2035 Outlook of Korea Power System based on Optimal Investment Approach:

How the falling cost of clean energy can help Korea accelerate decarbonization in electricity sector by 2035

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Agenda

Overview

- Project Drivers and Context
- Model, Data, Assumptions and Scenarios
- Results
- Policy Recommendations

Project Drivers and Context

For Korea, is a more aggressive clean energy target feasible and cost effective, while reducing energy supply risk from fossil fuel import?

- Given rapid cost reductions in solar, wind, and battery storages, can Korea achieve deep decarbonization technically feasible and cost effective in the electricity sector by 2035?
- What would be optimal generation mix considering the falling cost of clean energy subject to the national emission target?
- What would be needed for achieving 80%+ clean energy target in Korean policy environment?

Optimal Investment Model (PLEXOS)

For this study, we built **an integrated transmission and generation expansion planning model** with optimal investment decisions and hourly dispatches

- **Obj. function**: min [Generation cost + O&M cost + Generator investment cost + Transmission investment cost + Storage investment cost – Salvage value]

- **Reliability constraints:** Planning reserve (22%) for peak time, Operating reserves
- **Generation constraints:** Max/Min gen., Ramp up/down, Min up/down time
- **Renewable constraints:** Regional potential cap, annual deployment cap
- **Transmission constraints:** Max rating (Constrained rating considering N-1)
- **Emission constraints:** Annual GHG emission cap
- **Simulation period:** 2022 ~ 2035 / **Simulation time unit:** an hour

Optimal Investment Model (PLEXOS)

Handling complexity of model, 2-step optimization is used

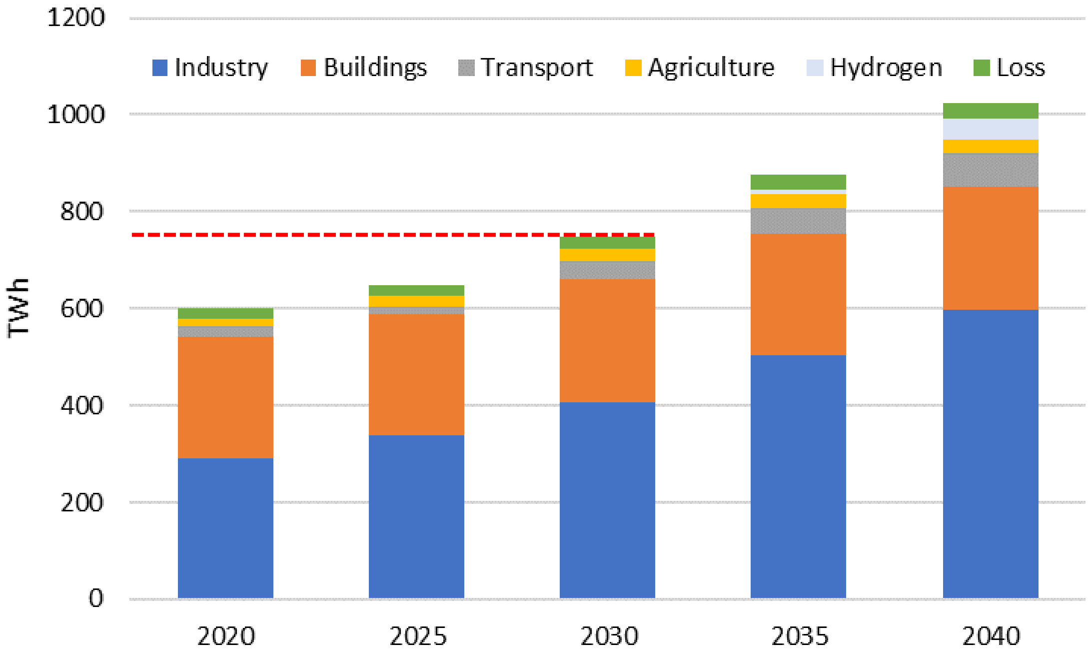
- **First step(Long-term planning):** 3-year rolling optimization with 1-year overlap, 10 representative days in a year

- **Second step(mid-term and short-term planning):** Operation and maintenance schedule using results of the first step as input

- Mid-term: Maintenance and energy storage operation schedule
- Short-term(daily): Hourly dispatch for 365 days

Electricity Demand

- A bottom-up demand forecast scenario that considers electrification in each sector (K-MAP project)
- Transmission and distribution loss: 3.5%
- Demand increase by 29% (2030) and 75% (2040), compared to the 2020 baseline
- Projected electrification rates in 2035 (Industry 31%; Buildings 63%; Transport 35%)



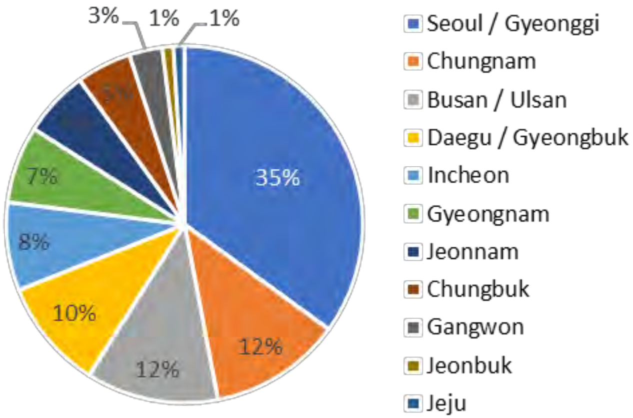
Source: NEXT Group et al. (2022) 2050 Climate Neutrality Roadmap for Korea: K-Map Scenario

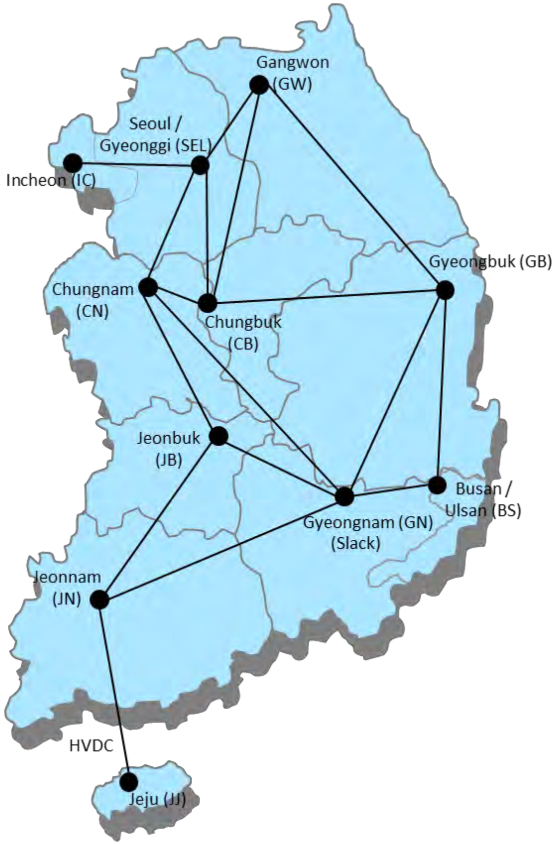
Transmission Network in the Model

o 11 Nodes (Reduced Network)

- 10 nodes in the Land, 1 node in Jeju
- 17 lines between nodes
  Max Flow – short-term, long-term, emergency
  JJ-JN: HVDC(fixed load, band)

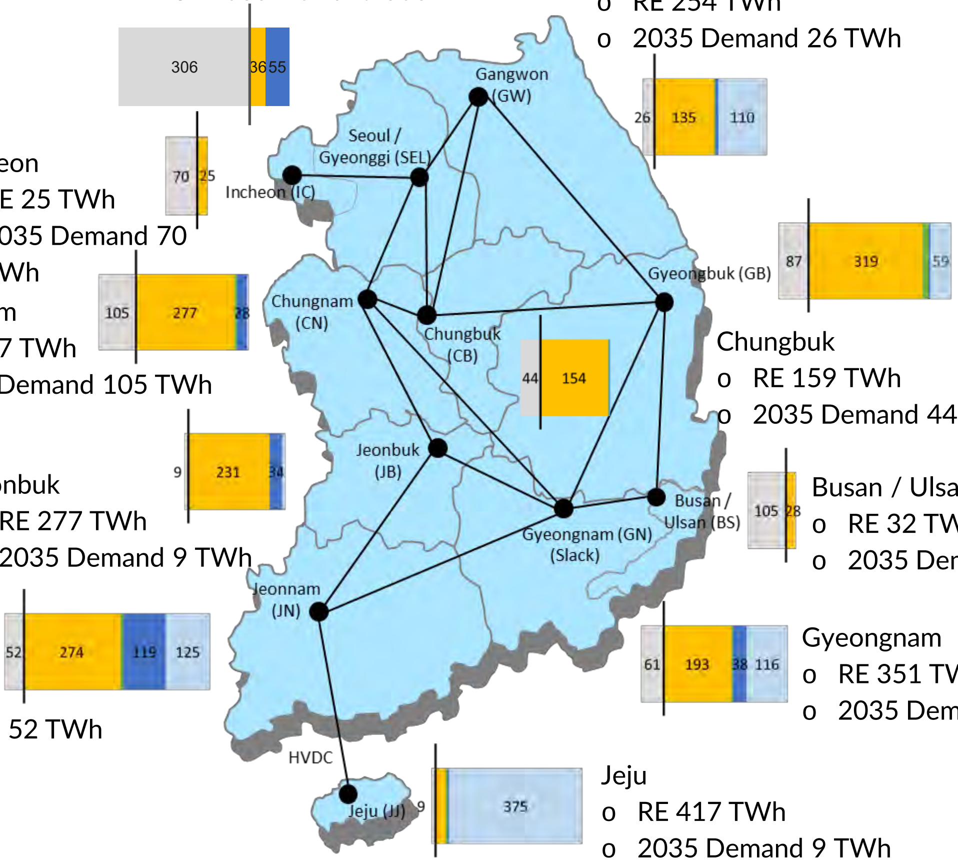
- Load by regional node





RE Potential

- 🟨 PV
- 🟩 Onshore Wind
- 🟦 Offshore Wind – Fixed
- ▨ Offshore Wind – Floating
- ⬜ 2035 Electricity Demand



Seoul / Gyeonggi
- RE 91 TWh
- 2035 Demand 306 TWh

Gangwon
- RE 254 TWh
- 2035 Demand 26 TWh

Incheon
- RE 25 TWh
- 2035 Demand 70 TWh

Gyeongbuk
- RE 400 TWh
- 2035 Demand 87 TWh

Chungnam
- RE 317 TWh
- 2035 Demand 105 TWh

Chungbuk
- RE 159 TWh
- 2035 Demand 44 TWh

Jeonbuk
- RE 277 TWh
- 2035 Demand 9 TWh

Busan / Ulsan
- RE 32 TWh
- 2035 Demand 105 TWh

Jeonnam
- RE 527 TWh
- 2035 Demand 52 TWh

Gyeongnam
- RE 351 TWh
- 2035 Demand 61 TWh

Jeju
- RE 417 TWh
- 2035 Demand 9 TWh

Source: LBNL's work with data from NEXT Group and MOTIE

Modeling Scenarios

Run these scenarios through optimal investment model based on an hourly-dispatch (PLEXOS)

National Goals

- 2030 NDC Target
- 2050 Carbon Neutrality Goal

Policy

- Current Policy (National Goals + 9th Basic Plan + Nuclear extension)
- Clean Energy 80% incl. Nuclear extension
  - **Nuclear extension (under consideration)**
  - 10 nuclear reactors (8.45 GW)

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RE Cost

- High (Conservative)
- Base (Moderate)
- Low (Advanced)

×

Fuel Price

- Base
- High

- Policy Scenarios
- RE Cost Scenarios
- Fuel Price Scenarios

Policy Scenarios

Run these scenarios through optimal investment model based on an hourly-dispatch (PLEXOS)

	NATIONAL GOALS	CURRENT POLICY SCENARIO	CLEAN ENERGY SCENARIO
Reference policies/plans	• New 2030 NDC Target • 2050 Carbon Neutrality Goal	NATIONAL GOALS + • 9th Basic Plan for Power Supply and Demand • Nuclear extension (under consideration)	-
Coal generation capacity additions	5.4 GW	5.4 GW	No new coal generation is forced into the model
RE generation capacity additions	Limited to policy targets, (RE 30%; 70GW solar and 22.5GW wind capacity) by 2030	Limited to emission reduction targets by 2035	Determined by model to meet 80% clean electricity by 2035
Clean (non-fossil) energy generation share	-	Least-cost optimization subject to limits on emission reduction targets	40% in 2025; 60% in 2030; 80% in 2035
Nuclear extension	Not included	10 nuclear reactors (8.45 GW) operation extended	
H_2 or NH_3	Included	Not included (Industry-use first)	

RE and Battery Storage Capital Cost Scenarios

Our assumed costs are benchmarked against US NREL ATB scenarios.

		2020 Baseline (USD/kW)	2021-2035 (Low)	2021-2035 (Base)	2021-2035 (High)
Offshore Wind	Fixed Bottom	Korea ($4906) > US ($3252-$4263)	Assumed to converge on NREL ATB *Advanced* in 2030.*	Assumed to converge on NREL ATB *Moderate* in 2035.*	Assumed to converge on NREL ATB *Conservative* in 2035.*
	Floating	Korea ($6966)* > US ($4621-$6335)			
Onshore Wind		Korea ($2204) > US ($1369-$1396)			
Utility Scale 4Hr Battery Storage		Korea ($1780) > US ($1363)			
Utility Solar PV		Korea ($1176) < US ($1377)			Assumed to decrease at the same rate as NREL ATB *Conservative*.

*** Authors' assumption as Korea's baseline cost is uncertain.**

**** For off-shore wind technologies, it refers to Class 1 for fixed-bottom types and Class 8 for floating types.**

RE and Battery Storage Operation Cost Scenarios

Our assumed costs are benchmarked against US NREL ATB scenarios.

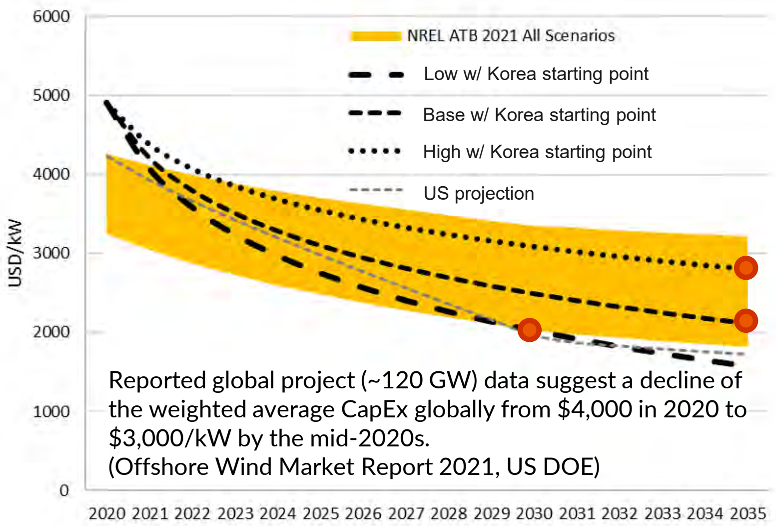
		2020 Baseline (USD/kW-yr)	2021-2035 (Low)	2021-2035 (Base)	2021-2035 (High)
Offshore Wind	Fixed Bottom	Korea ($102-$116)* ≈US ($102-$118)	Assumed to be the same as NREL ATB *Advanced.***	Assumed to be the same as NREL ATB *Moderate.***	Assumed to be the same as NREL ATB *Conservative.***
	Floating	Korea ($75-85)* ≈ US ($75-$95)			
Onshore Wind		Korea ($44) ≈ US ($42-$43)			
Utility Scale 4Hr Battery Storage		Korea ($34)* = US ($34)			
Utility Solar PV		Korea ($15) < US ($23)	Assumed to decrease at the same rate as NREL ATB *Advanced.*	Assumed to decrease at the same rate as NREL ATB *Moderate.*	Korea's costs are assumed to decrease at the same rate as NREL ATB *Conservative.*

*** Authors' assumption as Korea's baseline cost is uncertain.**

**** For off-shore wind technologies, it refers to Class 1 for fixed-bottom types and Class 8 for floating types.**

Wind Capital Cost Assumptions

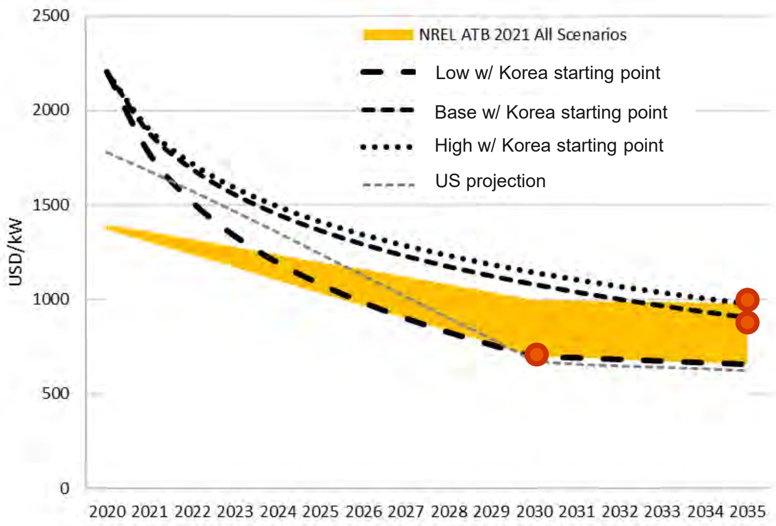
Total Installed Costs for Offshore Wind – Fixed Bottom



Reported global project (~120 GW) data suggest a decline of the weighted average CapEx globally from $4,000 in 2020 to $3,000/kW by the mid-2020s.
(Offshore Wind Market Report 2021, US DOE)

	2020 (Baseline)	2035 (Low/Base/High)
Offshore Wind	4906	1568/2110/2799

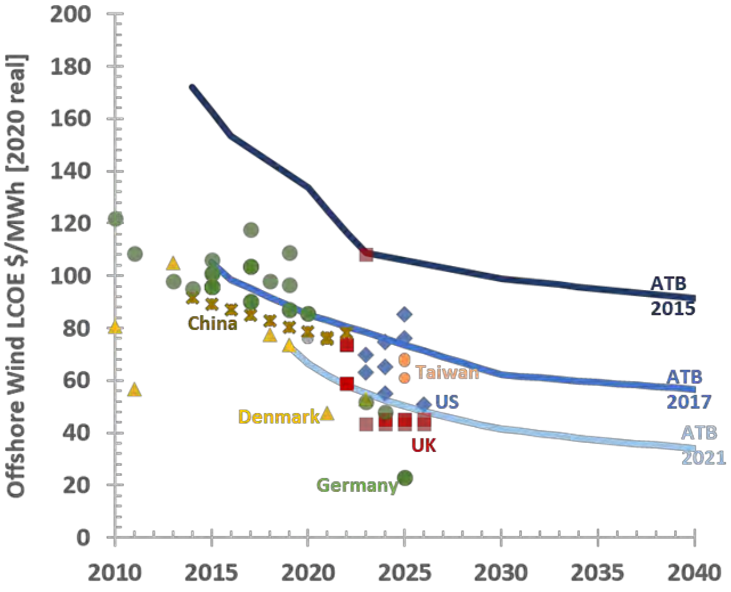
Total Installed Costs for Onshore Wind (USD/kW)



	2020 (Baseline)	2035 (Low/Base/High)
Onshore Wind	2204	656/903/975

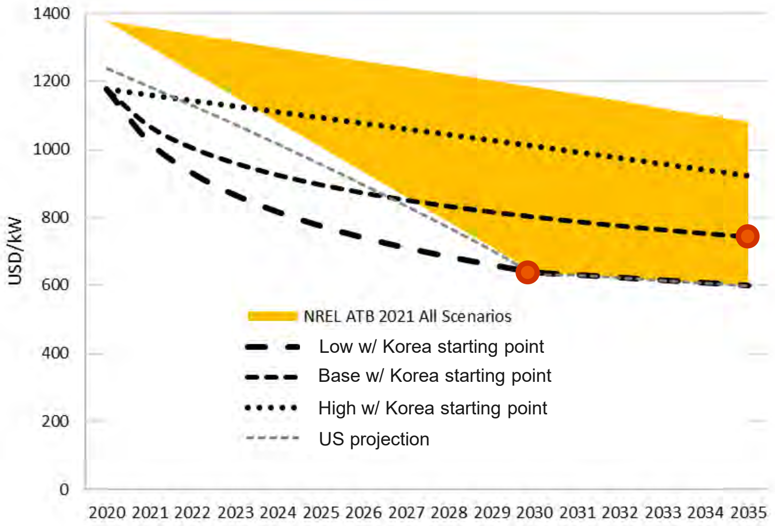
Offshore wind costs have fallen faster than anticipated

- Offshore wind is competitive/close to being competitive already.
- Significant future cost declines are projected.



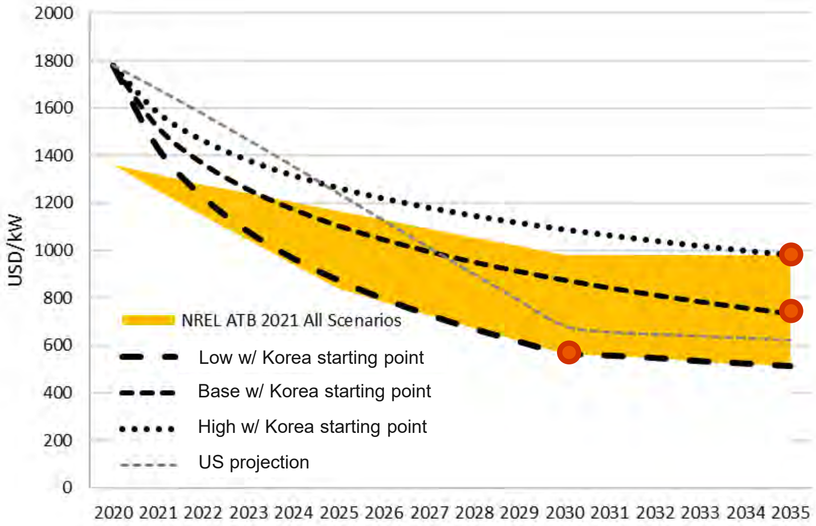
Solar and Battery Capital Cost Assumptions

Total Installed Costs for Utility PVs



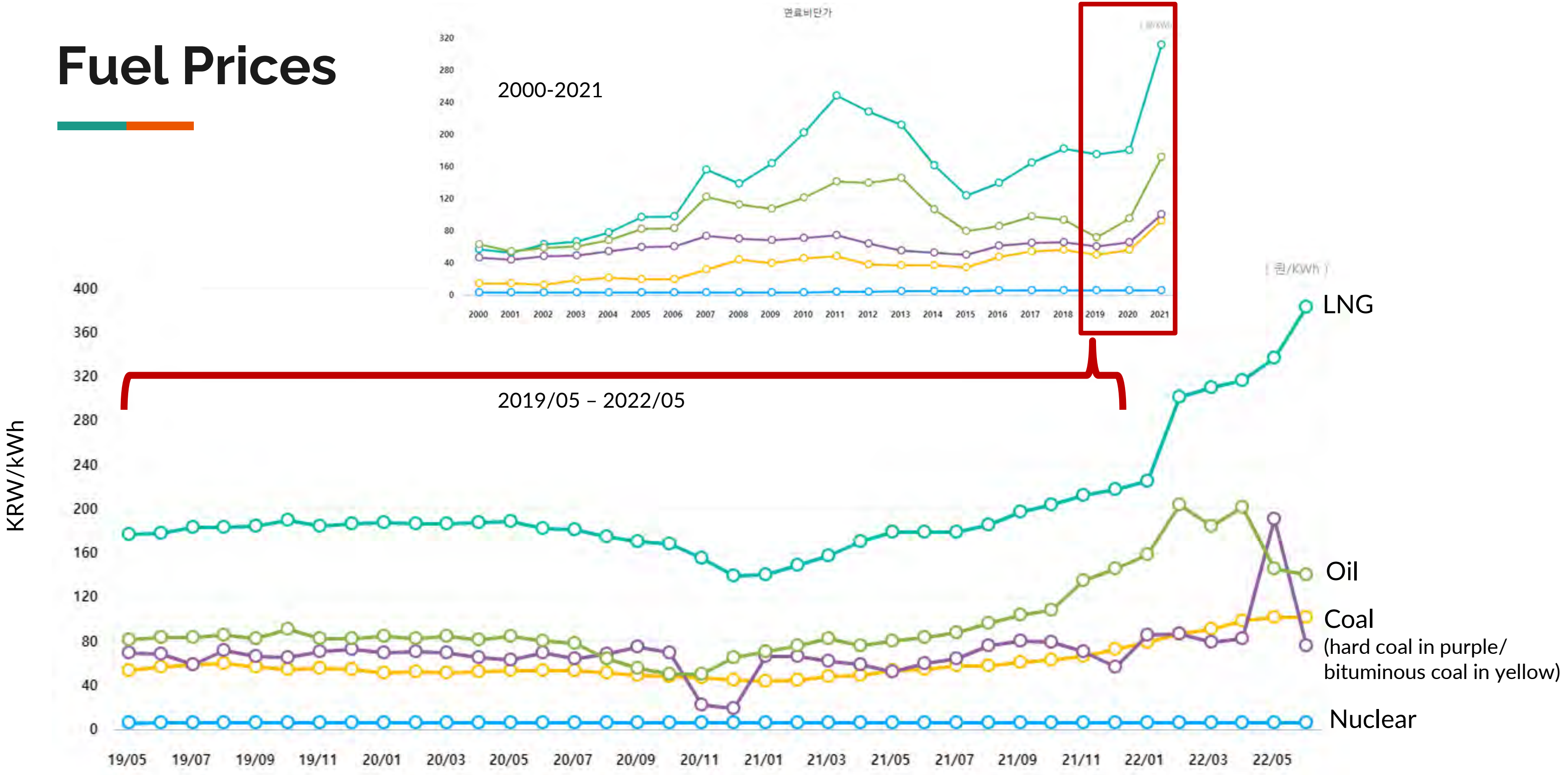
	2020 (Baseline)	2035 (Low/Base/High)
Utility Solar	1176	598/741/923

Total Installed Costs for 4-Hr Utility Battery Storage



	2020 (Baseline)	2035 (Low/Base/High)
4-Hr Battery	1780	512/735/981

Fuel Prices

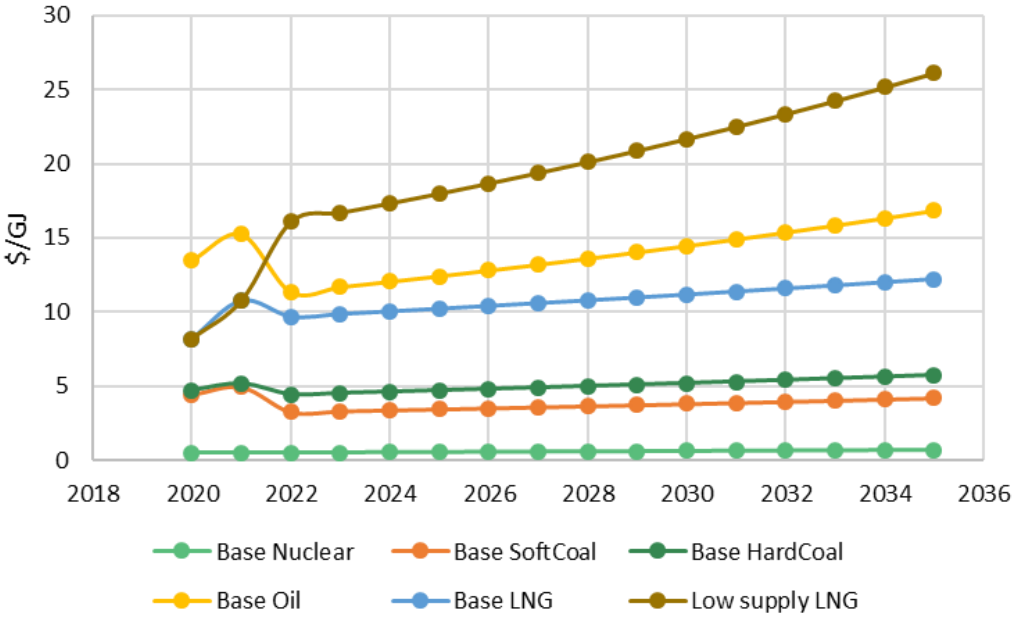


Source: Electric Power Statistics Information System

Fuel Price Assumptions

The High Fuel scenario assumes LNG price increase by 1.6x between 2022 and 2035.

	2022 (Baseline)	2023-2035 (Projected)
Base	Median (Apr 2001 - May 2022)	Projected rates by US Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2022 Reference Scenario
High (LNG)	Top 5% (Apr 2001 - May 2022)	Projected rates by US AEO Low Oil and Gas Supply Scenario



Other Assumptions and Constraints

- **Existing coal** retires based on an average age (30 years)

  PLEXOS does not endogenously retire based on economic life
- **Existing gas** retires based on an average age (30 years)
- **PV** retires based on an average age (25 years)
- **Wind turbine** retires based on an estimated average age (25 years), lead-time (7 years) for offshore wind
- **Annual RE deployment**: PV (≤15 GW), Onshore Wind (≤5 GW), Offshore Wind (≤20 GW)

Results | Current Policy vs. Clean Energy 80%

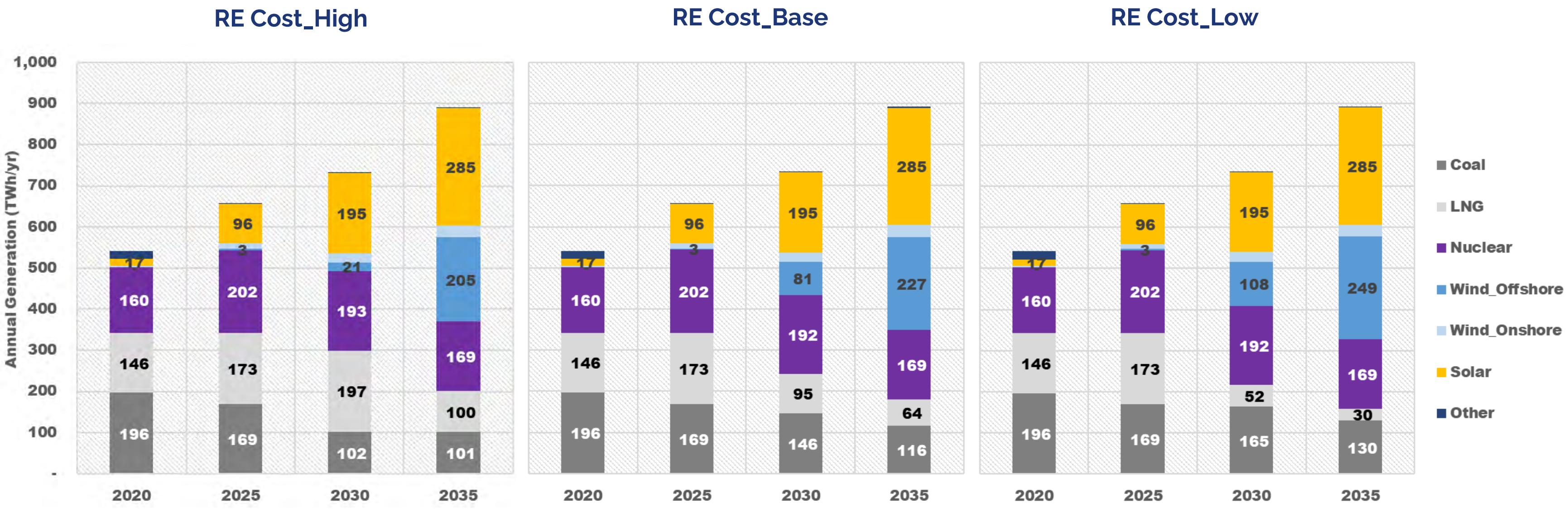
	CURRENT POLICY	CLEAN ENERGY
Reference policies/plans	NATIONAL GOALS + • 9th Basic Plan for Power Supply and Demand • Nuclear extension (under consideration)	-
Coal generation capacity additions	5.4 GW	No new coal generation is forced into the model
RE generation capacity additions	Limited to emission reduction targets by 2035	Determined by model to meet 80% clean electricity by 2035
Clean (non-fossil) energy generation share	Least-cost optimization subject to limits on emission reduction targets	40% in 2025; 60% in 2030; 80% in 2035
Nuclear extension	10 nuclear reactors (8.45 GW) operation extended	

The Clean Energy Scenario (80%) results are aligned with those of the Current Policy Scenario.

Clean energy generation share in 2035 by scenario
( ) represents RE share

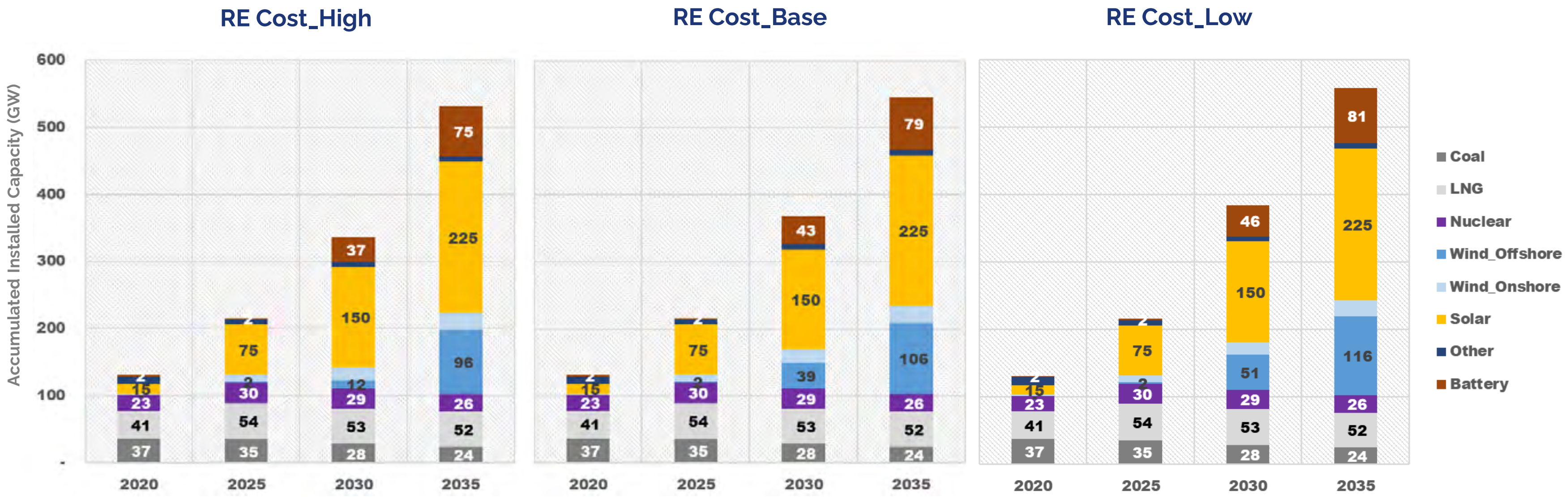
		RE Cost_High	RE Cost_Base	RE Cost_High
CURRENT POLICY	**Fuel Price_Base**	77% (58%)	80% (61%)	
CLEAN ENERGY		80% (61%)	80% (61%)	
CURRENT POLICY	**Fuel Price_High**			86% (67%)
CLEAN ENERGY				87% (68%)

Results | Annual Generation at *Base* Fuel Price



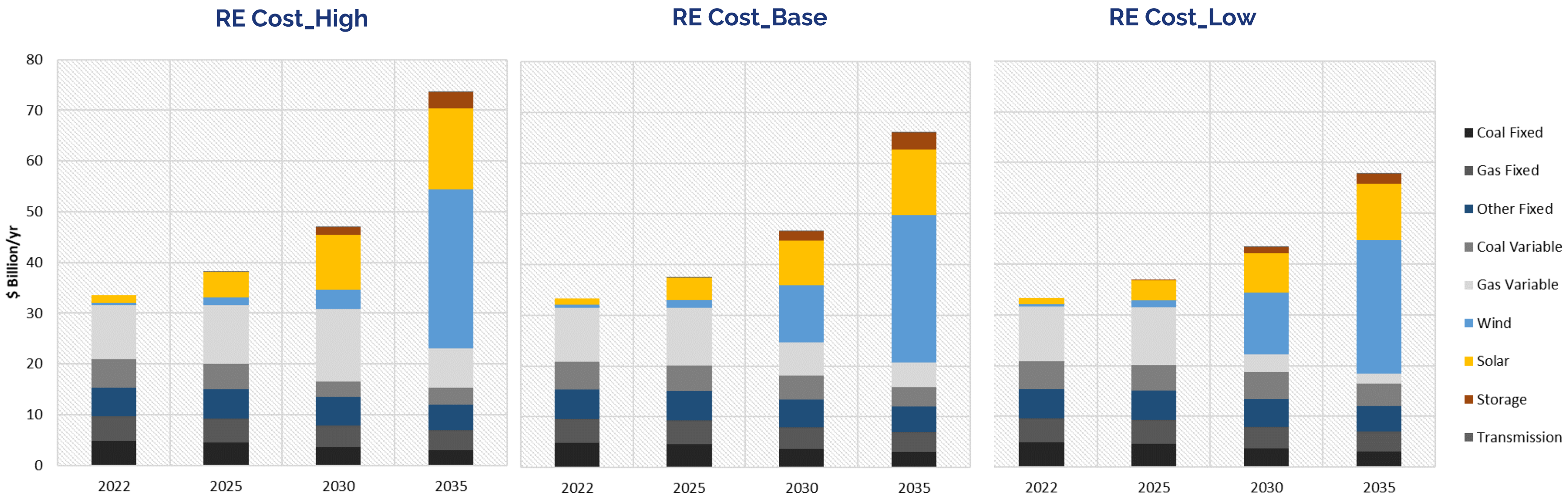
	2020	2030	2035	2020	2030	2035	2020	2030	2035
Clean Energy	34%	59%	77%	34%	67%	80%	34%	71%	82%
RE	4%	33%	58%	4%	41%	61%	4%	44%	63%

Results | Installed Capacity at *Base* Fuel Price



	2020	2030	2035	2020	2030	2035	2020	2030	2035
Clean Energy	31%	70%	81%	31%	79%	84%	31%	83%	86%
RE	13%	61%	76%	13%	70%	78%	13%	74%	80%

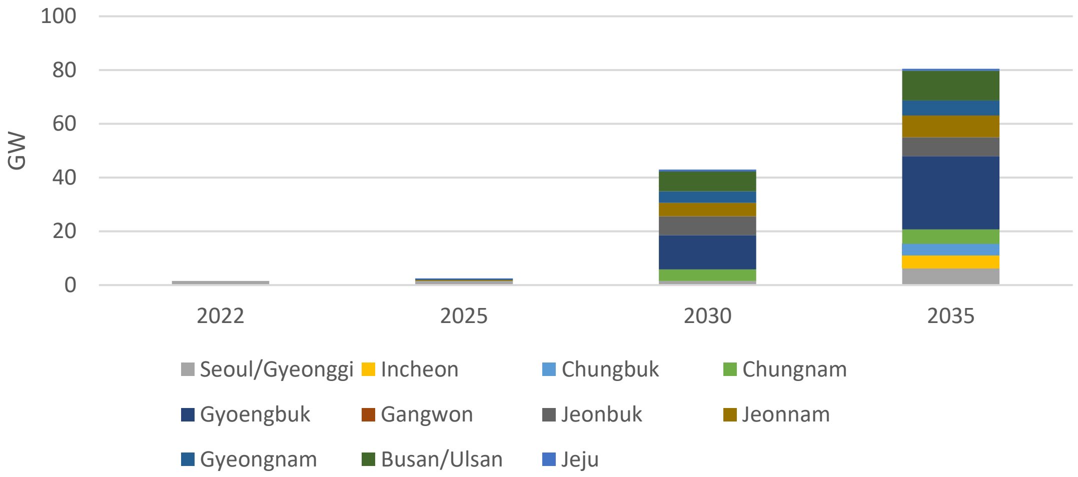
Results | Annual Generation Cost at *Base* Fuel Price



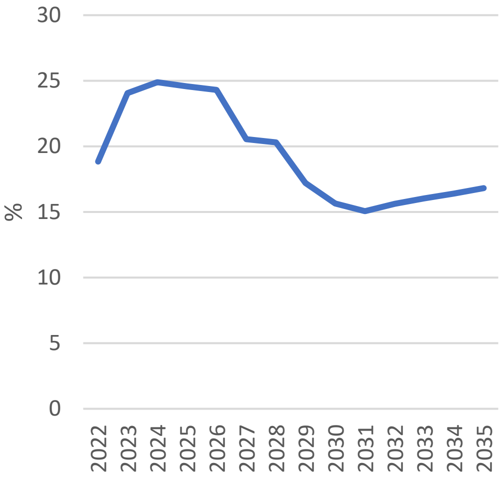
The generation costs would shift from **variable cost(fuel) dominated to fixed cost dominated.**
→ **Marginal pricing is still sustainable?**

Results | Storage expansion results at *Base* Fuel Price

Installed power capacity



Capacity factor of storage



Huge amount of storage capacity (>4hr) will be needed, but capacity factor of storage is not enough to get profitability(Storage cannot survive with arbitrage profit).

→ Capacity mechanism for storage would be needed

Results | Trans. expansion results at *Base* Fuel Price

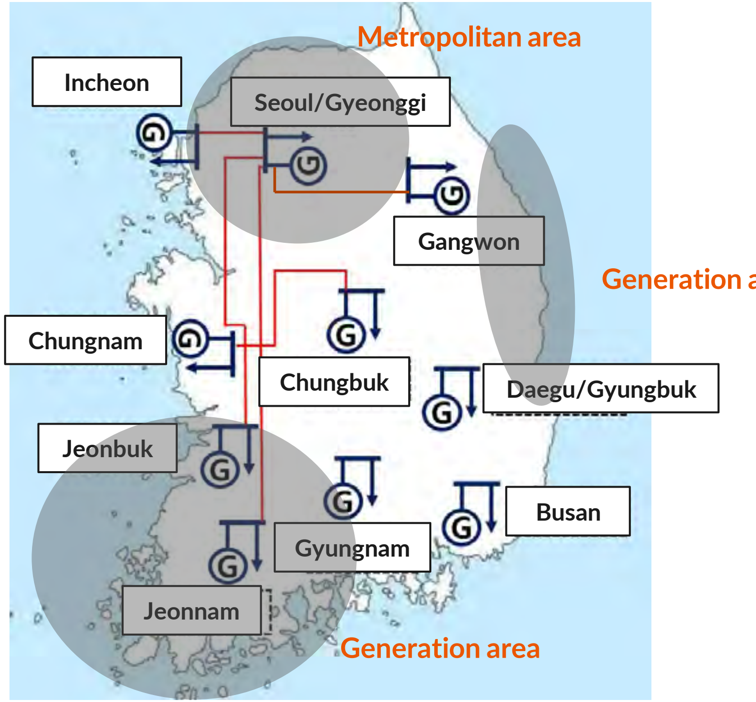
Unavoidable mismatch between generation area with high renewable potential and demand area

Long distance HVDC link can be an innovative solution for the mismatch and system strengths

→ **Government support for HVDC will be needed**

UK Eastern Green Link 2

Transmission network expansion



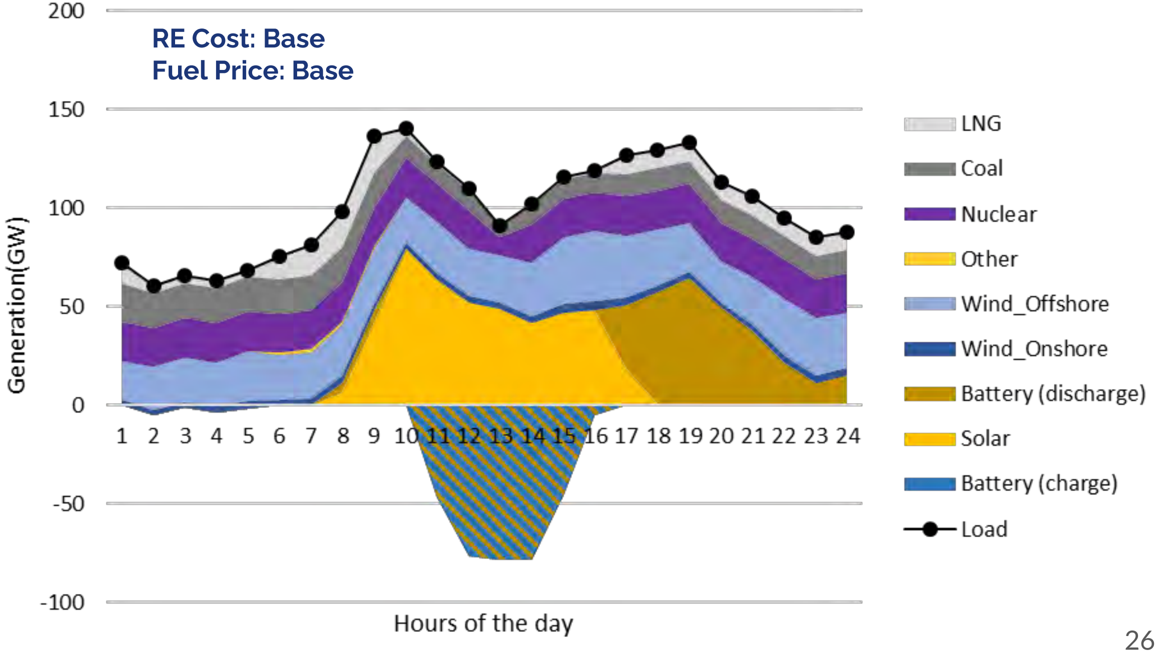
Results | One day example

How would the grid be dispatched in 2035 ?

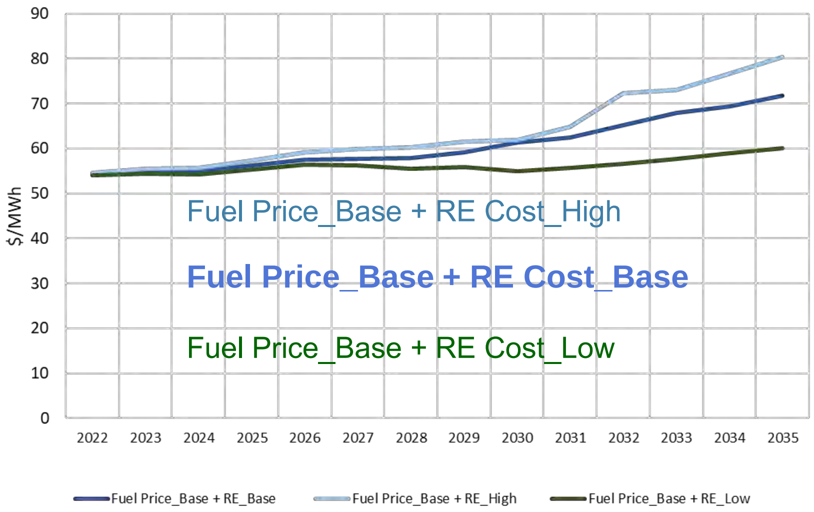
- Offshore wind provides ~17-38% (26% on average) of the energy with significant all-day round support.
- Batteries and pumped hydro charge during the day (solar) and early morning (wind) discharge mainly during evening and morning peaks.

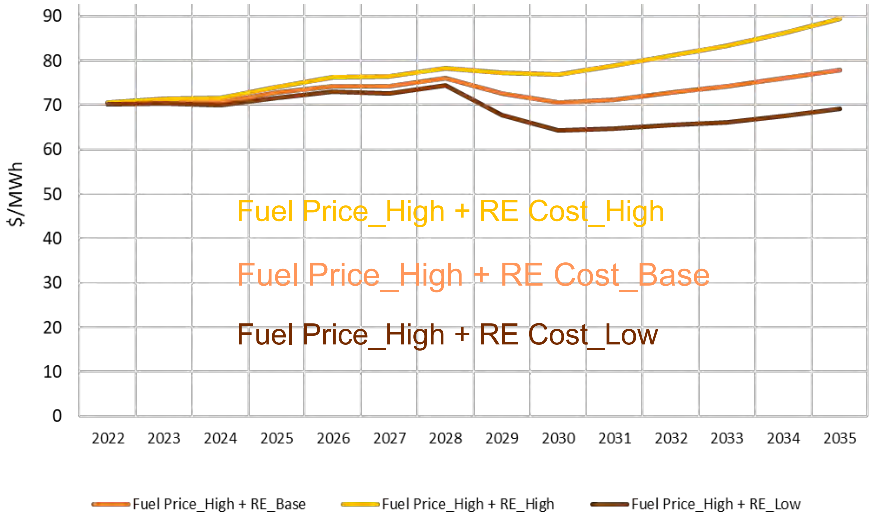
Average day in 2035

(Based on capacity expansion model results)


RE Cost: Base
Fuel Price: Base

Results | Avg Generation Cost at *Base vs High* Fuel Price





The best way for seeking energy security under high fuel price environment is realizing RE Cost_Low scenario with large-scale deployment (learning effect), soft cost reduction, and R&D support.

Policy Recommendations: How to fill the gap?

1. Huge number of storage(w/ grid-forming inverter) should cover system inertia and reliability issues (+support of synchronous condenser)
2. System generation cost shift from **variable to fixed cost** -> Should prepare transition of market pricing scheme
3. Innovative transmission expansion solution is needed
4. Acceleration of renewable deployment is key (Local acceptance, Industry capability, grid connection)