NATURAL GAS:
OVERCOMING THE CHALLENGES TO GAS TURBINES "GTs" IN ADOPTING CARBON CAPTURE UTILIZATION & STORAGE

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DO NOT COUNT NATURAL GAS / GAS TURBINES OUT YET 2030 & 2050 TARGETS – ECONOMICS WILL GOVERN – 9th HAEE Symposium June 2024 - Focus on Greece

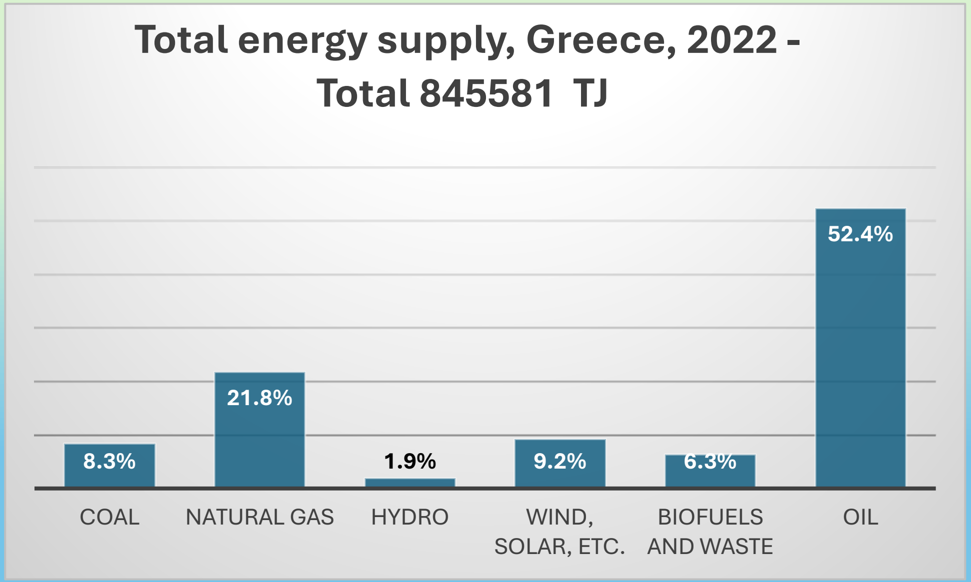
- **Difficulties in reaching commercial targets for large Green H2 applications.**
- **Realistically, Blue H2 is attainable for some Industrial applications & mixing H2 with NG is making good progress in GTs'**
- **A More realistic posture - Factoring NG/LNG Power Generation in <u>combination with CCUS.</u>**
- Prices of Natural Gas & LNG / Methane Leakage

- Well developed Natural Gas System: Supply to Industries, Residential and
- <u>Power Generation</u> - Why Natural Gas / LNG?
  - Lowest CO2 emission compared to oil and coal
    ~ 0.358, 0.867, 1.049 kg CO_2/kWh_e
  - Robust Gas Turbine & Combined Cycle Plants with demonstrated track record.
  - Support RE that have intermittent operational characteristic.

Greece: Towards Net Zero 2050 2024 EEA GHG emission projections

Share of global emissions 0.1%of CO_2 emission from combustible fuels, 2022

CO_2 emissions from fuel combustion in Greece Total, 2022 50.823 Mt CO_2



Source IEA

Transport

Implied emissions 27.4%

from 2022 level by 2030

- **Historical rate of change**
- **2.7 Mt**
- on average from 2010-2022
- **Change needed to 2030**
- **1.8 Mt**
- annually from 2022 to meet target
- **Net Zero pledge**
- **Change needed to 2050**
- **1.9 Mt**
- annually to meet pledge

Challenges to Meet Greece's Pledge for NET ZERO

- From 2025, Short Spans of 5 years (to 2030) and 25 years (to 2050).
- Unknowns for new technologies to reach commercial scale
- Needed long term commitment for assets 20 -25 years.
- Financing uncertainties
- Need to meet Energy required for economic growth .
- The increased dependence on **electricity** for mobility , commercial and industrial sectors "meeting large electricity demand"
- Low CO_2 concentration in CCGT – the large plants

Considering. Existing Plants

CO2 Emissions from NG GasTurbine and Combined Cycle Plants – Siemens representative for the leading 4 OEMs

Simle Cycle GT	Type	HL	F		E	SGT-800					SGT-700	
Gross Power Output	MW	593	329	385	198	62.5	57	55.6	49.9	45.3	35.2	32.8
Eff.		> 43%	41%	41.5%	37.60%	41.10%	40.10%	39.50%	39.40%	38.40%	38.00%	37.20%
High Heat Rate	kJ/kwh	8,375.00	8780	8675	9582	8759	8970	9123	9147	9381	9466	9675
A/F Ratio		41.24	49.08	51.64	57.76	48.45	52.38	53.24	53.59	53.12	58.18	58.81
CO2 in the Exhaust by Mass	%	10.9%	9.2%	8.8%	7.9%	9.3%	8.6%	8.5%	8.5%	8.5%	7.8%	7.7%
Combuned Cycle		HL (1+1)	F (1+1)		E (1+1)	SGT-800 (1+1)					SGT-700 (1+1)	
Gross power output		880 MW	485 MW	570 MW	290 MW	89 MW(e)	81.5 MW(e)	80.0 MW(e)	71.9 MW(e)	66.5 MW(e)	49.8 MW	46.7 MW
Gross plant efficiency		>64 %	61.00%	62.00%	55.60%	59.60%	58.50%	57.90%	57.70%	57.20%	54.50%	54.20%
Gross heat rate		<5,625 kJ/kwh (<5331 Btu/kWh)	5,900 kJ/kWh (5,592 Btu/kWh)	5,807 kJ/kWh (5,503 Btu/kWh)	6,474 kJ/kWh (6,136 Btu/kWh)	6,040 kJ/kWh (5,725 Btu/kWh)	6,154 kJ/kWh (5,833 Btu/kWh)	6,218 kJ/kWh (5,893 Btu/kWh)	6,239 kJ/kWh (5,914 Btu/kWh)	6,294 kJ/kWh (5,965 Btu/kWh)	6,609 kJ/kWh (6,264 Btu/kWh)	6,648 kJ/kWh (6,301 Btu/kWh)
Number of gas turbines		1	1	1	1	1	1	1	1	1	1	1
CO2 / h	ton/h	413.08	240.26	277.79	157.80	45.53	42.53	42.19	37.96	35.35	27.71	26.39
CO2 base load 8102 h/y	MT/y	3.35	1.95	2.25	1.28	0.37	0.34	0.34	0.31	0.29	0.22	0.21

A/F ratio: Reciprocating Engines / Conventional Steam ~ 18-20

Carbon Reduction Approaches

- Pre-Combustion (still in Research)
  - Converting a **hydrocarbon fuel** (e.g., natural gas or coal) into **syngas (H_2 + CO)** through gasification or reforming. Then, using a **water-gas shift reaction** to convert CO into CO_2 and more H_2.**CO_2 is removed** before combustion (hence, "precombustion"). The remaining **hydrogen is then burned** in a turbine or other power

  - The Allam-Fetvedt (supercritical carbon dioxide (sCO2) power cycle)
    - Oxygen is separated from the air, then it joins with NG in Combustion Chamber *Flue gas containing CO2 and water vapor drives a special sCO2 turbine to produce electricity, after which water is separated to get a pure CO2 stream. This CO2 is then compressed, and part of it is sent for sequestration, while the other part is recirculated to mix with incoming oxygen in combustor.*
- Post Combustion – CCUS (Mature and applied on large scale)

  Utilization close to emission source

  Storage – CO2 Valley

  Direct Air Capture Technolgy

For transport Compressed Gaseous CO2 / Liquified CO2

Carbon Capture Utilization CCU – Applications

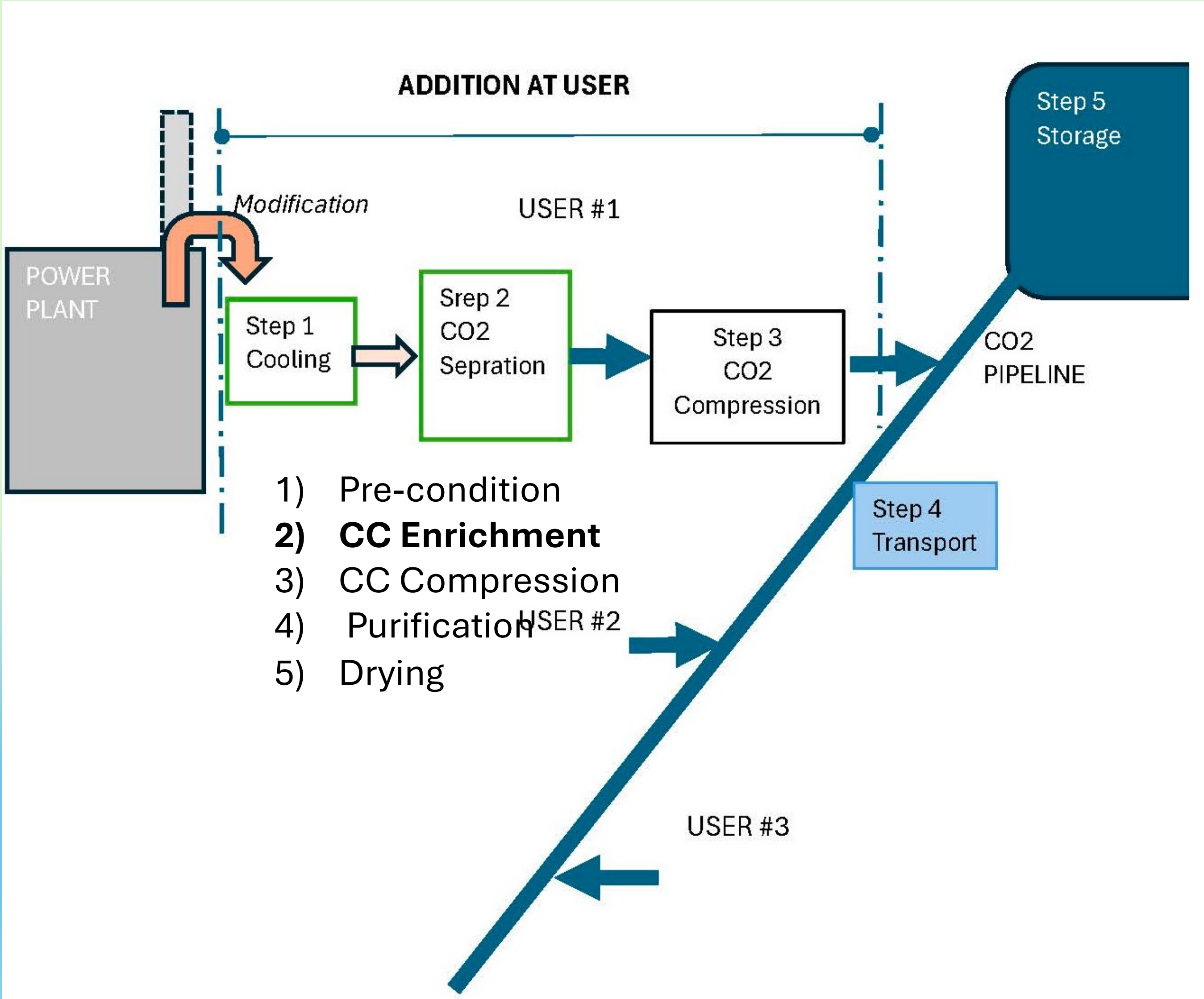
Factors affecting CO_2 production versus the quantity-time requirements for the application

- Low: $CO_2 < 100$ t/d
  - ❖Carbonated drinks
  - ❖Greenhouses
  - ❖Algae
- Medium: CO_2 between 100 to 1000 t/d
  - ❖Chemicals production (urea, methanol, polycarbonates)
  - ❖Construction Materials (cement, concrete and aggregate)
- Large: $CO_2 > 1000$ t/d
  - ❖Enhanced Oil recovery
  - ❖Synthetic Fuels (e.g. SAF Sustainable Aviation Fuel)

Typical Carbon Capture Storage CCS

CC Enrichment
Separation of CO_2 from the exhaust gases

- PSA Pressure Swing Adsorption
  - Linde
- Amine Wash
  BASF
  Shell
  MHI



1) Pre-condition
2) **CC Enrichment**
3) CC Compression
4) Purification
5) Drying

CCS – CO2 Cluster / CO2 Valley

Transport – CO2 Pipeline

- Operating Pressure Range: 10 to 15 MPa – 20 MPa
- Operating Temperature: 15°C to 30°C
- Maintaining CO_2 in a supercritical state requires pressures above 7.38 MPa and temperatures above 31.1°C.

Examples

- Alberta Carbon Trunk Line (ACTL), Canada:
  - Length: 240 km, Diameter16 inches, Capacity: 14.6 Mtpa
  - Transports captured CO_2 from industrial sources to oil fields for enhanced oil recovery (EOR).
- Cortez Pipeline, USA:
  - Length: 808 km, Diameter: 30 inches, Capacity: 20 Mtpa
  - Delivers CO_2 from natural sources in Colorado to EOR sites in Texas.
- Open Grid Europe (OGE) CO_2 Network, Germany:
  - Planned Length: 1,000 km. Diameter: Up to 70 cm, Capacity: 18 Mtpa
  - Will transport CO_2 from industrial centers to North Sea ports for storage or utilization.
- Equinor–GRTgaz CO_2 Highway Europe:
  - Initial Capacity: 3 to 5.5 Mtpa
  - Connects industrial emitters in France and Belgium to offshore storage sites in Norway

CO2 Storage

Onshore / Offshore

- **Pressure Capacities**
  - Operating Pressures
  - Pressure Management
- **Injection Rates**
- **Allowable Leakage or Losses**
  - Regulatory Standards:
  - Observed Leakage Rates
  - Leakage Pathways

Encouraging News: CCS Projects

- DOE CCUS Projects Map lists includes over 400 projects, USA 175, Australia 31, Canada 27, Norway 24, China 20, Japan 16, Germany 10, Netherlands 8, and other. The list shows strong interest with large projects already in operation , under construction.
- Uniper, UK **Connah's Quay Low Carbon Power project, expanding an existing power plant 1.38 GW CCTG with Carbon Capture target operation 2030.**
- HyNet, UK North West Large project J2 with CCUS.
- Teeside, UK North East, Northern Endurance Partnership (NEP) is the CO2 transportation and storage provider for the East Coast Cluster and will provide the infrastructure that will serve three initial carbon capture projects on Teesside: NZT Power, H2Teesside and Teesside Hydrogen CO2 Capture.
- Viking UK CCS South East
- Acorn is Scotland's only advanced CO_2 transport & storage network

Encouraging News:
Additional Important Projects

Norwegian Petroleum

https://www.norskpetroleum.no/en/environment-and-technology/carbon-capture-and-storage/

The Netherlands

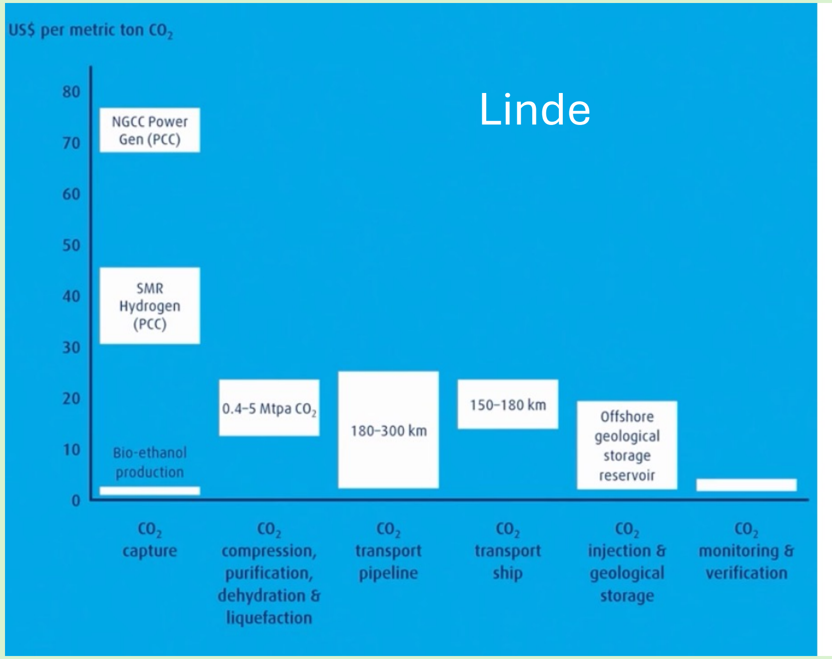
https://www.gasunie.nl/en/projects

Aeamis

Portthos

CEMENT

https://www.heidelbergmaterials.com/en/sustainability/we-decarbonize-the-construction-industry/ccus



For CCTG Recirculation of Exhaust in GTs to boost the CO2 concentration.

Integration of Carbon Capture with Electric Generation Plants – The Roles / Sharing Risks

- Power Plant Owner / Operator
- Power Plant Construction Project Main Contractor
- NG Gas Supplier
- Electricity Off-taker
- ADDITIONAL projects
- Carbon Capture –project 1
- CO2 Piping system – project 2
- Storage – project3p
- Operational Phase with Additional Stakeholders of the Additional Projects

Electricity Pricing Evolution #1

2000 Early Privatization

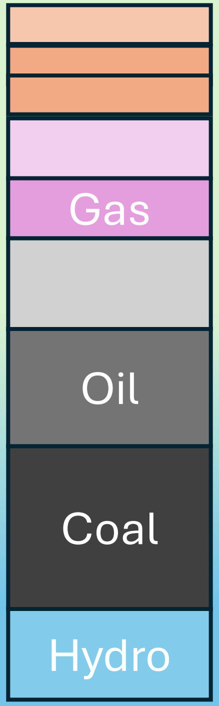
2010 Private takes hold

Capacity Charge + Energy Charge

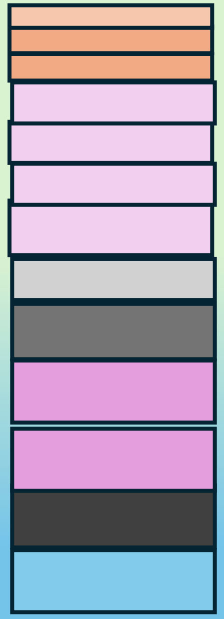
Capital Recovery + Fuel (Heat Rate)

O&M

with Escalation related to Indexes



Dispatch – Merit Order



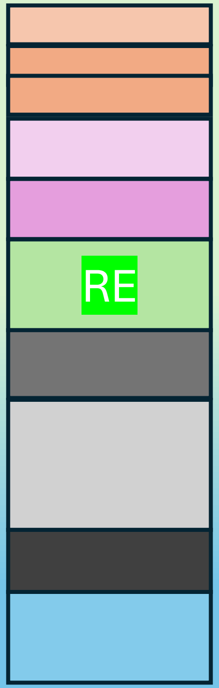
Electricity Pricing Evolution #2

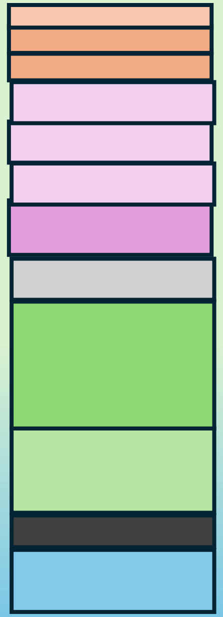
2015 Renewable

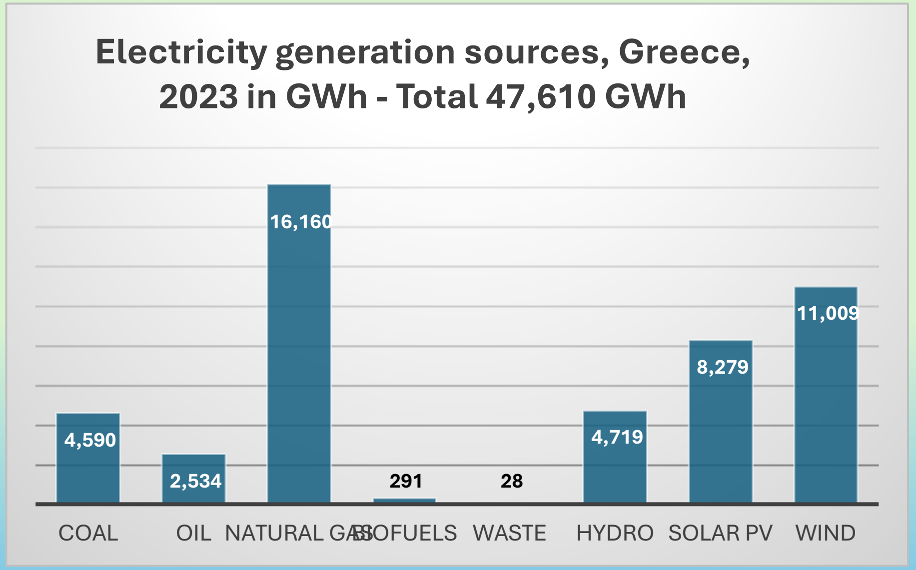
2020 Significant Renewable

Increased Dependence on Natural Gas & LNG

RE: Contracted Capacity @ fixed price for RE (wind and PV)

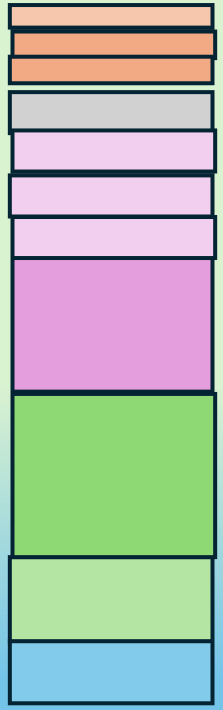






Installed Capacity ~ 24 GW in 2023

Electricity Pricing Evolution # 3
2025 Towards 2030 & 2050: Curbing GHG



Pricing CO2 – Carbon Credit

Electricity Price = Agreed Price + **CO2 Penalty**

New Plants

Please refer to the next slide

Through CCS avoid the + **CO2 Penalty**

At the Power Plant: 1) preparatory,
2) Concentration, 3). Compression

4) Transport in CO2 Pipeline

5) Storage

Greece : Power Plants Main-Land , Islands and under construction

#	Large Plants in Mainland Location	Type	Capacity MW	Owner	Notes
1	Agios Dimitrios, Kozani	Lignite-	1,595	PPC	Will be retired in 2025
2	Agios Nikolaos, Boeotia	NG CTTG	1,604	Mytilineos Group	High efficiency
3	Arcadia, Peloponnese	Lignite	850	PPC	Older signficnt for South Greece
4	Lavrio, Attica	NG	914	PPC	Important fo Attica
5	Ptolemaida, Western Macedonia	Lignite-	660	PPC	Modern plant 2023
6	Drama, E. Macedonia	Hydro	384	PPC	includes pumped-storage capabilities.
7	Aitoloakarnania, W. Greece	Hydro	437	PPC	Largest Hydro in Greece
8	Komotini, E Macedonia & Thrace	NG	485	PPC	Important for the region
9	Aliveri, Euboea	NG	417	PPC	Modernized to run on NG
10	Thisvi, Boeotia	NGNG	410	Elpedison	One of two plants owned & operated by Elpedison
#	Large Plants ib Islands	Type	Capacity ~MW		Notes
1	Souda Power Plant Crete	Oil	250		One of the main plants on Crete, run by PPC
2	Atherinolakkos Power Plant Crete	Oil	310		Largest on Crete; base-load thermal plant
3	Rhodes Power Plant (Soroni)	Oil	220		Serves the Dodecanese islands
4	Kos Power Plant	Oil/Diesel	100		Key for Kos and surrounding islands
5	Mykonos Power Station	Diesel	20		Seasonal peak demand due to tourism
6	Syros Power Station	Diesel	35		Central to the Cyclades island network
7	Lesvos Power Station (Mytilene)	Diesel	85		Supplies power for North Aegean islands
8	Chios Power Station	Diesel	50		One of the largest in North Aegean
#	New Plans under construction		Capacity MW	Developers / Owners	Status & Timeline
1	GEK Terna â€“ Motor Oil Komotini CCGT	CCGT	877	GEK Terna & Motor Oil Hellas	Commercial early 2025.
2	Alexandroupolis Combined Cycle Power Plant	CCTG	840	PPC (51%), DEPA Commercial (29%), Damco Energy (20%)	Commercial operation end of 2025
3	Agios Nikolaos (Viotia) CCGT	CCGT	826	Mytilineos Group	Commercial operation 2025
4	Thessaloniki II CCGT (Elpedison)	CCTG	826	Elpedison (Hellenicq Energy & Edison)	Expected commisxioning 2027
5	Ptolemaida V (Lignite)	Lignite	660	Public Power Corporation (PPC)	Ligne Unit operation on 2025, potential conversion to NG
	Larissa CCTG	CCGT	792	Glavenia Ltd, DEPA Commercial S.A., EUSIF Larissa S.A., and Volton S.A	Agrrement signed May 2025

Conclusions

- **GREECE HAS MADE AN EXCLLENT PROGRESS FOR HANDLING THE CLIMATE CHANGE UNDER THE NET ZERO PROGRAM IT UNDERTOOK OVER THE LAST 5 YEARS SHOPWING AN EXCLLENT EXAMPLE AMONG EUROPEAN COUNTRIES. The results are cover many directions, Energy Savings, RE, Natural Gas, retiring the Lignite units, Digitization, supporting electric vehicles, and gas buses.**

EXPECTED ELECRIC LOAD GROWTH – DATA CENTERS / AI.

- Electricity is the backbone for meeting Energy requirements (Greece may reach 65 GW in 20250):

  dispatchability, proximity to load centers, economic merit & CO_2 emissions.

- Challenges for Battery storage costs will hamper RE additions,
- Large plants thermal (existing, and new) will need to be dispatched, and hence Carbon Capture & Storge CCS. Depending on the load level, the CO_2 emissions will be determined, this will represent constraint for CO_2 utilization. The range of level of plant load will affect the design of the transport and storage.,
- Strategically, guarded investment for Green Hydrogen and limited adoption of imported of the transport Ammonia may be prudent investment for the future depending on the H_2 Technology.
- However, Carbon Capture will support the operation of the Thermal plants, Priority could be on the Thermal plants Lignite in Mainland , Oil in the Islands (with Utilization).
- Carbon Capture from the CCGT plants is problematic because of the low CO_2 concentration.
- **DECISIONS OF EU AND THE GREEK GOVERNMENT TO ASSESS THE VIABILITY OF CCUS.**
- **The author would welcome thd opportunity to partner to further investigate Carbon Capture in Greece building on what he has done in 2024 and 2025.**

Thank YOU

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