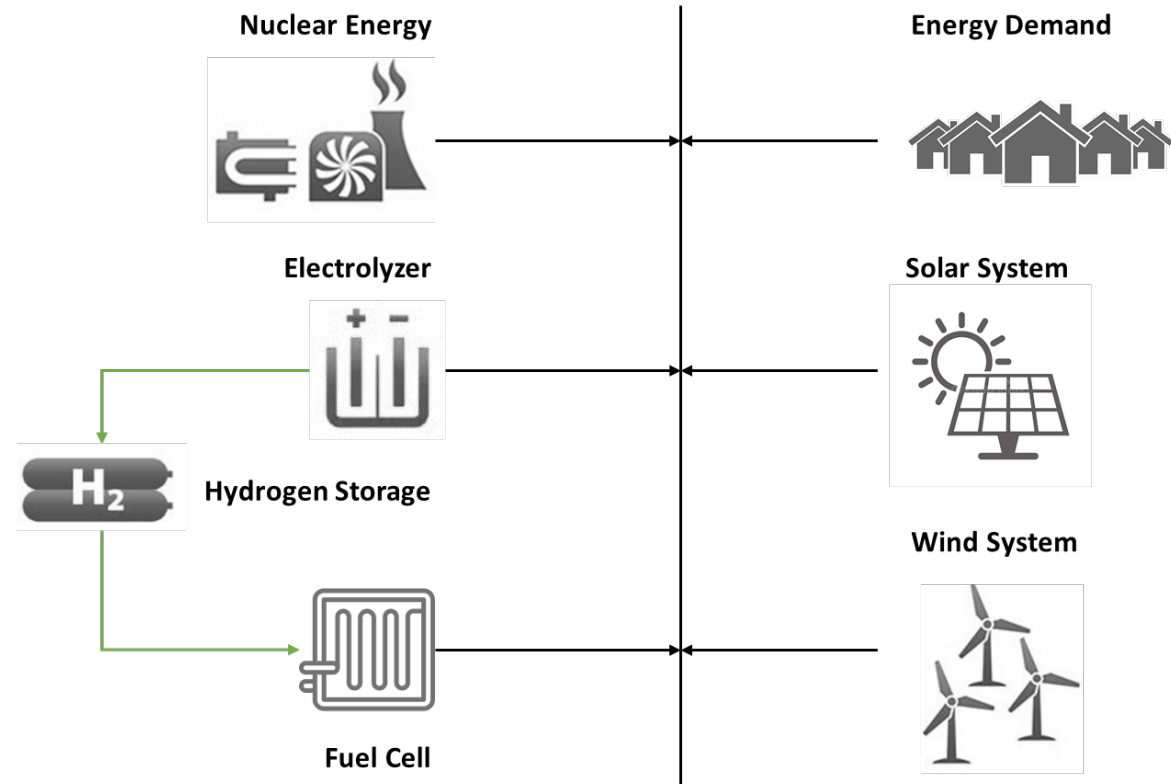
Optimal Ratio of Nuclear- Renewable Energy Systems

System Schematic

- Base Case



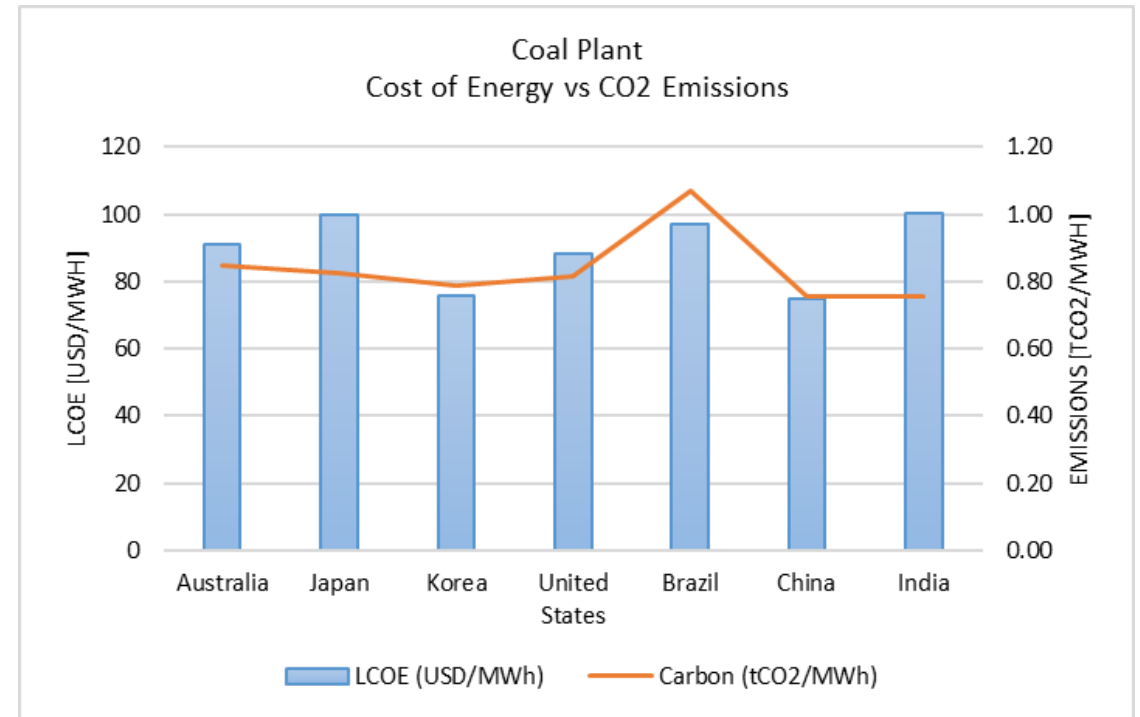
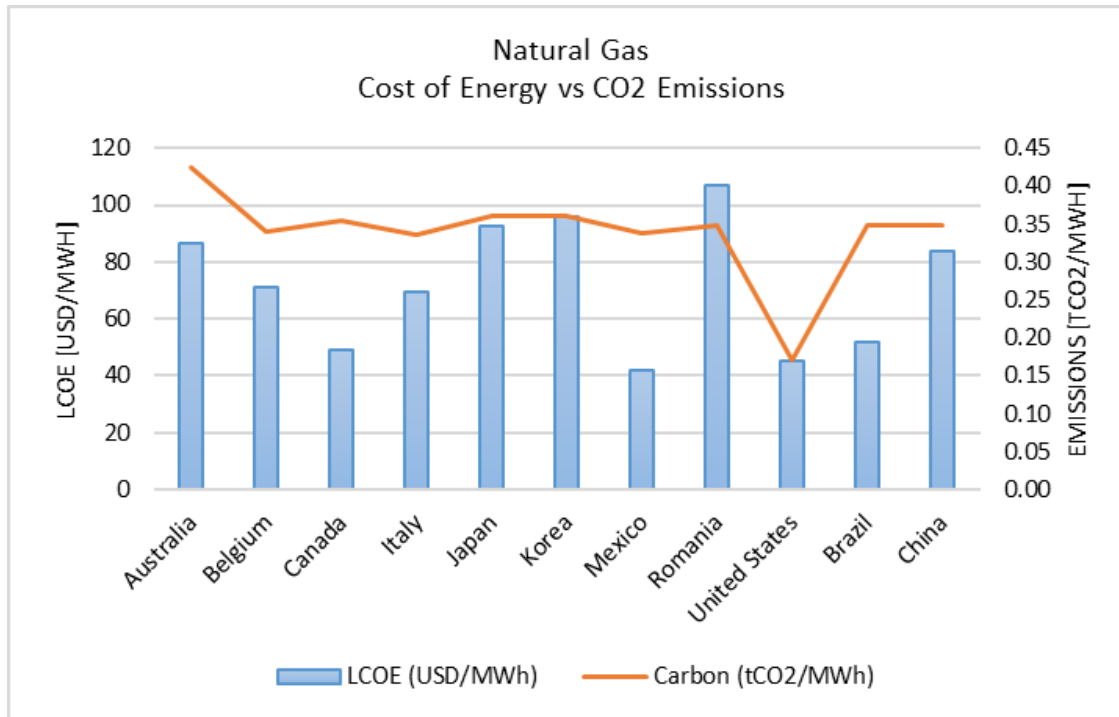
- Proposed System



Base Case: Cost of Generating Electricity

Gas and Coal Fired Power Plant

- Reference:
 - Projected Costs of Generation Electricity
 - 2020 Edition
 - International Energy Agency (IEA) and Nuclear Energy Agency (NEA)



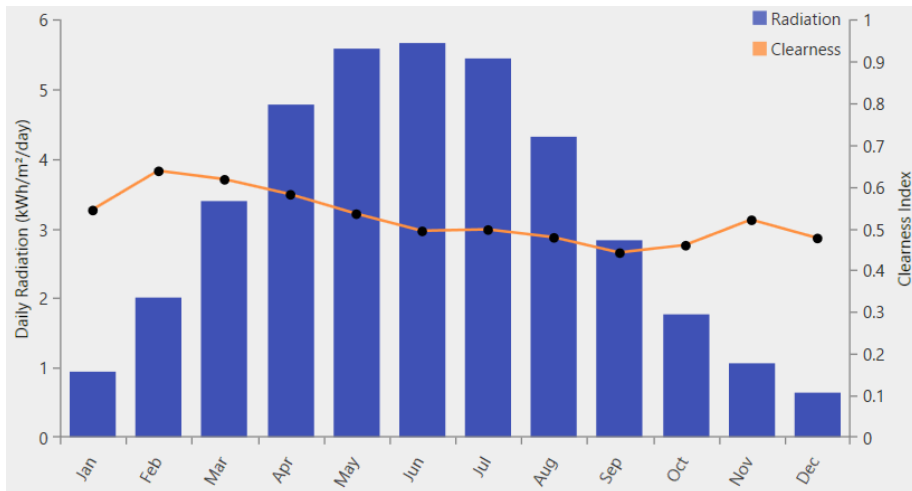
Input

Renewable Resources

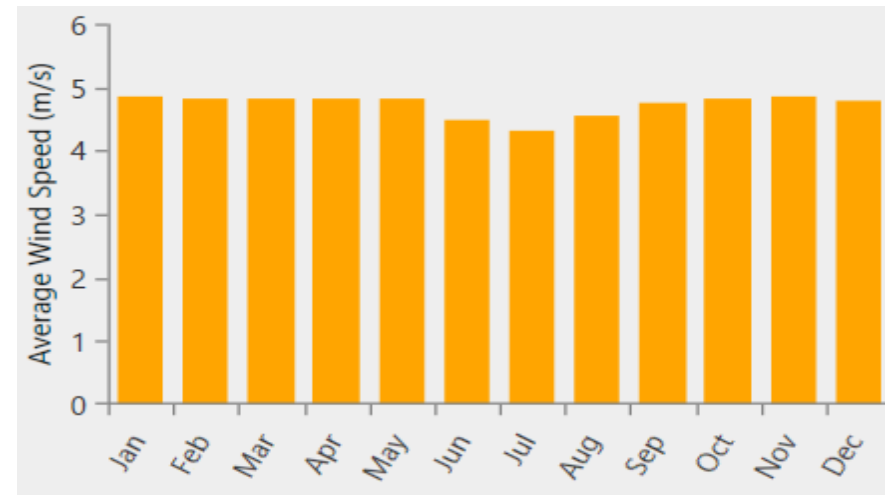
- Location: Remote Community
 - Northern Ontario, Canada
- Database:
 - NASA Prediction of Worldwide Energy Resource (POWER)



- Solar Resource: 3.2 kWh/m²/day



- Wind Resource: 4.73 m/s

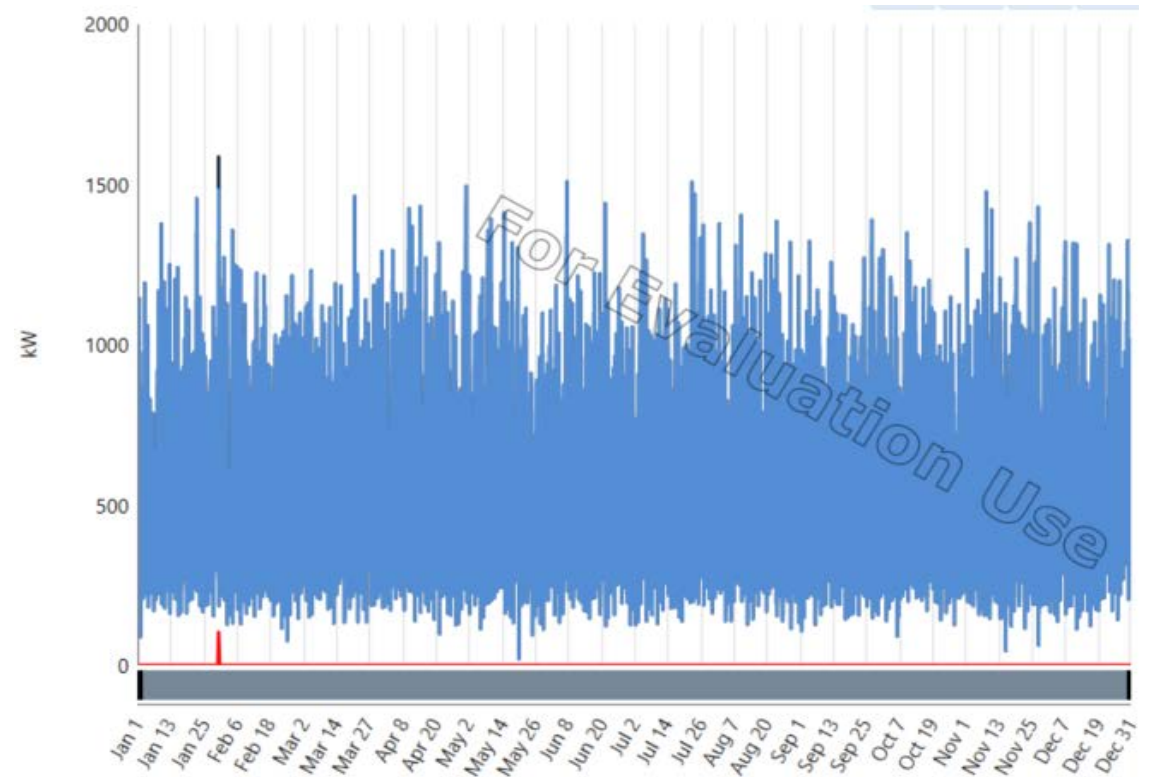


Input

Energy Profile

- Generic energy profile for a remote community

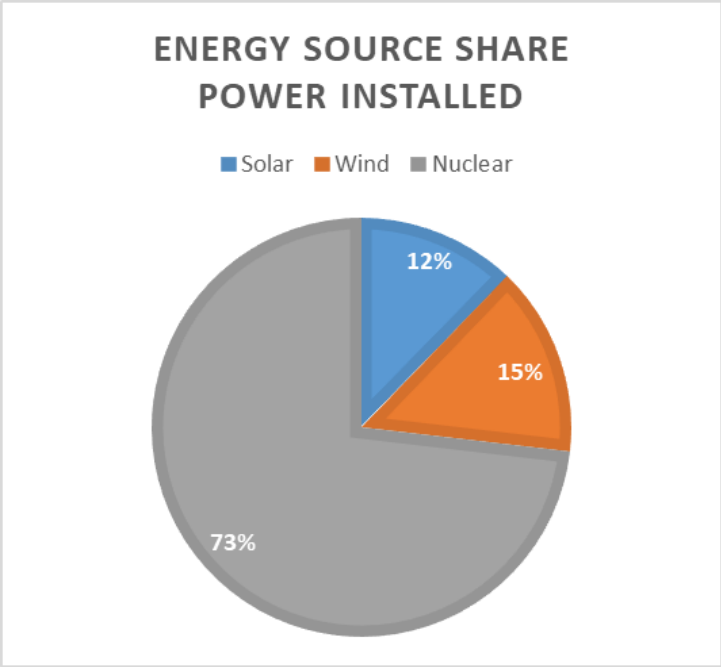
Metric	Value	Unit
Average Consumption	14,000	kWh/day
Average Power	583.33	kW
Power Peak	1,586.4	kW
Load Factor	0.37	-



Case Study - Results

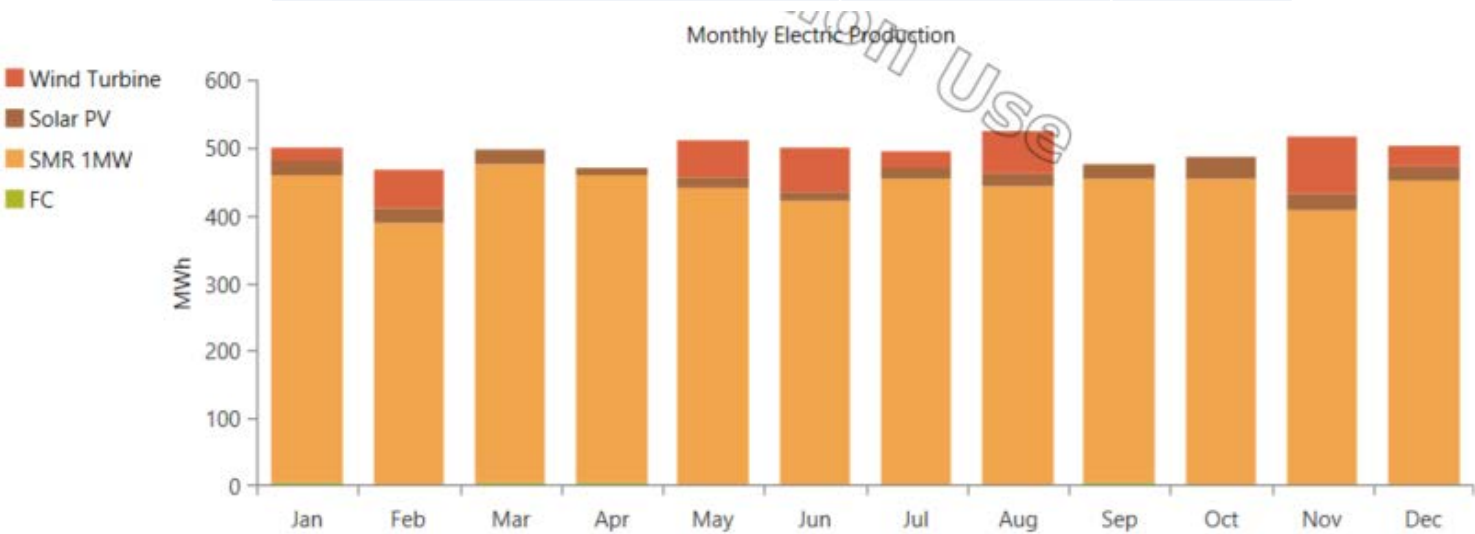
Electrical Analysis – Ratio Nuclear vs Renewable

- Simulation: HOMER Pro
 - System configuration that provided lowest Cost of Electricity: **Levelized COE \$0.5148**



Power Installed	kW	%
Solar Energy	167	12
Wind Energy	200	15
Nuclear Energy	1000	73

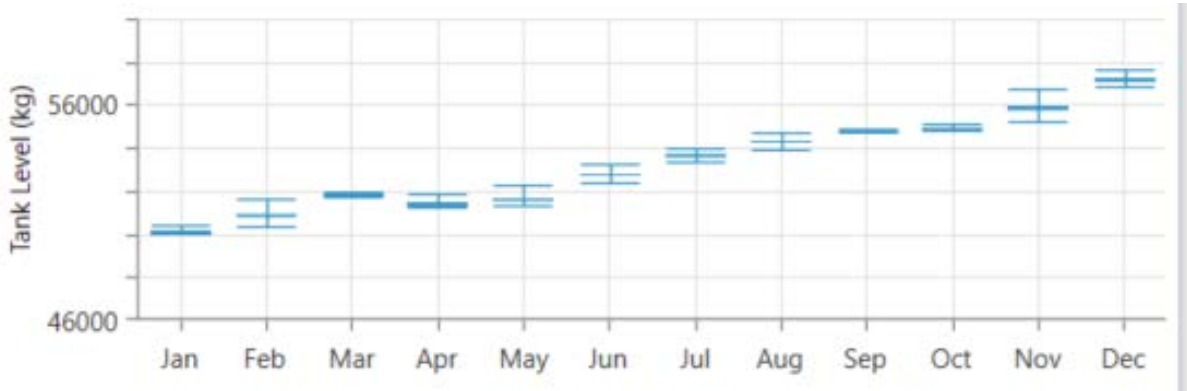
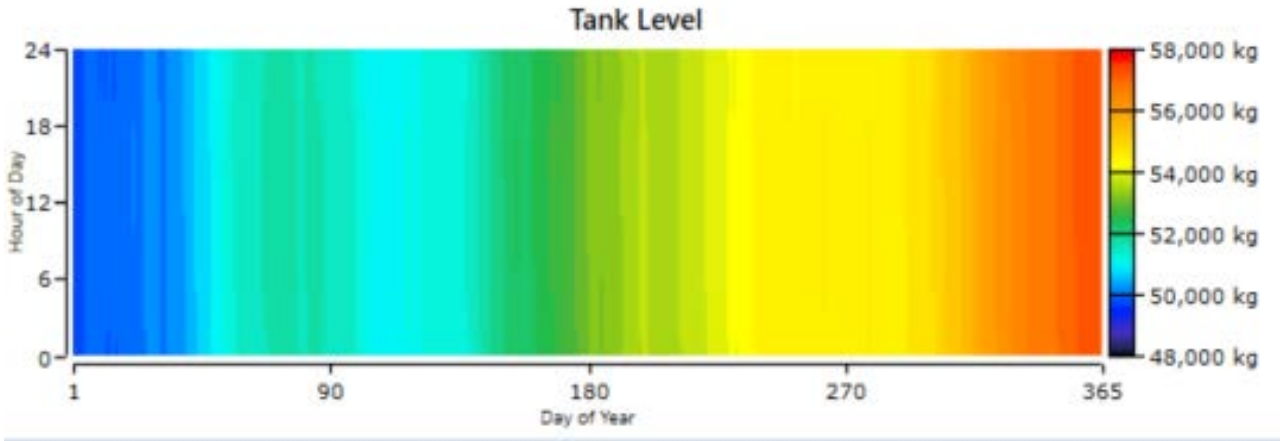
Energy Generation	kWh/yr	%
Solar Energy	233,793	3.94
Wind Energy	403,680	6.8
Nuclear Energy	5,257,640	88.5
Generator – Fuel Cell	44,025	0.74



Case Study - Results

Energy Storage – Hydrogen Tank

Metric	Value	Unit
Hydrogen Storage Capacity	100,000	kg
Energy Storage Capacity	3,334	MWh
Autonomy	5,714	hr



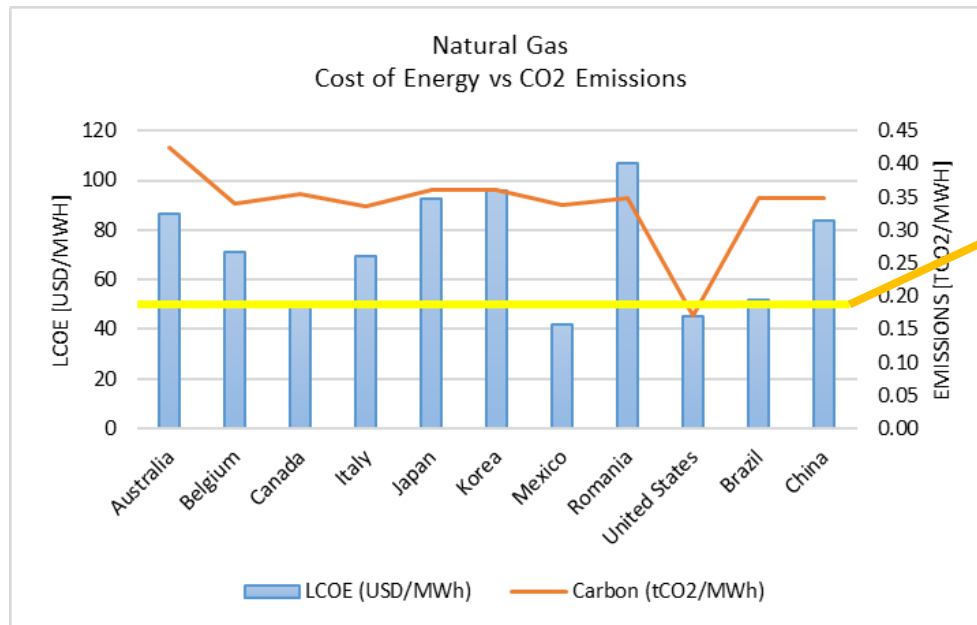
Case Study - Results

Economic Analysis

- Proposed System:

Metric	Value
NPC – Net Present Cost	\$40,175,660
Levelized Cost of Energy	\$0.5148
Operating Cost	\$2,239,157.00

- Base Case:



Case Study:

Levelized Cost of Energy: **\$0.5148**

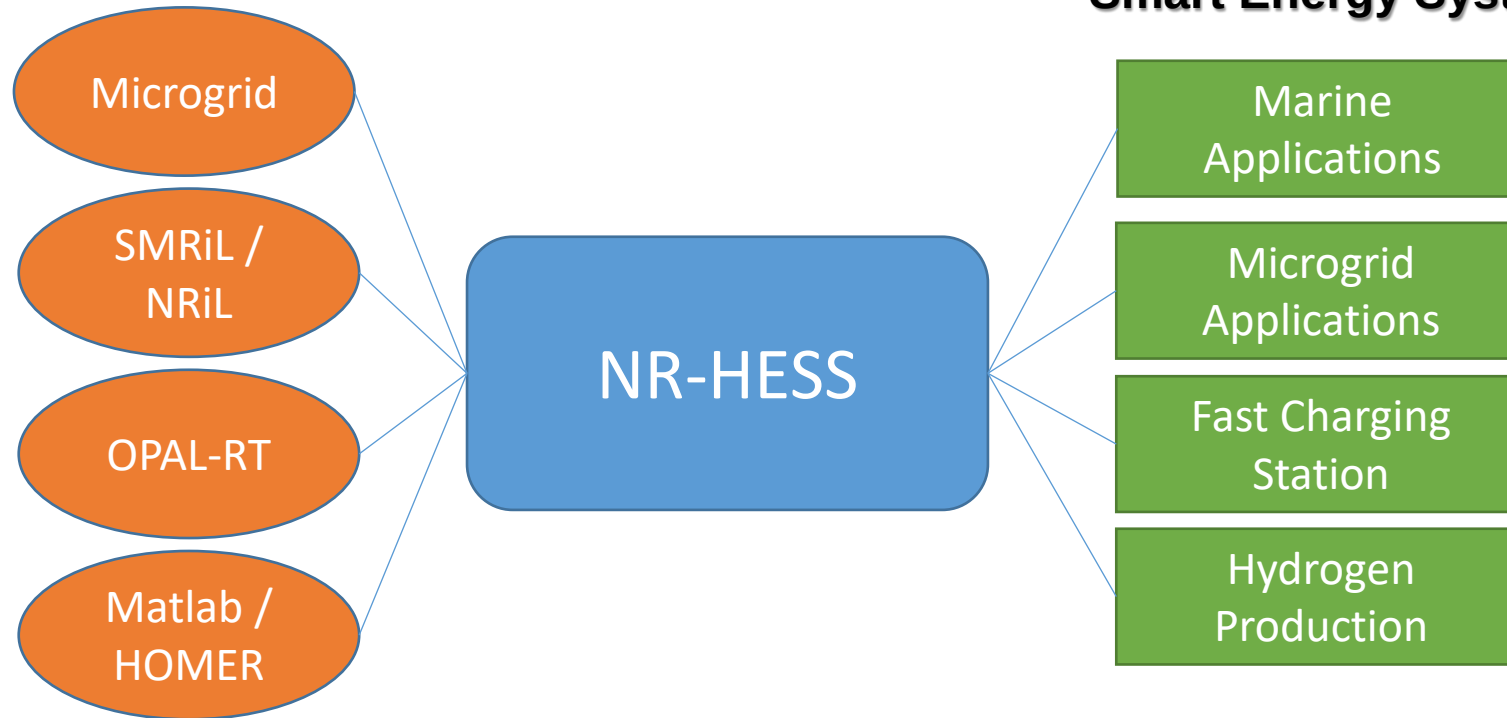
CO2 Emission:

Natural Gas - Canada: **0.36 tCO2/MWh**

Considering energy consumption:
5,110 MWh/year

Total emission using Natural Gas:
1,840 tonnes of CO2 per year

Nuclear-Renewable Hybrid Energy Systems Simulator (NR-HESS)



- Renewable Energy and Energy Storage Systems
- Nuclear Power Technologies
- Nuclear-Renewable Hybrid Energy Systems
- Demand Side Management
- Micro Hybrid Energy Systems
- Techno-Economic Analysis
- Group Discussions and Individual Work

SIMULATOR INPUT

- Energy Demand
- Daily Profile Projection:
 - **Projection Base:** Library of daily demand profiles.
 - **Daily Demand (Per-Unit):** Hourly values set by the user, representing the energy demand at different times of the day. The "per-unit" concept normalizes demand to a base value, allowing for easier comparison and analysis of different profiles.
- Key Features:
 - This section is essential as it influences how energy sources will operate throughout the day.
 - Similar to the yearly projection, users can save up to 10 different daily profiles.

Nuclear-Renewable Hybrid Energy System Simulator

Energy Demand | Location | System Schematic

ENERGY DEMAND PROJECTION

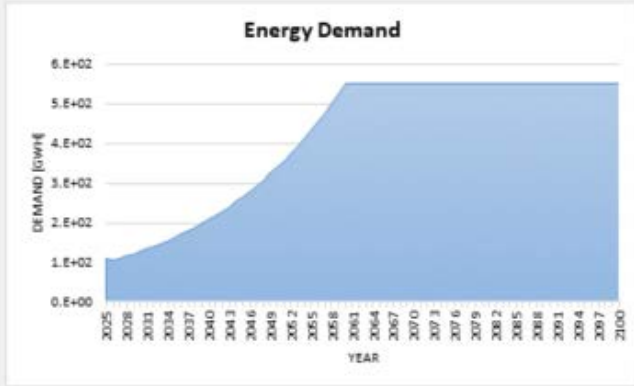
Projection Base: Demand 1

Energy Demand [GWh]: 100

Period [yrs]

2025-30:	5
2030-35:	5
2035-40:	5
2040-45:	5
2045-50:	5
2050-55:	5
2055-60:	5
2060-100:	0

Average growth rate [%]



Energy Demand

DEMAND [GWh]

YEAR

DAILY PROFILE PROJECTION

Projection Base: Profile 2

Daily Demand [Per-Unit]

00:00	0.870406	12:00	1.041952
01:00	0.887757	13:00	0.994681
02:00	0.873541	14:00	1.107912
03:00	0.873630	15:00	1.067146
04:00	0.884214	16:00	1.105163
05:00	0.879654	17:00	1.063797
06:00	0.787328	18:00	1.204542
07:00	0.818759	19:00	1.256092
08:00	0.818458	20:00	1.232111
09:00	0.939220	21:00	1.139467
10:00	1.025451	22:00	1.067378
11:00	1.080445	23:00	0.980882



Daily Energy Profile

PU

TIME OF DAY

RANDOM VARIABILITY:

Day-to-day [%]: 10

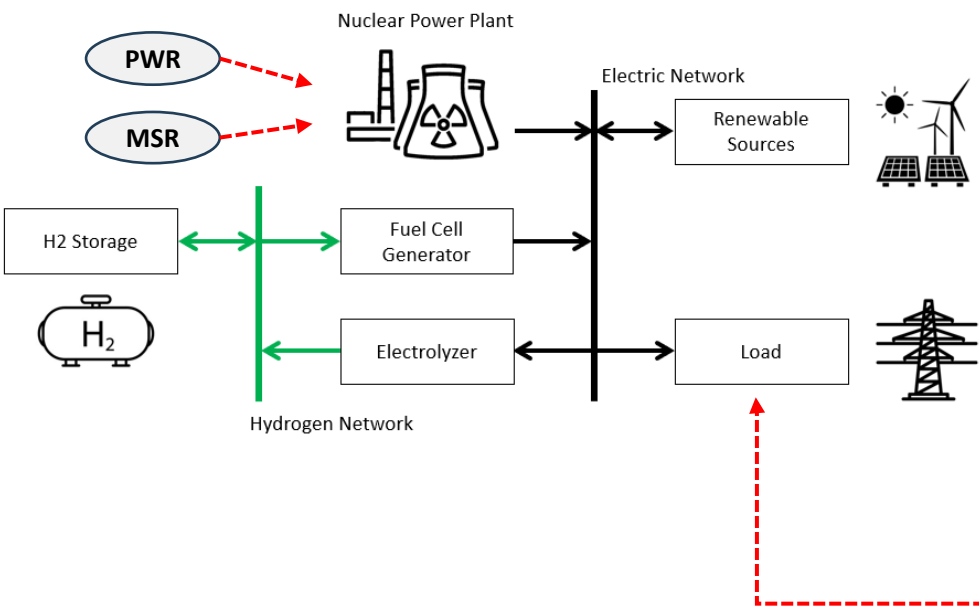
Timestep [%]: 5

Generate Energy Demand

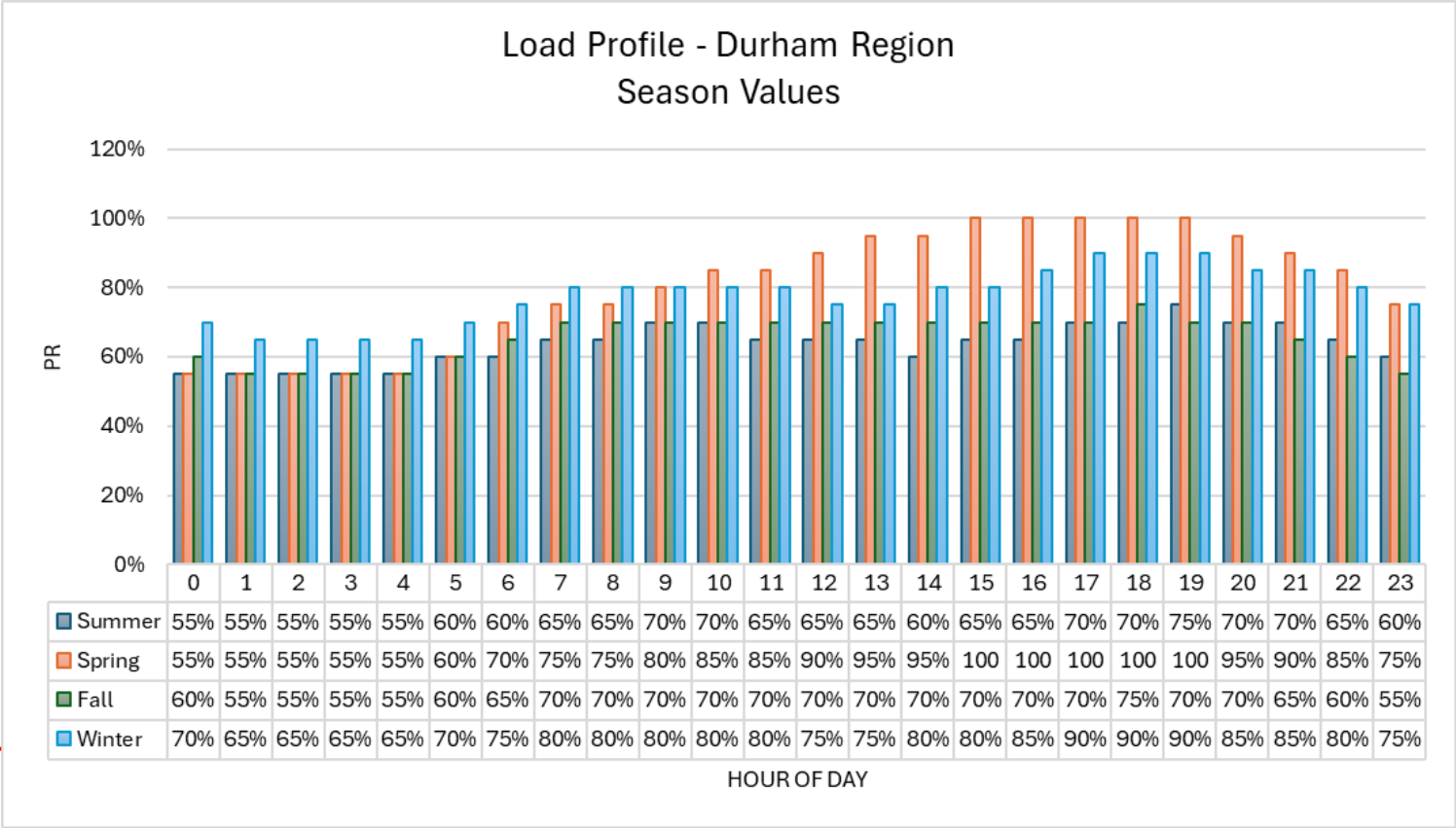
Application in the NRHESS



- Schematic:



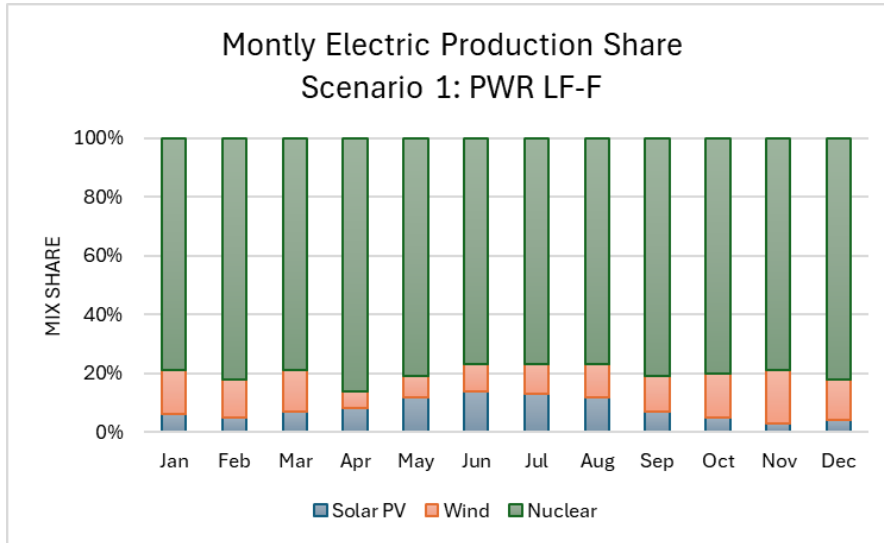
Load Following Profile:



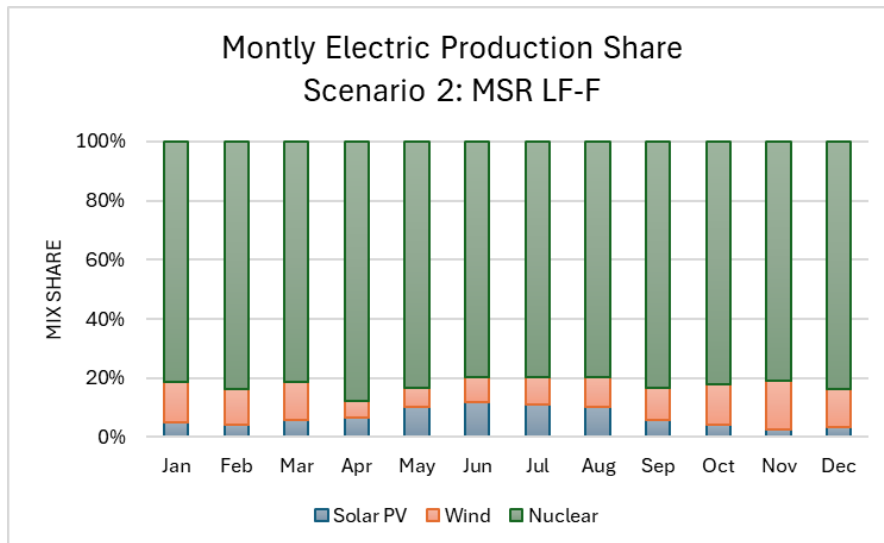
Application in the NRHESS



- Outcomes:
- **PWR Model:**
- **MSR Model:**

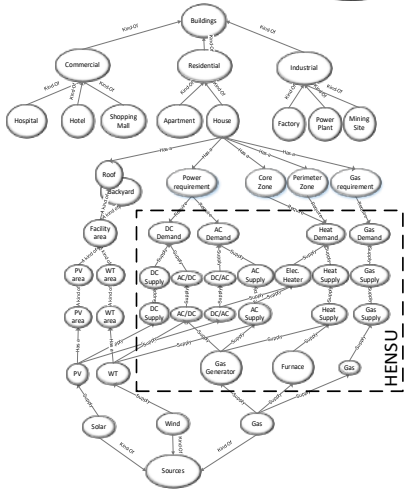
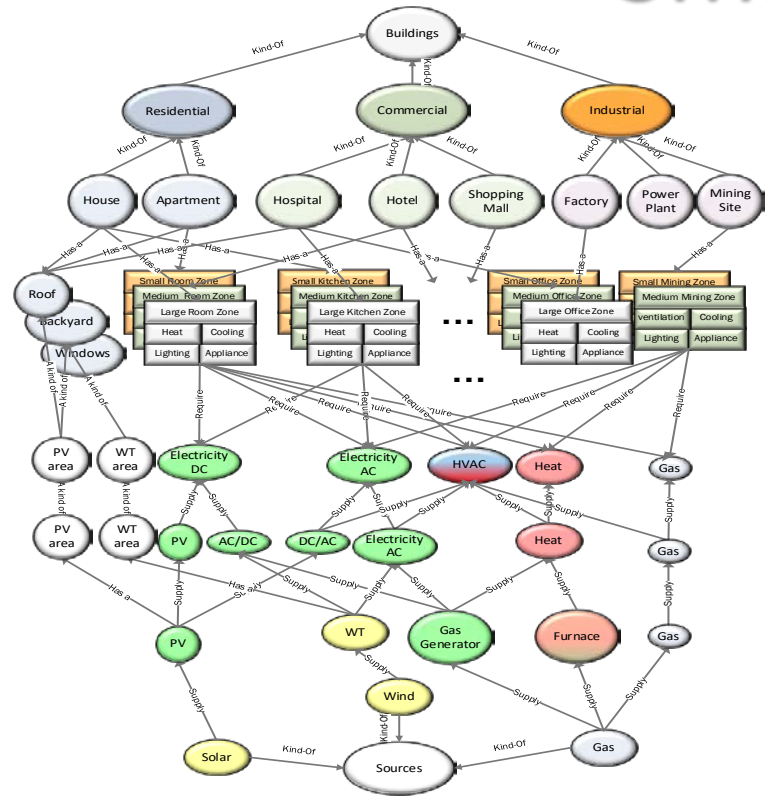


Component	kWh/year	Share
Solar PV	1,082,112,350.37	7.998%
Wind Turbine	1,623,168,525.55	11.997%
Nuclear	10,824,316,488.68	80.005%
Total	13,529,597,364.60	100%
Surplus	7,462,513,344.60	23%
COE	\$ 0.152	

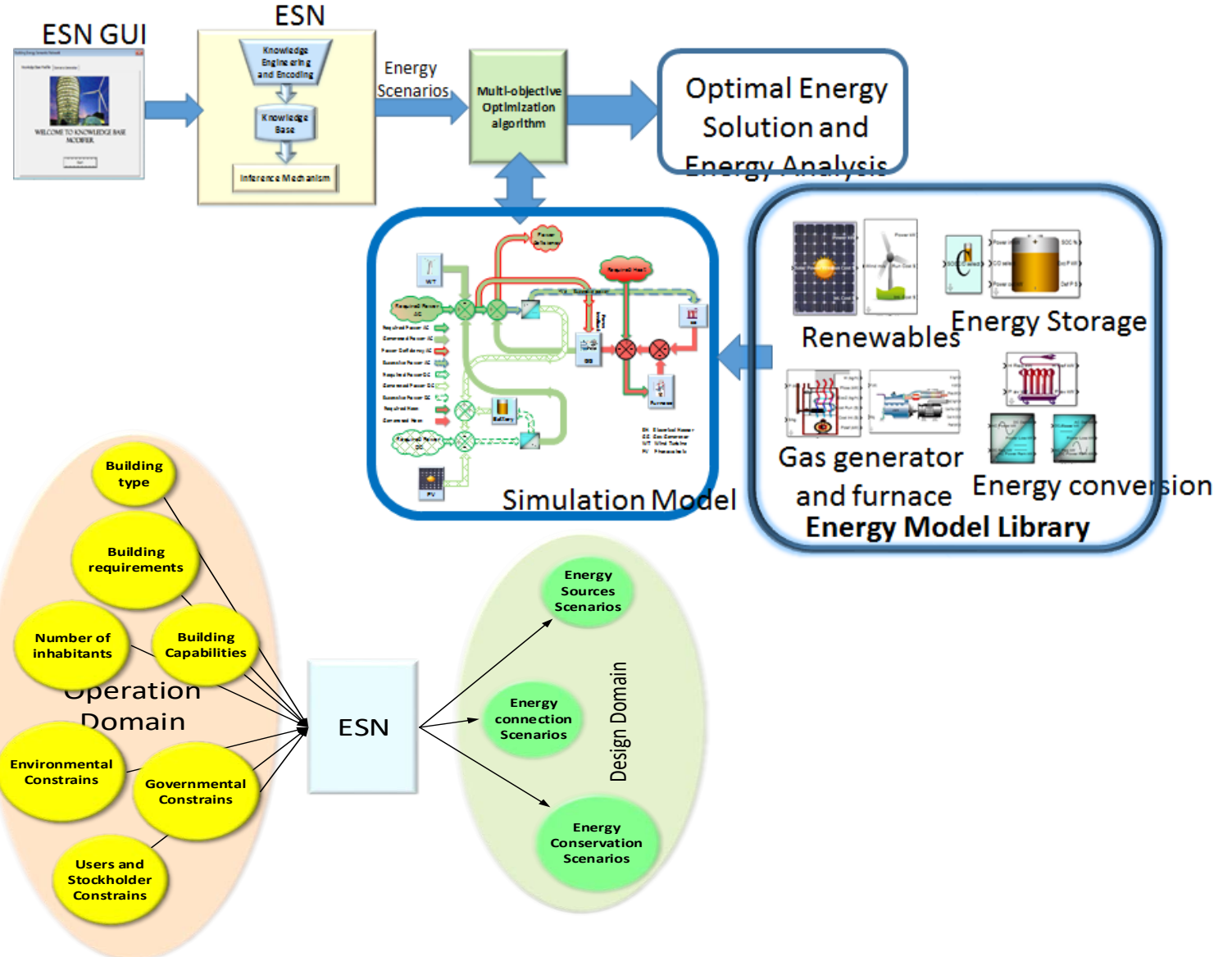


Component	kWh/year	Share
Solar PV	913,906,707.44	6.816%
Wind Turbine	1,464,181,520.71	10.920%
Nuclear	11,030,167,456.05	82.264%
Total	13,408,255,684.20	100%
Surplus	7,341,171,664.20	21%
COE	\$ 0.134	

Smart Energy Infrastructures

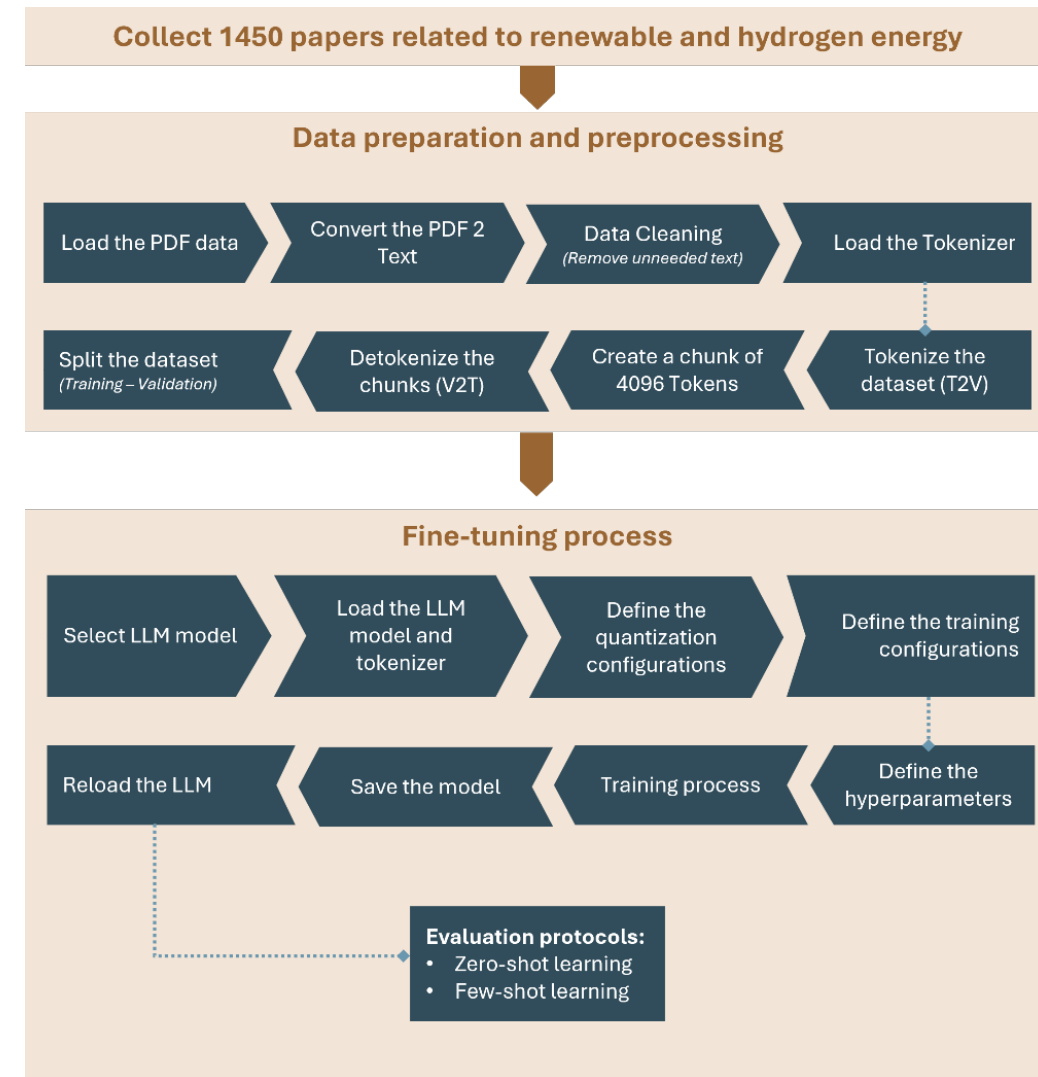


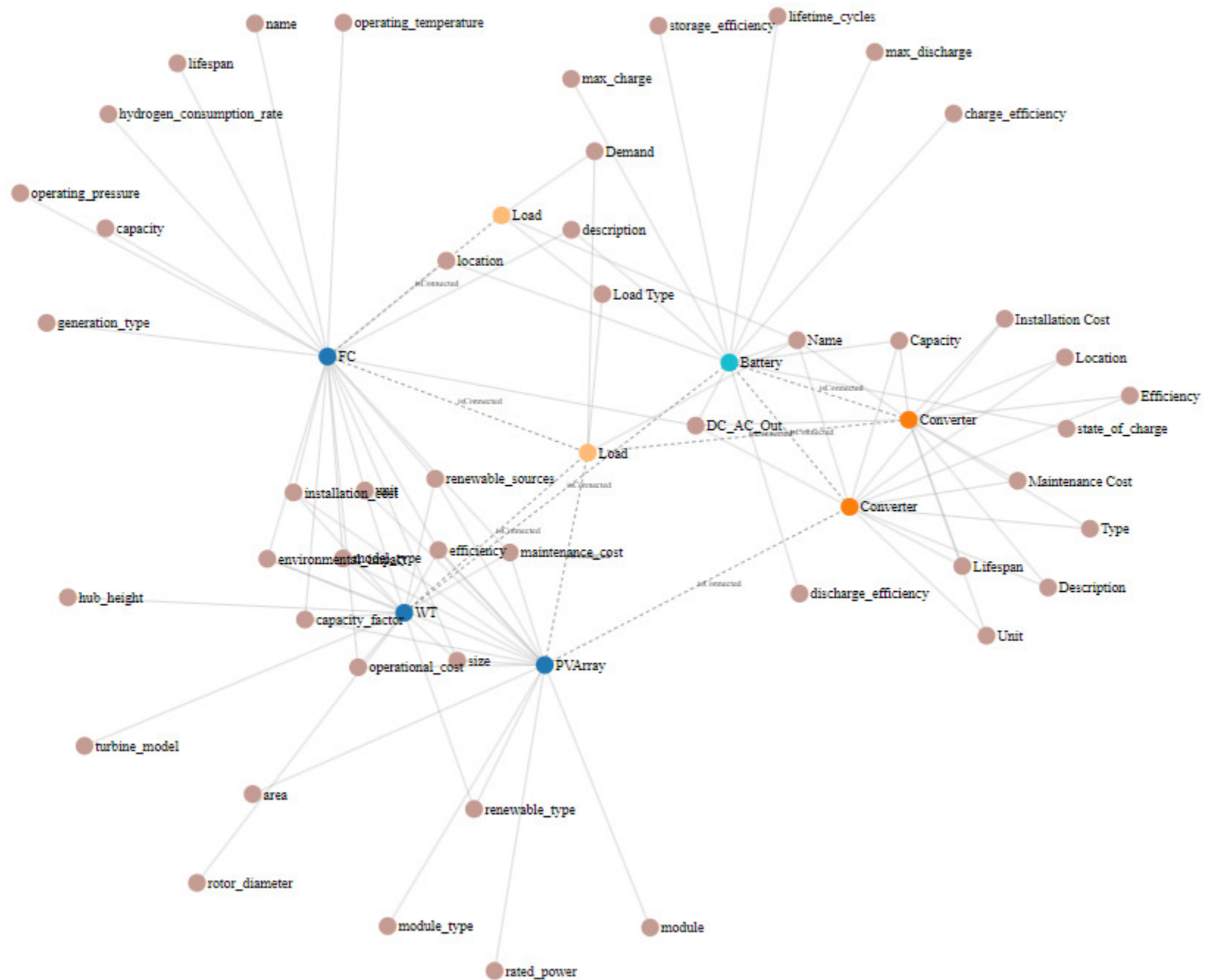
$$C^i = \begin{bmatrix} c_{1,1}^i & \dots & c_{1,J_i-1}^i \\ \vdots & & \vdots \\ c_{J_i,1}^i & \dots & c_{J_i,J_i-1}^i \end{bmatrix}_{J_i-1 \times J_i}$$

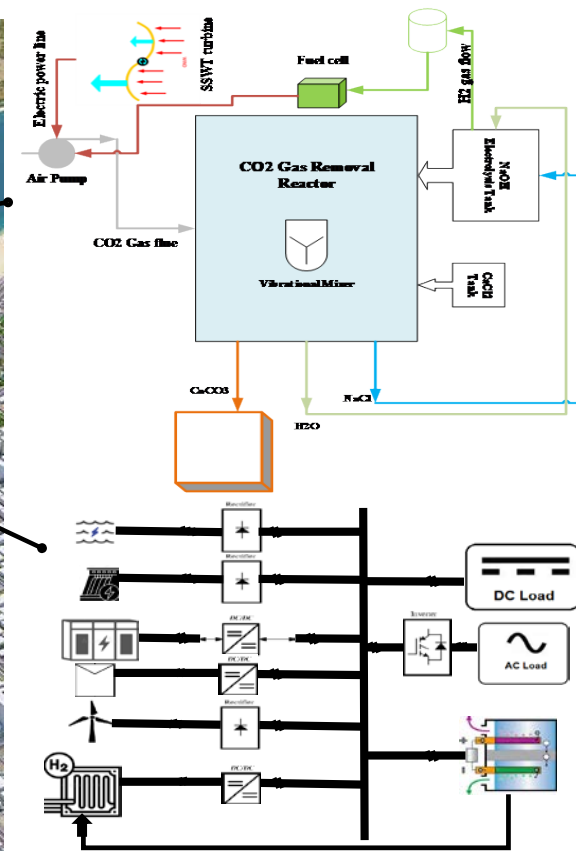
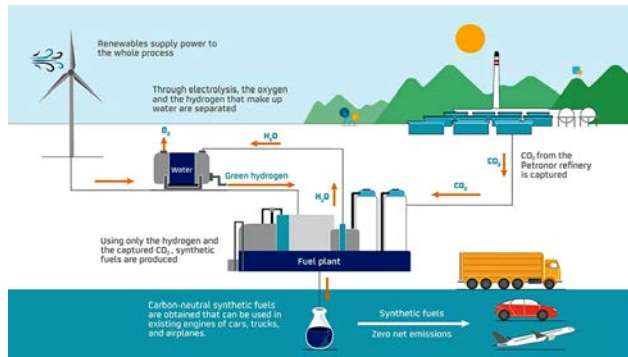
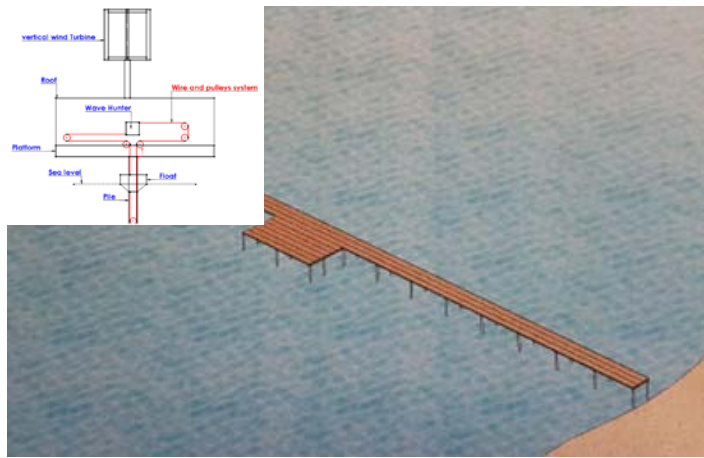


RE-LLaMA, Domain-Specific Large Language Models for Renewable Energy Planning

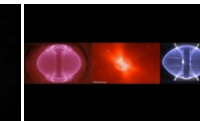
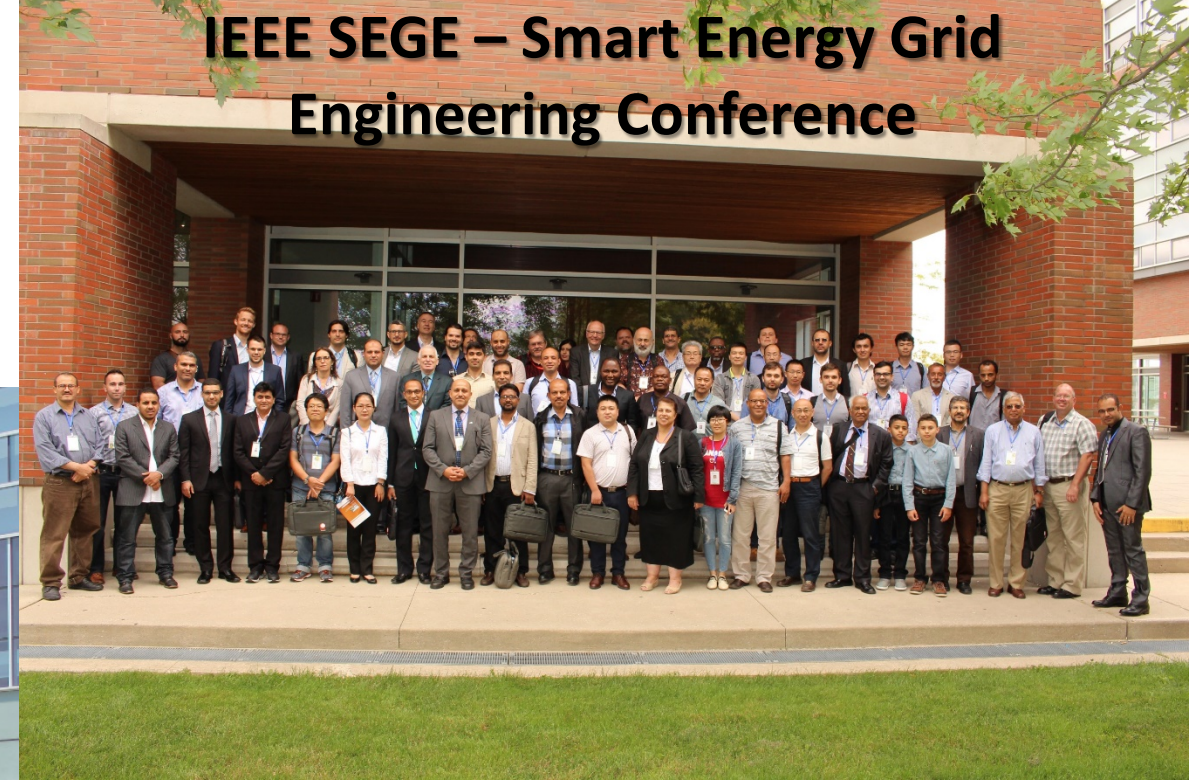
- Data Preparation: Created a comprehensive dataset of 1450 renewable energy papers that underwent rigorous cleaning
- Model Adaptation: Leveraged LLaMA 3.1 8B as the foundation and employed domain-adaptive pretraining with autoregressive next-token prediction to enhance the model's renewable energy domain expertise.







Thank You



Advanced Plasma Engineering Lab



Energy Safety and Control Lab