أكاديمية كاوست
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Tawazun

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Abdulellah Mojalled, Almaan Khan, Alzahraa Al Ensaif, Khadijah Boathman, Fares Alshebromi, Nisrin Balhareth, Hadeel Althbiti

Ibrahim Alyahya

abdulellah.mojalled@kaust.edu.sa, almaan.khan@kaust.edu.sa, alzahraa.ensaif@kaust.edu.sa, khadijah.baothman@kaust.edu.sa, fares.shebromi@kaust.edu.sa, nisreen.balharith@kaust.edu.sa, hadeel.thbiti@kaust.edu.sa

ibrahim.alyahya@energyexemplar.com

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Executive Summary

Project Tawazun develops a six-region representation of the Saudi electricity system in PLEXOS to examine how carbon pricing influences long-term capacity expansion, generation cost, emissions, reliability, and price pressure. The model covers 2026–2050, applies 2% annual demand growth, represents 66 existing generating units, and makes CCGT, OCGT, solar PV, and wind candidates available across the six operating areas. Hourly renewable availability is represented by 29 site-level 2019 profiles obtained from Renewables.ninja. The synchronized model revision also contains 19 fixed battery-energy-storage-system (BESS) projects totaling 9.95 GW and 42.3 GWh.

All five current-revision carbon-price scenarios (0, 25, 50, 75, and 100 $/tCO$_2$) are evaluated using their extracted PLEXOS results. Carbon 0 is used as the baseline scenario for comparison. Carbon 100 produces the greatest emissions reduction: cumulative CO_2 falls from 7.058 Gt in Carbon 0 to 5.368 Gt, a 23.95% reduction, while modeled unserved energy remains zero. Carbon 0 has the lowest average wholesale price at 14.48 $/MWh. Carbon 100 also has the lowest available Log Generation Cost at $134.74 billion, compared with $148.60 billion in Carbon 0; this is a system/generation-cost indicator, not a producer-profit measure.

The stakeholder trade-off analysis selects Carbon 25 as the overall balanced scenario. It reduces cumulative emissions by 17.30%, or 1.221 Gt, which is approximately 72.2% of the total reduction achieved by Carbon 100. It introduces 8.20 GW of wind, reduces OCGT expansion from 20.27 to 7.89 GW, maintains zero reported unserved energy, and limits average wholesale price to 29.77 $/MWh. Moving from Carbon 25 to Carbon 50 adds only 1.61 percentage points of emissions reduction while raising the wholesale-price indicator by approximately 54.2%. Under the current Tawazun assumptions, Carbon 25 therefore provides the most balanced observed trade-off between decarbonization, system performance, and price pressure.

1 Introduction

Saudi Arabia's electricity sector is undergoing a significant transformation driven by demand growth, energy-mix diversification, and national sustainability objectives. Vision 2030 reporting identifies a target of approximately 50% renewable energy in the electricity mix by 2030, which makes the timing and location of new generation investment a central planning question [1]. The existing system nevertheless remains strongly connected to natural gas and liquid fuels. Reducing emissions while maintaining adequacy and affordability therefore requires explicit analysis of the trade-off between environmental benefit and total system cost.

This study uses the PLEXOS Long-Term Planning (LT Plan) framework to examine those trade-offs. PLEXOS links long-term investment decisions with operational, adequacy, and transmission representations and is designed for both zonal and nodal power-system studies [2]. A carbon price is modeled as an emission shadow price: emitting technologies face an additional marginal cost, allowing the optimization to trade capital expenditure, operating cost, and emissions cost when choosing a future generation portfolio.

The Tawazun model represents six Saudi operating areas, 66 existing generators, interregional transmission corridors, regional loads, gas, oil, solar, and wind technologies, and a portfolio of fixed battery projects. The planning horizon is 2026–2050 and demand is extended at 2% per year. Five carbon-price cases are evaluated from 0 to 100 $/tCO$_2$. Current-revision PLEXOS Cloud outputs are available for all five cases, enabling comparison of cumulative CO_2, the carbon-inclusive solver objective, capacity expansion, average price, and adequacy. The report distinguishes this solver objective from a separately verified PLEXOS System NPV property

and records the remaining solver and reproducibility limitations.

2 Objectives

Main Objective

To evaluate how carbon pricing changes the long-term development of the Saudi electricity system and to identify expansion pathways that balance emissions reduction, reliability, and economic performance.

Specific Objectives

1. Develop a six-region PLEXOS LT Plan model with existing generation, fuel memberships, regional demand, transmission connections, and emissions accounting.
2. Configure gas, solar, and wind expansion candidates in every region so that the optimization can choose the location, technology, and build year of new capacity.
3. Replace generic renewable availability assumptions with hourly, location-specific solar and wind capacity factors from Renewables.ninja.
4. Run carbon-price cases at 0, 25, 50, 75, and 100 \$/tCO_2 and compare expansion, price, cumulative CO_2, and cumulative NPV/system cost.
5. Translate the scenario results into preliminary implications for government, producers, and consumers while documenting uncertainty and model limitations.

3 Methodology

3.1 Modeling Framework

The study employs PLEXOS Long-Term Planning (LT Plan) to simulate the Saudi electricity sector over 2026–2050. Figure 1 summarizes the evidence chain from hourly input data to policy outputs.

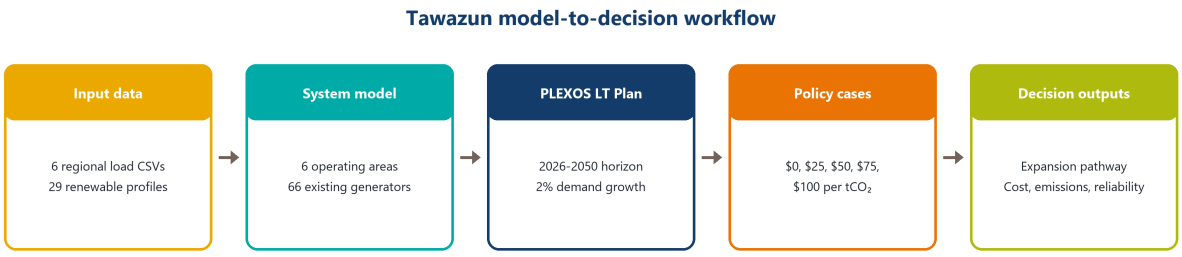


Figure 1 Tawazun model-to-decision workflow.

Five carbon-price scenarios were configured:

Scenario	Carbon Price ($/tCO$_2$)
S0	0
S1	25
S2	50
S3	75
S4	100

Table 1 Carbon-price scenarios configured for the LT Plan.

Each scenario is represented by a separate LT model linked to the matching PLEXOS scenario. The CO_2 price is applied as an Emission Shadow Price, with unit conversion to the PLEXOS property units where required. The optimization reports expansion, retirements, generation, costs, regional prices, adequacy, and emissions. The analysis distinguishes the carbon-inclusive solver objective from a separately verified PLEXOS System NPV property; the former is used for the current trade-off plot with this limitation stated explicitly.

3.2 System Representation

The Saudi power system is represented using six operating areas:

- Central Operating Area (COA)
- Eastern Operating Area (EOA)
- Western Operating Area (WOA)
- Southern Operating Area (SOA)
- Northeast Operating Area (NEOA)
- Northwest Operating Area (NWOA)

The model includes conventional generation technologies such as:

- Combined Cycle Gas Turbines (CCGT)
- Open Cycle Gas Turbines (OCGT)
- Crude-oil steam plants
- Heavy Fuel Oil (HFO) steam plants
- Cogeneration units

Renewable technologies include:

- Solar PV
- Wind

Carbon emissions are represented by a CO_2 emission object linked to fossil-fuel consumption. The emissions method follows the fuel-based stationary-combustion structure of the IPCC inventory guidance rather than applying one generic emissions factor per MWh [3].

3.3 Demand and Planning Horizon

Six regional load files represent COA, EOA, WOA, SOA, NEOA, and NWOA. The hourly profiles span 1 January 2026 through 31 December 2050. Demand is escalated by 2% annually while preserving the regional intraday shape. Across the 25-year horizon the completed LT cases report 13,387.81 TWh of cumulative demand and a system peak of 119.02 GW.

3.4 Expansion Candidates

CCGT, OCGT, solar PV, and wind candidate objects are available in every operating area. Candidate size follows the project rule of approximately twice the regional maximum requirement, producing deliberately large, region-specific candidate blocks. Build Cost is populated, Min Units Built is explicitly set to zero, and Max Units Built is set to one for all 24 candidates. Each candidate is therefore optional but can be selected at most once by the LT Plan. This formulation is transparent and computationally manageable, although it also makes expansion decisions relatively lumpy.

3.5 Hourly Renewable Profiles

Site coordinates were supplied in the renewable-coordinate workbook. The Renewables.ninja point API was used to obtain 2019 hourly profiles in CSV format [4]. Solar simulations use MERRA-2 weather data, unit capacity, 10% system loss, fixed tilt of 35 degrees, and azimuth of 180 degrees. Wind simulations use MERRA-2, a 100 m hub height, and the Vestas V80 2 MW turbine specification. The underlying PV and wind modeling approaches are documented by Pfenninger and Staffell and by Staffell and Pfenninger [5, 6].

The API output was transformed to PLEXOS daily-row format with columns `Year, Month, Day, 1...24`. Capacity factors are stored as percentages from 0 to 100 in the Cloud-linked CSVs. The final dataset contains 29 profiles: 22 solar and 7 wind, including one candidate solar and one candidate wind profile for each of the six regions.

3.6 Battery Storage Representation

The latest synchronized Cloud database contains 19 named BESS objects linked to COA, EOA, SOA, and WOA nodes. Together they represent 9.95 GW of discharge power and 42.3 GWh of energy capacity. Individual systems have four- or five-hour duration, 100% modeled charge efficiency, and 95% discharge efficiency. Project Start Date values schedule the portfolio between 2024 and 2029, so these batteries are treated as fixed projects rather than endogenous LT expansion candidates. No corresponding BESS objects are currently assigned to NEOA or NWOA.

The synchronized database also contains a `Base` model linked to the `2026-50` horizon, the `LDC r=10` LT Plan settings, the `Long Term` report, and the Gurobi performance configuration. The reported zero-price baseline comes from the separate `LT_Carbon_0` model rather than from this generic Base configuration.

3.7 Solution Review

The latest successful PLEXOS Cloud outputs were downloaded for all five carbon cases. Solver logs were parsed for objective value, convergence gap, runtime, capacity expansion, capital cost, demand, generation, average price, unserved energy, and random seed. Current Parquet property tables were queried for cumulative System CO_2, generator Capacity Built, Build Cost, and the object inventory. Every output contains the synchronized 19-project BESS portfolio, confirming that the five comparisons use the current model revision. The cost–emissions curve uses the reported solver objective; formal System NPV and a resource-cost decomposition remain separate extraction tasks.

3.8 Stakeholder and Scenario Evaluation Framework

The five current-revision PLEXOS cases—Carbon 0, Carbon 25, Carbon 50, Carbon 75, and Carbon 100—are evaluated from government, producer/electricity-system, and consumer perspectives, followed by an overall trade-off assessment. Carbon 0 is used as the baseline scenario

for comparison. All numerical evidence comes from the already-extracted PLEXOS outputs; no stakeholder weighting is imposed.

The government perspective considers cumulative CO_2, percentage reduction relative to Carbon 0, modeled unserved energy, renewable expansion, and available system-cost indicators. The producer/electricity-system perspective considers Log Generation Cost, generation mix, capacity expansion, and the transition among CCGT, OCGT, wind, and solar. Log Generation Cost is a system/generation-cost indicator and is not interpreted as company revenue, cash flow, or profit.

The consumer perspective uses Average System/Wholesale Price as a relative price-pressure indicator. PLEXOS average system price is not a residential retail tariff and is therefore used only as a relative indicator of consumer price pressure. Household bills are not calculated because no approved retail pass-through method is applied in this report.

Energy burden remains a supporting methodology for future affordability analysis:

$$Energy\ Burden = \frac{Household\ Energy\ Cost}{Household\ Income} \times 100$$

Energy burden is commonly used as an affordability indicator. The 6% threshold reported by the U.S. Department of Energy LEAD tool is retained only as an external reference benchmark; it is not an official Saudi affordability threshold [7].

The overall balanced scenario is selected through transparent trade-off analysis across emissions reduction, generation-cost performance, reliability, portfolio transition, and wholesale price pressure. The method examines absolute and incremental scenario changes to identify diminishing returns and does not use arbitrary multi-criteria weights.

4 Data Collection

The working model combines regional demand, generation and fuel properties, transmission memberships, emissions parameters, and hourly renewable availability. Table 2 records the principal datasets now available in the project workspace.

Dataset	Files	Coverage	Use in Tawazun
Regional demand	6 CSV	2026–2050; hourly	Load for COA, EOA, WOA, SOA, NEOA, and NWOA, including 2% annual growth.
Renewable profiles	29 CSV	2019; 8,760 hours/site	Rating-factor input for 22 solar and 7 wind sites, including 12 regional candidates.
Site coordinates	1 XLSX	29 sites	Latitude and longitude inputs for the Renewables.ninja API requests.
PLEXOS database	1 XML	Six-region model	Existing fleet, candidates, 19 BESS projects, nodes, lines, fuels, emissions, scenarios, and LT models.
Cloud solutions	5 Parquet exports + logs	Current successful runs	Carbon 0, 25, 50, 75, and 100 LT outputs used for the common-revision comparison.

Table 2 Current Tawazun data inventory.

4.1 Demand Data Quality

Each regional load file contains 9,131 daily rows and 24 hourly columns, equivalent to 219,144 hourly values per region and 1,314,864 values overall. Automated checks found no missing or non-positive values. Regional hourly demand ranges from 834.9 MW in NEOA to 35,385.6 MW in EOA over the modeled horizon. The files are aligned to the PLEXOS calendar format and cover leap years within 2026–2050.

4.2 Renewable Data Quality

The 29 renewable files contain 254,040 hourly capacity-factor observations. Automated checks found no missing values and no values outside the valid 0–100% range. Across the six candidate profiles of each technology, mean annual capacity factor is 21.1% for solar PV and 23.4% for wind. Figure 2 shows the average diurnal pattern and the 10th–90th percentile range across candidate site-days. Solar output is concentrated in daylight hours, whereas wind retains substantial hour-to-hour and day-to-day dispersion, supporting the decision to use site-specific wind profiles rather than a single generic factor.

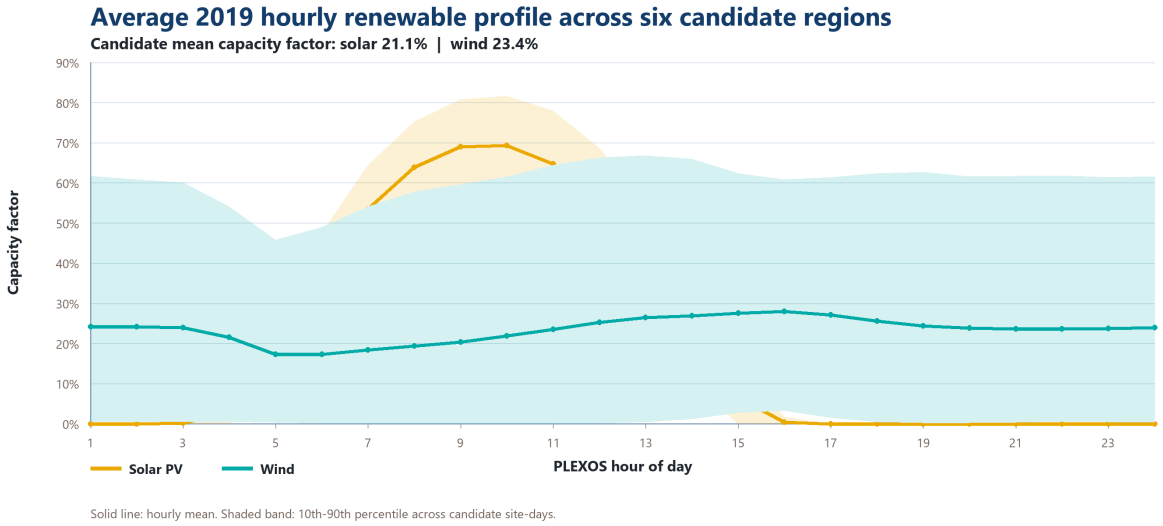


Figure 2 Average hourly capacity factors across the six regional solar and wind candidates.

The profiles use a single historical weather year. They therefore provide realistic hourly chronology for the initial model but do not represent interannual climate variability. Renewables.ninja documents the API parameters, CSV structure, and MERRA-2 spatial resolution used for point simulations [4, 8].

4.3 Cloud Model Synchronization Audit

A fresh Cloud clone on 24 August 2026 was compared semantically with the earlier working XML. The existing generators, demand links, renewable profiles, scenario values, and shared property values were unchanged. The synchronized revision adds a `Base` model, explicitly records Min Units Built = 0 for each of the 24 gas/solar/wind candidates, and replaces the single generic `Bisha_BESS` object with 19 region-tagged BESS projects. The latest Parquet exports for all five carbon cases contain the same 19 BESS objects, confirming that the reported scenario results belong to this synchronized revision. Table 3 summarizes the fixed storage portfolio.

Region	Projects	Power (GW)	Energy (GWh)
COA	5	2.50	11.0
EOA	1	0.50	2.0
SOA	5	2.95	12.3
WOA	8	4.00	17.0
Total	19	9.95	42.3

Table 3 Fixed battery portfolio in the synchronized PLEXOS Cloud database.

5 Model Development Progress

The Tawazun database has progressed from a four-region teaching model to a six-region planning model with plant-specific generation, hourly data, expansion candidates, emissions accounting, and Cloud execution. The main milestones are summarized below.

Regional Representation

The model was initially divided into four geographic regions:

- Central Operating Area (COA)
- Eastern Operating Area (EOA)
- Southern Operating Area (SOA)
- Western Operating Area (WOA)

It was subsequently expanded to include NEOA and NWOA. The current six-area representation captures regional demand, resource quality, generation, and interregional power exchange.

Generation Fleet Development

A simplified generation fleet was established for each region by creating seven representative generator technologies. These technologies were selected to reflect the primary sources of electricity generation currently operating within Saudi Arabia, as well as renewable technologies targeted under future energy transition plans.

The modeled generation technologies include:

- Open Cycle Gas Turbine (OCGT)
- Combined Cycle Gas Turbine (CCGT)
- Combined Heat and Power (CHP) / Cogeneration
- Crude Oil-Fired Steam Turbine
- Heavy Fuel Oil (HFO)-Fired Steam Turbine
- Solar Photovoltaic (PV)
- Wind Power

A total of 28 generic objects formed the first model. These were replaced by 66 individually represented existing generating units distributed across the six operating areas. Generator–Node and Fuel–Generator memberships link each unit to its location and fuel.

Node Configuration

The four original network nodes were:

- COA_Node
- EOA_Node
- SOA_Node

- WOA_Node

NEOA and NWOA nodes were later added, and the corresponding regional loads are now linked through the six completed 2026–2050 demand files.

Transmission Network Development

To represent power exchange between regions, transmission interconnections were established between the regional nodes. The network topology was configured using the following transmission corridors:

- COA ↔ EOA
- COA ↔ SOA
- COA ↔ WOA

The Central Operating Area was selected as the primary hub in the initial topology. Additional interregional connections were then added as the six-region model developed.

Current Status of the Model

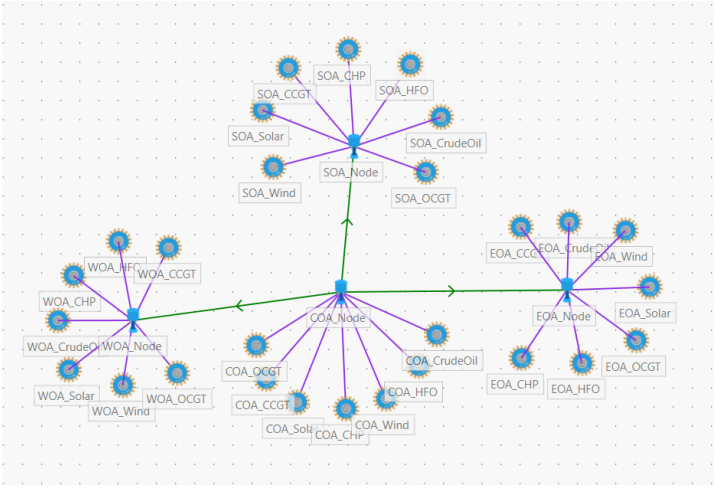


Figure 3 Early four-region Tawazun model status.

Week 3 Progress

- Expanded the generation fleet model from an initial 28-unit placeholder configuration to 66 individually represented generating units, replacing generic technology groupings with plant-specific assets distributed across the six-region KSA network (COA, EOA, SOA, WOA, NWOA, and NEOA).
- Established Generator–Node memberships for all 66 generators, ensuring each unit was correctly linked to its corresponding regional node.
- Configured Fuel–Generator memberships for all generating units, assigning the appropriate fuel source (Natural Gas, Crude Oil, or Heavy Fuel Oil) to each plant.
- Developed the transmission network topology by creating interregional transmission line connections between the six modeled regions.

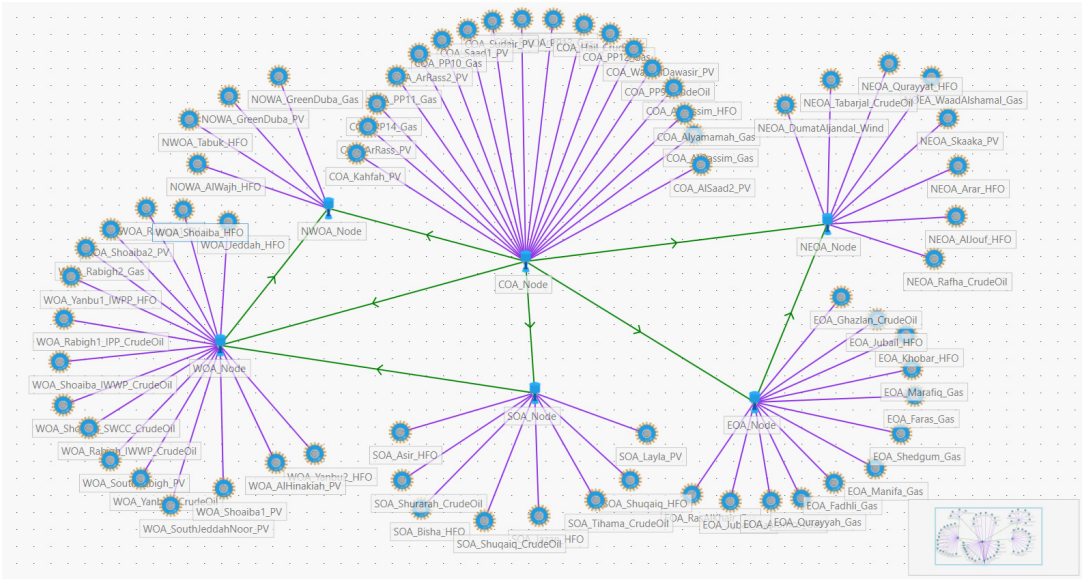


Figure 4 Six-region PLEXOS network after fleet and transmission expansion.

Week 4 Progress

- Completed the input of all generator properties in the PLEXOS model, including the technical and operational parameters required for simulation.
- Imported and linked the relevant CSV data files to support generator operation and system modeling.
- Added renewable energy generation resources, including solar and wind power units, to represent clean energy contributions within the system.
- Configured CO_2 emissions data for the generation fleet, enabling the assessment of environmental impacts and emissions-related scenarios.
- Verified the integration of generation, fuel, renewable energy, and emissions data to ensure model consistency and readiness for simulation.

Long-Term Planning and Cloud Execution

- Extended the electricity-demand projection through 2050 using 2% annual growth and updated the planning horizon to 2026–2050.
- Confirmed that CCGT, OCGT, Solar, and Wind expansion candidates are available in all regions. Candidate sizing follows the Region Max × 2 rule.
- Added Build Cost, set Min Units Built to 0, and set Max Units Built to 1 for all 24 expansion candidates. The LT Plan can therefore leave a candidate unbuilt or select it once.
- Synchronized the database with PLEXOS Cloud on 24 August 2026. The current revision contains 19 fixed BESS projects totaling 9.95 GW / 42.3 GWh and a `Base` model configuration in addition to the five carbon-price models.
- Configured five carbon-price scenarios at 0, 25, 50, 75, and 100 \$/tonne CO_2. Each scenario was linked to the LT model and assigned the corresponding Emission Shadow Price so that carbon cost affects the long-term optimization.
- Created a separate LT model for each carbon-price scenario and submitted the cases to PLEXOS Cloud.

- Downloaded the latest successful Parquet outputs and solver logs for Carbon 0, 25, 50, 75, and 100 from PLEXOS Cloud on 24 August 2026.
- Confirmed from each solution object inventory that all five results contain the synchronized 19-project BESS portfolio and therefore use the current model revision.
- Verified zero infeasibilities in every case. Carbon 25 solved to a 0.0000% MIP gap; Carbon 50, 75, and 100 ended below 0.01%; Carbon 0 reached the four-hour limit with a feasible 1.0311% gap.
- Extracted cumulative CO_2, solver objective, generation, price, generator builds, and capital cost for the five-scenario comparison.

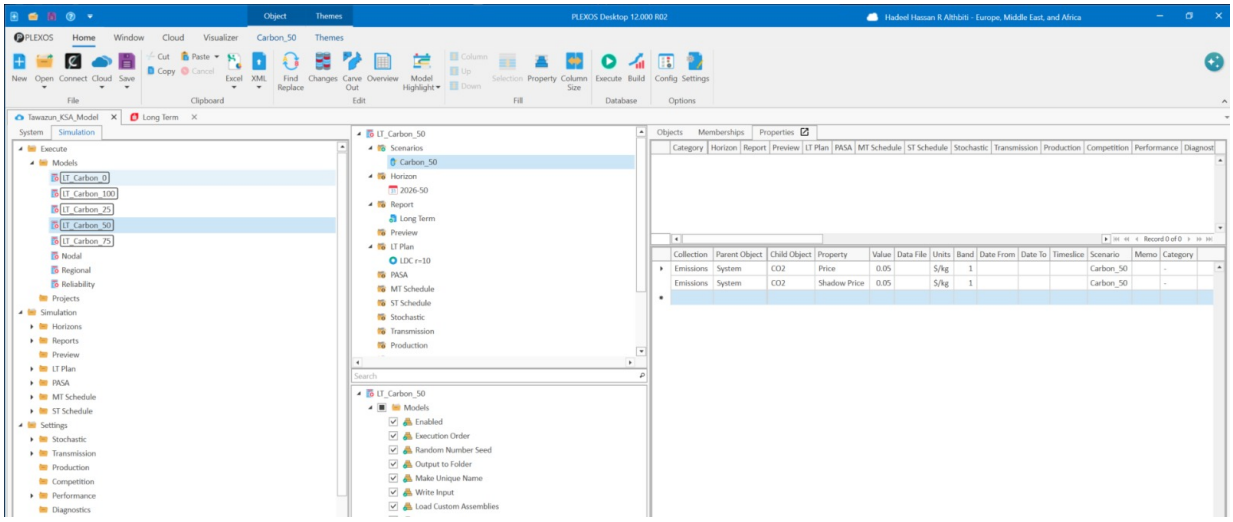


Figure 5 PLEXOS configuration of the carbon-price LT models and scenario shadow prices.

Component	Status	Current evidence
Six-region system and 66-unit fleet	Complete	Model database and network screenshots
2026–2050 regional demand	Complete	Six validated hourly CSV files
Hourly renewable profiles	Complete	29 validated solar/wind CSV files
Expansion candidates and build costs	Complete	CCGT, OCGT, solar, and wind in all regions
Fixed BESS portfolio	Added to current model	19 projects; 9.95 GW and 42.3 GWh
Carbon 25–100 LT solutions	Complete	Four current-revision successful outputs; gaps at or below 0.0094%
Carbon 0 LT solution	Comparison baseline	Successful feasible output used as the baseline
Cumulative CO_2–cost curve	Complete with caveat	Five scenarios; objective includes the emissions shadow-price term

Table 4 Model development status at the time of this draft.

6 Results

Key Insight

All five current-revision carbon-price cases are compared on the same 2026–2050 horizon. Carbon pricing reduces cumulative CO_2, introduces wind expansion, and reduces OCGT expansion. No scenario reports unserved energy or infeasibility.

6.1 Run Status and Common Basis

The extracted solutions represent Carbon 0, 25, 50, 75, and 100 \$/tCO_2. Each case has cumulative demand of 13,387.81 TWh, zero reported unserved energy, and zero reported infeasibilities. Carbon 0 is used as the baseline scenario for comparison.

6.2 Cost, Emissions, and Price

Table 5 summarizes the principal extracted results. Log Generation Cost is the available generation/system-cost indicator. Average wholesale price is a relative price-pressure indicator and is not a residential tariff.

Scenario	Price \$/t	CO_2 Mt	Reduction %	Gen. cost \$bn	Wholesale \$/MWh	CCGT GW	OCGT GW	Wind GW	Solar GW	Total build GW	USE GWh
Carbon 0	0	7,057.989	0.00	148.60	14.48	23.87	20.27	0.00	0.00	44.14	0
Carbon 25	25	5,836.827	17.30	135.52	29.77	31.47	7.89	8.20	0.00	47.56	0
Carbon 50	50	5,723.495	18.91	136.95	45.91	31.47	7.89	8.20	0.00	47.56	0
Carbon 75	75	5,484.897	22.29	135.87	58.40	31.47	7.89	8.20	0.00	47.56	0
Carbon 100	100	5,367.671	23.95	134.74	71.06	31.47	6.58	12.38	0.00	50.43	0

Table 5 Master scenario comparison for 2026–2050. Carbon price is in \$/tCO_2; cumulative CO_2 is in Mt; USE denotes unserved energy.

Carbon 100 has the lowest cumulative emissions, whereas Carbon 0 has the lowest wholesale-price indicator. Log Generation Cost is lower in every priced case than in Carbon 0, but it is not a complete producer-profitability metric.

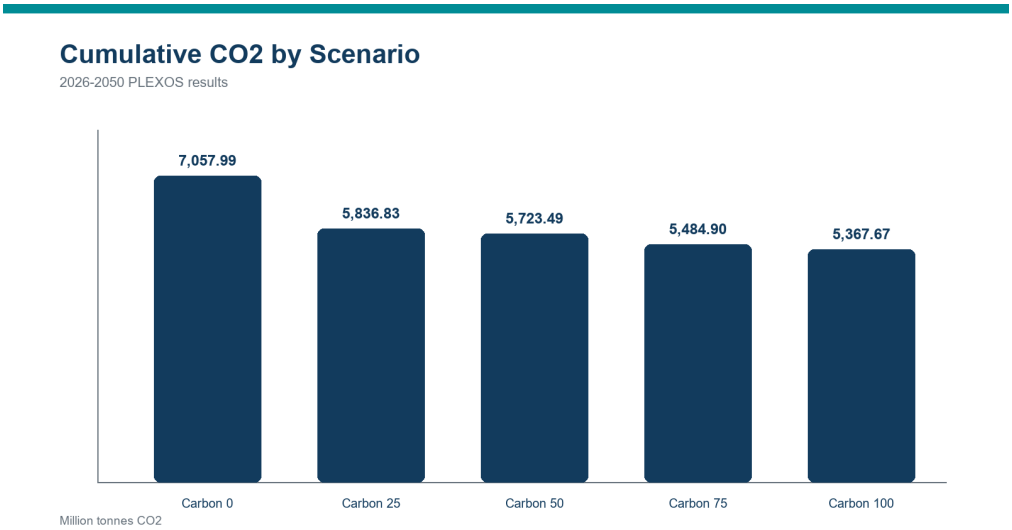


Figure 6 Cumulative CO_2 by scenario, 2026–2050. Emissions decrease as the modeled carbon price rises.

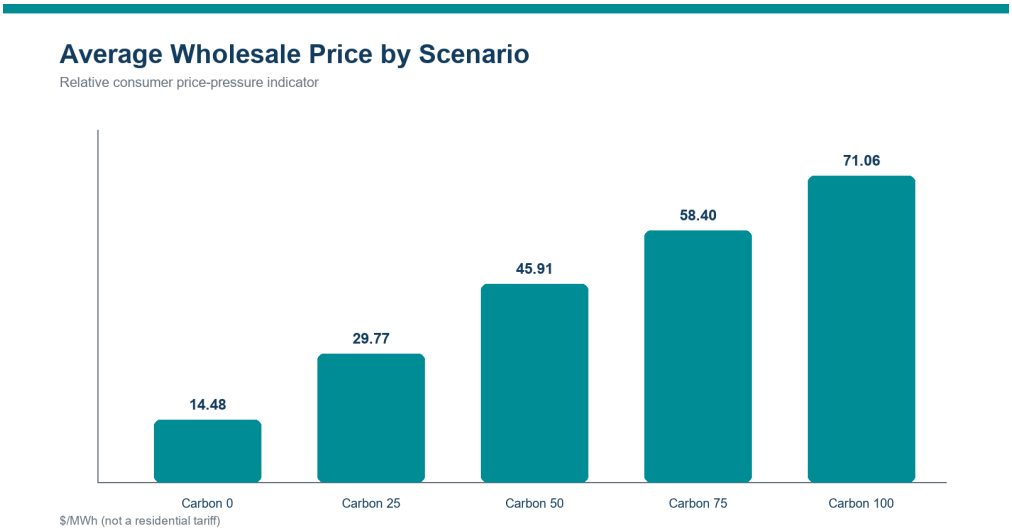


Figure 7 Demand-weighted average wholesale price by scenario. The measure indicates relative price pressure and is not a residential tariff.

6.3 Capacity Expansion

Carbon 0 builds 23.87 GW of CCGT and 20.27 GW of OCGT. Carbon 25–75 build 31.47 GW of CCGT, 7.89 GW of OCGT, and 8.20 GW of wind. Carbon 100 increases wind to 12.38 GW and reduces OCGT to 6.58 GW. No solar PV candidate is selected.

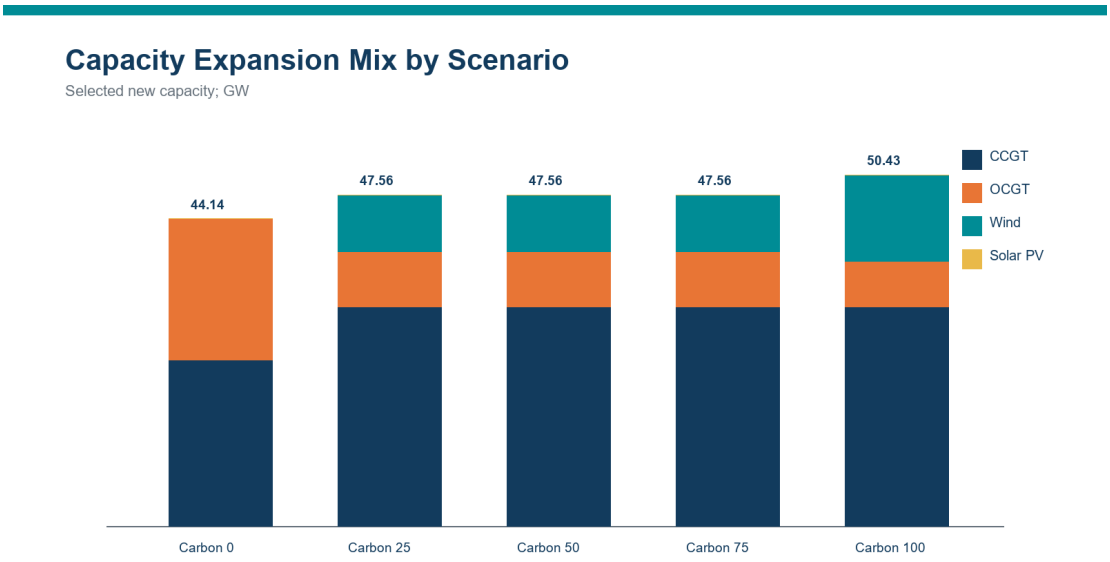


Figure 8 Selected capacity expansion by technology. Carbon pricing shifts expansion away from OCGT and toward wind and CCGT.

Figure 9 complements the build decision by showing cumulative generation. Higher carbon prices reduce crude-oil and HFO output, increase candidate CCGT output, and add wind generation. Solar output remains zero in the extracted results.

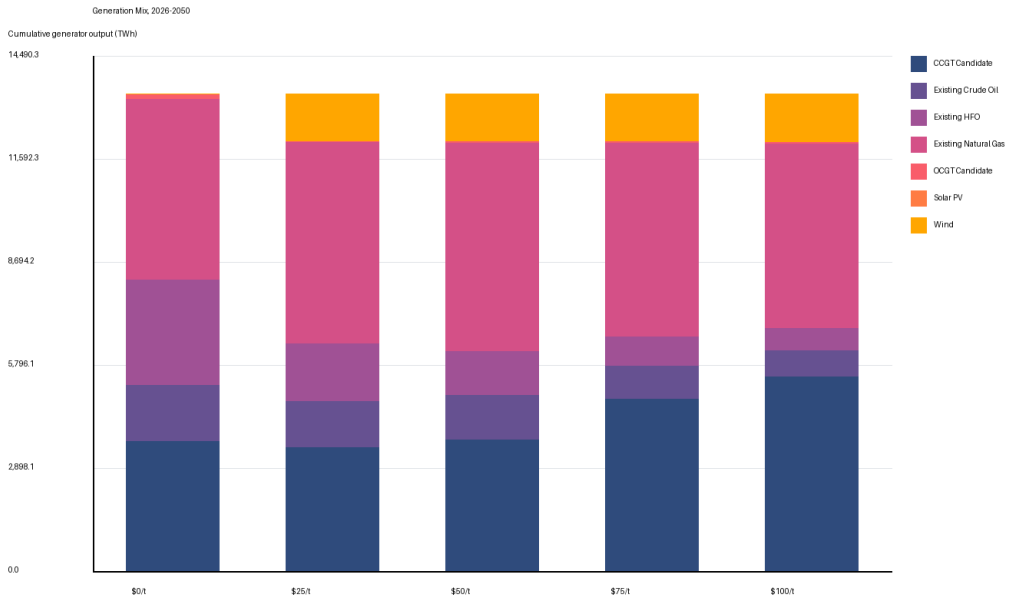


Figure 9 Cumulative generation mix by scenario, 2026–2050. Carbon pricing reduces oil-fired generation and increases wind and candidate CCGT output.

6.4 Adequacy and Result Boundaries

System-level unserved energy is zero in all five cases, supporting modeled adequacy under the represented assumptions. The 19 BESS projects are fixed rather than endogenous expansion decisions. The absence of selected solar is a result under the current candidate sizes, costs, profiles, and constraints, not a general conclusion about Saudi solar economics.

6.5 Stakeholder and Scenario Analysis

6.5.1 Analysis Approach

All comparisons use the extracted five-scenario results, with Carbon 0 as the baseline. Scenario-to-scenario changes are also examined to identify diminishing returns. The formulas are:

$$\text{CO}_2 \text{ Reduction (\%)} = \frac{\text{CO}_{20} - \text{CO}_{2s}}{\text{CO}_{20}} \times 100 \tag{1}$$

$$\text{Incremental CO}_2 \text{ Reduction} = \text{CO}_{2\text{previous}} - \text{CO}_{2\text{current}} \tag{2}$$

$$\text{Wholesale Price Change (\%)} = \frac{P_s - P_0}{P_0} \times 100, \qquad \text{Generation Cost Change (\%)} = \frac{C_s - C_0}{C_0} \times 100. \tag{3}$$

Wholesale price is used only as a consumer price-pressure proxy, and Log Generation Cost is used only as a system/generation-cost indicator. No arbitrary stakeholder weights are used.

6.5.2 Government Perspective

Carbon 100 is preferred when the primary objective is maximum emissions reduction while maintaining modeled adequacy. It produces 5,367.67 $MtCO_2$, avoiding 1,690.32 $MtCO_2$ relative to Carbon 0, or 23.95%. It selects 12.38 GW of wind and reports zero unserved energy. Its trade-off is the highest wholesale-price indicator, 71.06 $/MWh. Modeled carbon charges are not treated as government revenue.

6.5.3 Producer / Electricity-System Perspective

According to the available generation-cost indicator, Carbon 100 is preferred. Its Log Generation Cost is $134.74 billion, $13.86 billion or approximately 9.33% below Carbon 0, and it builds 50.43 GW. Carbon pricing increases CCGT and wind while reducing OCGT. This represents a system/generation-cost perspective and not a complete producer-profitability assessment.

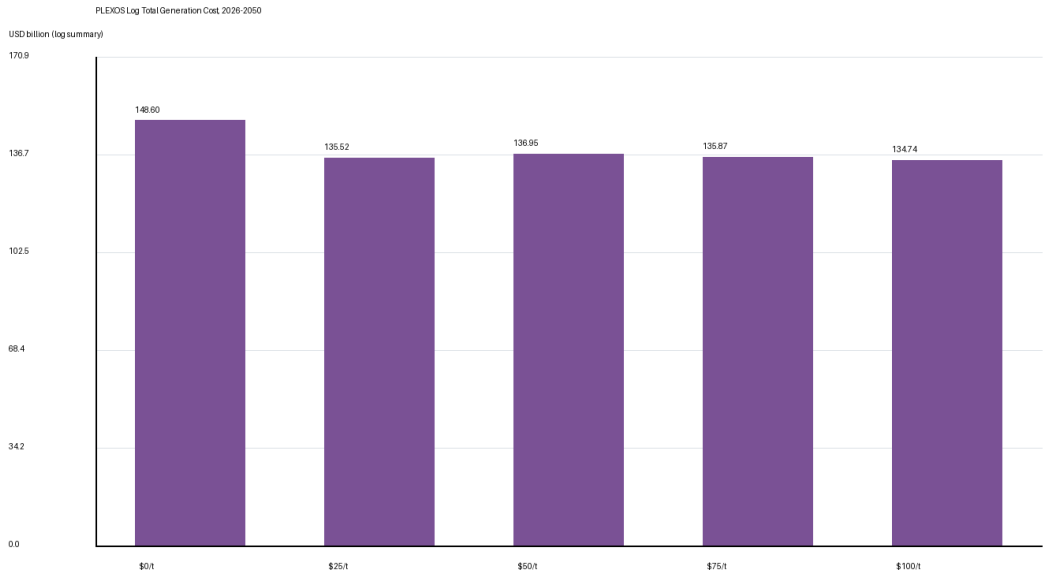


Figure 10 PLEXOS Log Generation Cost by scenario. This is the available generation/system-cost indicator and is not a measure of company profit.

6.5.4 Consumer Perspective

Carbon 0 is preferred under the available consumer proxy because it has the lowest average wholesale price, 14.48 $/MWh. Carbon 25, 50, 75, and 100 reach 29.77, 45.91, 58.40, and 71.06 $/MWh. Carbon 25 is approximately 105.6% above Carbon 0. Wholesale price is a relative consumer price-pressure indicator and not a direct residential electricity bill.

Average system price is used only as a relative consumer price-pressure indicator. It is not interpreted as a residential tariff because the pass-through from wholesale generation costs and carbon costs to final electricity prices depends on market structure, tariff design, subsidies, and regulatory arrangements. Evidence from electricity markets shows that emissions-cost pass-through exists but must be analyzed rather than assumed, and that its magnitude can vary substantially across countries and electricity-system structures [9–11]. Saudi residential electricity prices are also shaped by administered pricing and policy design rather than by an automatic wholesale-to-retail conversion [12]. Therefore, without a validated Saudi retail pass-through mechanism, this study does not convert PLEXOS wholesale prices directly into household electricity bills or apply a 100% pass-through assumption.

6.5.5 Selection of the Balanced Scenario

Carbon 25 is selected as the overall balanced scenario. It avoids approximately 1,221.16 $MtCO_2$, a 17.30% reduction relative to Carbon 0. This is approximately 72.2% of the 1,690.32 $MtCO_2$ reduction achieved by Carbon 100. It adds 8.20 GW of wind, reduces OCGT expansion from 20.27 to 7.89 GW, and maintains zero unserved energy.

The clearest diminishing return occurs between Carbon 25 and Carbon 50. That step avoids only another 113.33 $MtCO_2$, adds 1.61 percentage points of reduction, and leaves total capacity build unchanged, while wholesale price rises by 16.14 $/MWh, or approximately 54.2%.

Step	Additional CO_2 reduction (Mt)	Reduction (points)	Price change ($/MWh)	Build change (GW)	Interpretation
0–25	1,221.16	17.30	+15.29	+3.42	Largest emissions gain; wind enters
25–50	113.33	1.61	+16.14	0.00	Strong price increase for small added reduction
50–75	238.60	3.38	+12.49	0.00	Further reduction with unchanged build total
75–100	117.23	1.66	+12.66	+2.87	More wind; highest price pressure

Table 6 Incremental scenario comparison. Positive price changes indicate increasing wholesale price pressure.



Figure 11 Emissions-reduction and wholesale-price trade-off. Carbon 25 is highlighted as the balanced point before price pressure rises sharply.

Perspective	Preferred scenario	Primary indicator	Key numerical reason
Government	Carbon 100	CO_2 reduction	23.95% reduction; 12.38 GW wind; zero USE
Producer / electricity system	Carbon 100	Log Generation Cost	$134.74 bn; 9.33% below Carbon 0
Consumer	Carbon 0	Wholesale price pressure	Lowest indicator: 14.48 $/MWh
Overall balance	Carbon 25	Emissions–price–capacity trade-off	17.30% reduction; 29.77 $/MWh; 8.20 GW wind

Table 7 Stakeholder recommendation matrix based on the available PLEXOS indicators.

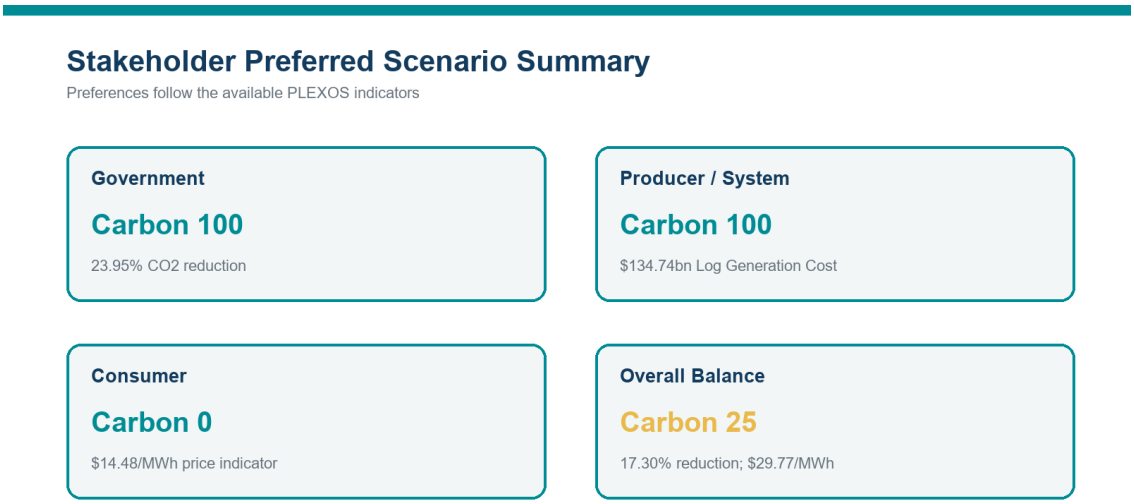


Figure 12 Preferred scenario by analytical perspective. The system-cost result is not a profit estimate, and the consumer result uses wholesale price only as relative pressure.

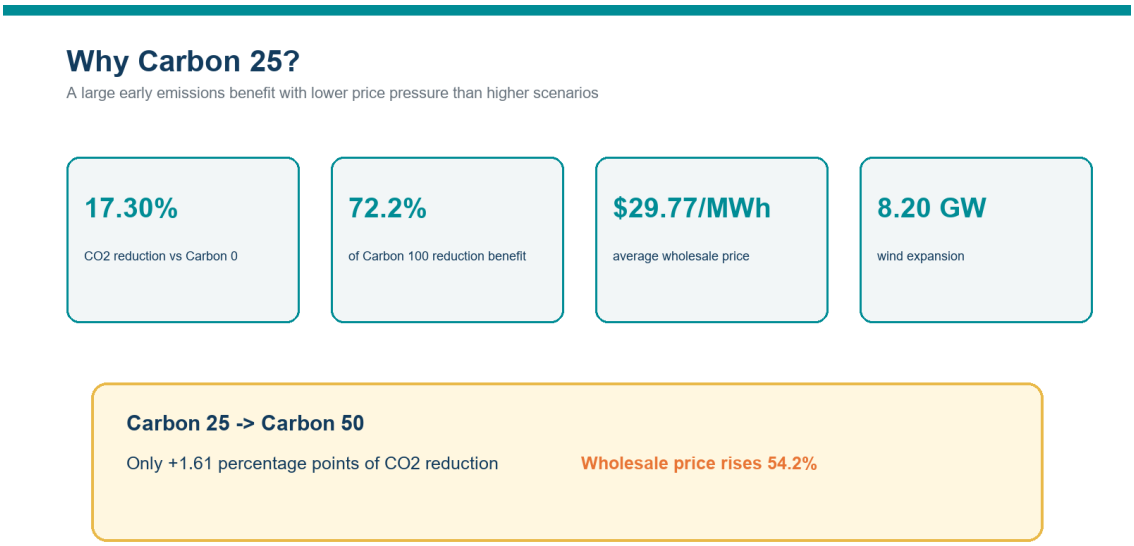


Figure 13 Why Carbon 25 is selected as the balanced scenario. It captures 72.2% of Carbon 100's emissions-reduction benefit while avoiding the higher wholesale-price levels of the higher-price cases.

Takeaway

Carbon 25 is selected as the overall balanced scenario based on the observed emissions–price–capacity trade-off, not on arbitrary stakeholder weights.

7 Discussion

7.1 Interpretation of the Expansion Portfolio

The current common-revision solutions show a clear portfolio response to carbon pricing. Carbon 0 selects 23.87 GW CCGT and 20.27 GW OCGT with no renewable build. Carbon 25–75 select 8.20 GW wind, increase CCGT to 31.47 GW, and reduce OCGT to 7.89 GW. Carbon 100 increases wind to 12.38 GW and reduces OCGT further to 6.58 GW.

No solar PV candidate is selected. This is not evidence that solar is generally uneconomic in Saudi Arabia. It is a result under the current candidate blocks, build costs, rating factors, operational representation, transmission assumptions, and one-unit build limit. The 19 batteries are fixed projects, so the optimization cannot choose additional storage expansion.

7.2 Economic and Emissions Response

Cumulative emissions decline monotonically from 7.058 Gt in Carbon 0 to 5.368 Gt in Carbon 100. The largest reduction occurs in the first pricing step: Carbon 25 cuts emissions by 17.30%. Average wholesale price rises from 14.48 to 71.06 $/MWh across the scenario range. By contrast, the available Log Generation Cost is lower in all priced cases than in Carbon 0 and reaches its minimum of $134.74 billion in Carbon 100. This cost measure is not producer profit, and the wholesale price is not a household tariff.

7.3 Reliability Implications

Zero reported unserved energy in all five cases indicates that the selected plans satisfy modeled system-level adequacy. This finding applies under the represented transmission, outage, storage, and demand assumptions and does not independently prove regional security under every contingency.

7.4 Stakeholder and Scenario Interpretation

The three perspectives lead to different preferred cases. Government prefers Carbon 100 because it provides the greatest emissions reduction, 23.95%, with zero modeled unserved energy. The producer/electricity-system perspective also identifies Carbon 100 under the available Log Generation Cost indicator, which is $13.86 billion below Carbon 0. Consumers prefer Carbon 0 under the wholesale-price-pressure proxy because its 14.48 $/MWh value is the lowest. These preferences are conditional on the indicators available in the PLEXOS outputs and do not imply government revenue, producer profit, or household bills.

7.5 Selection of the Balanced Scenario

Carbon 25 provides the strongest overall balance. It captures a 17.30% emissions reduction—approximately 72.2% of the reduction achieved by Carbon 100—while limiting average wholesale price to 29.77 $/MWh. It also introduces 8.20 GW of wind, reduces OCGT expansion by 12.38 GW relative to Carbon 0, and maintains zero unserved energy. Moving to Carbon 50 adds only 1.61 percentage points of emissions reduction but raises the wholesale-price indicator by approximately 54.2% relative to Carbon 25. This pronounced diminishing return supports Carbon 25 as the balanced case without imposing arbitrary stakeholder weights.

7.6 Reproducibility and Solver Quality

The extracted results are traceable to the five current-revision solution archives and logs. Different automatic random seeds and small solver-convergence differences can affect fine operational or build-timing details; however, the stakeholder comparison uses the extracted feasible results

consistently, with Carbon 0 as the normal baseline. Future controlled sensitivities can test the robustness of close differences without changing the present scenario conclusions.

8 Limitations and Future Work

8.1 Current Limitations

- **Cost interpretation:** Log Generation Cost is an available system/generation-cost indicator, not a complete producer-profitability metric. The solver objective should not be treated as a resource-cost-only NPV unless independently reconciled.
- **Consumer interpretation:** PLEXOS average wholesale price is not a residential retail tariff. Household bills and energy burden require an approved retail pass-through method and household income/consumption data.
- **Technology scope:** No solar candidate is selected in the current model, and the fixed BESS portfolio is not an endogenous expansion decision.
- **Sampling and convergence:** Different automatic random seeds and solver convergence can influence small scenario differences.
- **Weather and demand:** Renewable profiles use one weather year, while demand follows a deterministic 2% growth path without low/high growth or demand-response sensitivities.
- **Candidate representation:** Region Max × 2 sizing and Max Units Built = 1 create large indivisible investments that can produce step changes in the expansion portfolio.

8.2 Priority Future Work

1. Reconcile System NPV and individual cost components to establish a resource-cost metric without double counting the emissions-price transfer.
2. Investigate the absence of selected solar and test candidate-size, technology-cost, optional-storage, and transmission sensitivities.
3. Test common random seeds, additional renewable-weather years, and alternative demand-growth paths.
4. Apply an approved Saudi retail pass-through and billing methodology before calculating household bills or energy burden.
5. Examine regional adequacy and transmission dependence beyond the system-level zero-unserved-energy result.

9 Conclusion

Tawazun is an operational six-region PLEXOS planning model covering 2026–2050, with regional demand, existing generation, expansion candidates, carbon pricing, renewable profiles, transmission, and 19 fixed BESS projects. The final comparison uses all five current-revision scenarios, with Carbon 0 as the baseline.

Carbon 100 is the strongest emissions-reduction scenario. It reduces cumulative CO_2 from 7,057.99 to 5,367.67 $MtCO_2$, a 23.95% reduction, selects 12.38 GW of wind, and maintains zero reported unserved energy. Carbon 0 provides the lowest consumer price-pressure indicator at 14.48 $/MWh. Carbon 100 also has the lowest available Log Generation Cost at $134.74 billion, $13.86 billion below Carbon 0, although this is a system/generation-cost result rather than a producer-profitability assessment.

Carbon 25 is recommended as the overall balanced scenario. It reduces cumulative emissions

by 17.30%, or approximately 1,221.16 $MtCO_2$, equal to about 72.2% of the emissions reduction achieved by Carbon 100. Its average wholesale price is 29.77 $/MWh, substantially below Carbon 50, Carbon 75, and Carbon 100. It introduces 8.20 GW of wind, reduces OCGT expansion from 20.27 to 7.89 GW relative to Carbon 0, and retains zero reported unserved energy. Carbon 50 adds only 1.61 percentage points of emissions reduction beyond Carbon 25 while increasing the wholesale-price indicator by approximately 54.2%.

Takeaway

Under the current Tawazun assumptions, Carbon 25 provides the most balanced trade-off between decarbonization, system performance, and price pressure.

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