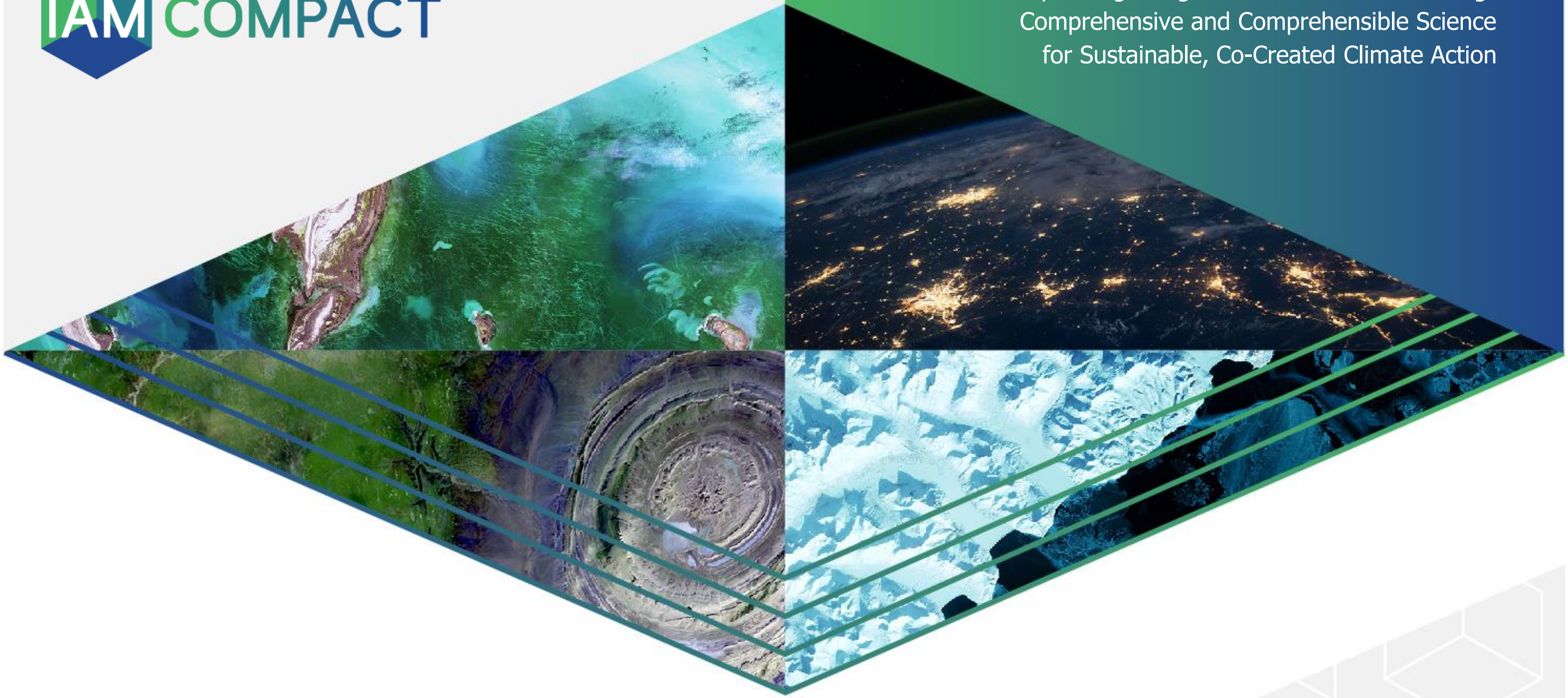
IAM COMPACT

Expanding Integrated Assessment Modelling:
Comprehensive and Comprehensible Science
for Sustainable, Co-Created Climate Action



Combining long-term capacity planning with flexibility assessment to explore decarbonisation pathways in the power sector

Mr. Nikos Kleanthis, Dr. Vassilis Stavrakas, Prof. Dr. Alexandros Flamos

Technoeconomics of Energy Systems laboratory (TEESlab), University of Piraeus Research Centre (UPRC)

Funded by
the European Union

www.iam-compact.eu

Funded by the European Union

Funded by the European Union

Amendment of the Greek **National Energy and Climate Plan** (NECP)

→ Increased ambition, including high **variable renewable energy** (VRE) capacity targets in the **power sector**

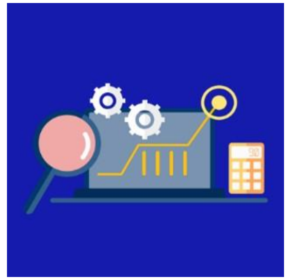
How can **carbon neutrality** in the power sector be achieved while transitioning to a **flexible**, VRE-based future instead of continuing to rely on natural gas?

→ **Need for modelling support** to provide feasible decarbonisation pathways

RQ part of the Horizon projects: IAM COMPACT & ENCLUDE Energy Citizens for Inclusive Decarbonization

"What are the capacity and flexibility requirements for a carbon neutral power sector?"

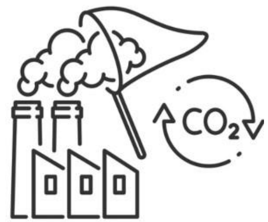
Funded by the European Union



Modelling tools capable of capturing VRE variability to analyse **flexibility issues** and provide relevant solutions.

……..we **soft-link** two **open-source** tools (OSeMOSYS + Flextool) to provide insights regarding three alternative cost-optimal decarbonisation pathways by 2050 in the power sector.

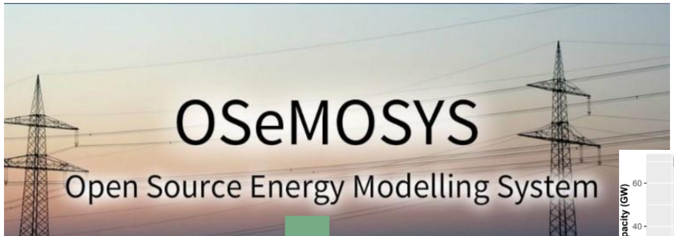
- ❑ Future role of natural gas and hydrogen,
- ❑ Integration of VRE with energy storage,
- ❑ Potential use of carbon capture and storage (CCS), etc.

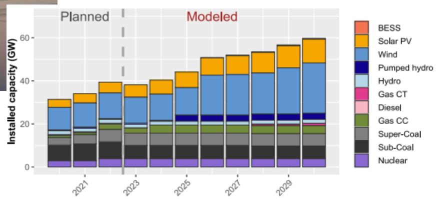


Funded by the European Union

Why these tools? **Open-source, well documented, transparency, replicability, scalability, fast learning curve** ✔

Capacity Expansion Model (CEM)



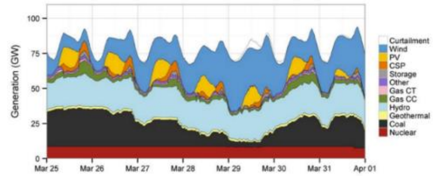


Delivery of long-term decarbonization pathways

Production Cost Model (PCM)

IRENA
International Renewable Energy Agency

FlexTool



Delivery of short-term dispatch to identify flexibility issues, e.g., loss of load, curtailment.

Funded by the European Union

Funded by the European Union

Coupling of two models .....

OSeMOSYS-GR
Linear Optimization Energy Planning Model

Newly developed Capacity Expansion Model for the Greek power sector

FlexTool

Adjusted based on the power sector design provided by OSeMOSYS-GR

... to develop a **bidirectional** soft-linking approach!

Funded by
the European Union

OSeMOSYS-GR – Linear Optimization Energy Planning Model

Long-term scenario analysis

→

IRENA – International Renewable Energy Agency
FlexTool (Dispatch mode)

Short-term assessment of flexibility: Identification of issues

↓

IRENA – International Renewable Energy Agency
FlexTool (Investment mode)

Short-term assessment of flexibility: Solving issues

→

OSeMOSYS-GR – Linear Optimization Energy Planning Model

Refined long-term scenario analysis (No loss of load, low curtailment)

Funded by the European Union

1 Introduction

2 Methods

3 Application to the power sector in Greece

4 Results

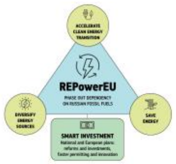
5 Conclusions and policy implications

Funded by the European Union

- Limited capacity for interconnections
- Heavy reliance on gas for electricity production
- Significant VRE potential

European Green Deal (2019) → **NECP (2019)** →

➢ Terminating **domestic lignite mining** & lignite-fired electricity generation by **2028**



National Climate Law (2022)

REPowerEU (2022)

→ **Revised draft NECP (2023)** →

➢ Decarbonisation of power sector by **2040**
➢ Focus on VRE (69 GW in 2050)

After 2022 & **energy crisis**, the government has been reconsidering the role of natural gas

Revised final NECP (August 2024) →

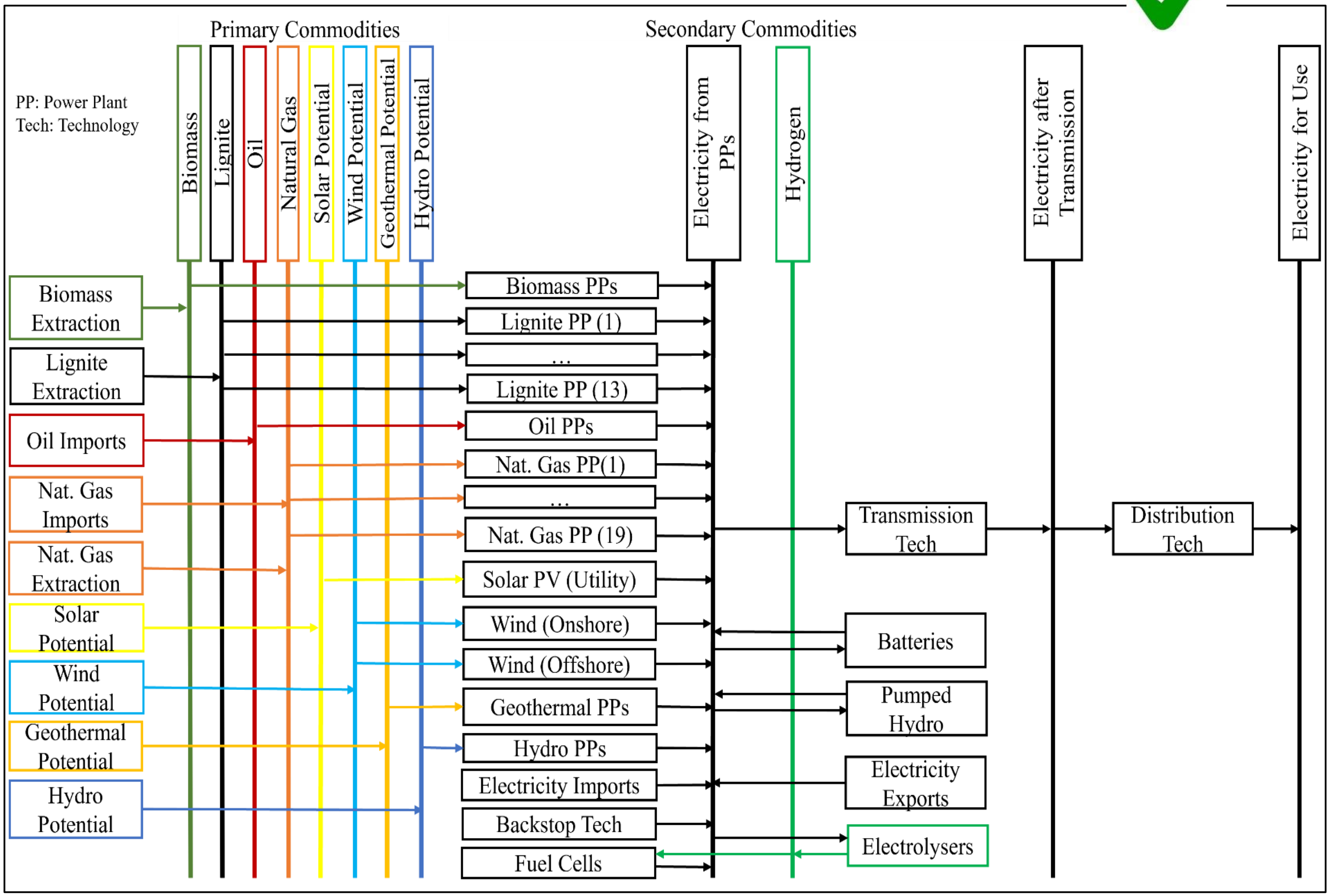
➢ Decarbonisation of power sector right after **2035**

Funded by
the European Union

Application to the power sector in Greece (2/4)

Reference Power System

- **Fossil-fired power plants:** lignite, natural gas, and oil.
- **RES:** hydro, wind onshore & offshore, solar PV, biomass & geothermal.
- **Energy storage:** battery & pumped hydro.
- **Hydrogen production & consumption:** electrolysers & fuel cells.
- **Interconnections** with neighbouring countries.
- **Transmission** & **distribution** losses.



Funded by the European Union

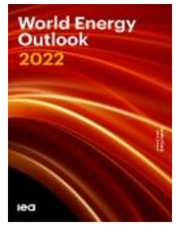
Application to the power sector in Greece (3/4)

IAM COMPACT

- Electricity demand, NG price, and ETS CO_2 emission allowance **prices**.

- **Data** concerning the **fossil-fired power plants**, such as capacities, minimum stable generation, efficiencies, minimum uptimes/ downtimes, their availabilities considering planned commissioning and de-commissioning of generating capacity.

Renewables.ninja



- **Technological data**, e.g., capital costs, fixed and variable O&M costs, efficiencies, capacity factors.

EU Reference Scenario 2020

World Energy Outlook 2022

- **Residual capacities** of existing electricity generation technologies.

entsoe
Transparency Platform

- **Import capacity** from interconnections.

Ten-year development plan of the Greek IPTO

Funded by
the European Union

IAM COMPACT

For all the scenarios

- **Carbon neutrality** should be achieved by **2040**
- **Phase out** of **lignite** by **2028**

Neutrality 1

2020 — 2024 — 2040 — 2050

- 2024: **Starting year**
- **Higher rate of capacity expansion** of **VRE**, **energy storage**, and **fuel cells**
- **Phase out** of **natural gas** **before** the milestone year
- 2040: **Milestone year**

Neutrality 2

2020 — 2024 — 2035 — 2050

- 2024: **Starting year**
- **Lower rate of capacity expansion** of **VRE**, **energy storage**, and **fuel cells**
- 2035: **Natural gas** & **biomass** plants retrofitted with **CCS**

Neutrality 3

2020 — 2024 — 2035 — 2050

- 2024: **Starting year**
- **Higher rate of capacity expansion** of **VRE**, **energy storage**, but **fuel cells** at a **lower rate**
- 2035: **Natural gas** plants switch to **hydrogen**

Funded by
the European Union

1 Introduction

2 Methods

3 Application to the power sector in Greece

4 **Results**

5 Conclusions and policy implications

Funded by the European Union

Results (1/15)

IAM COMPACT

OSeMOSYS-GR
Linear Optimization Energy Planning Model

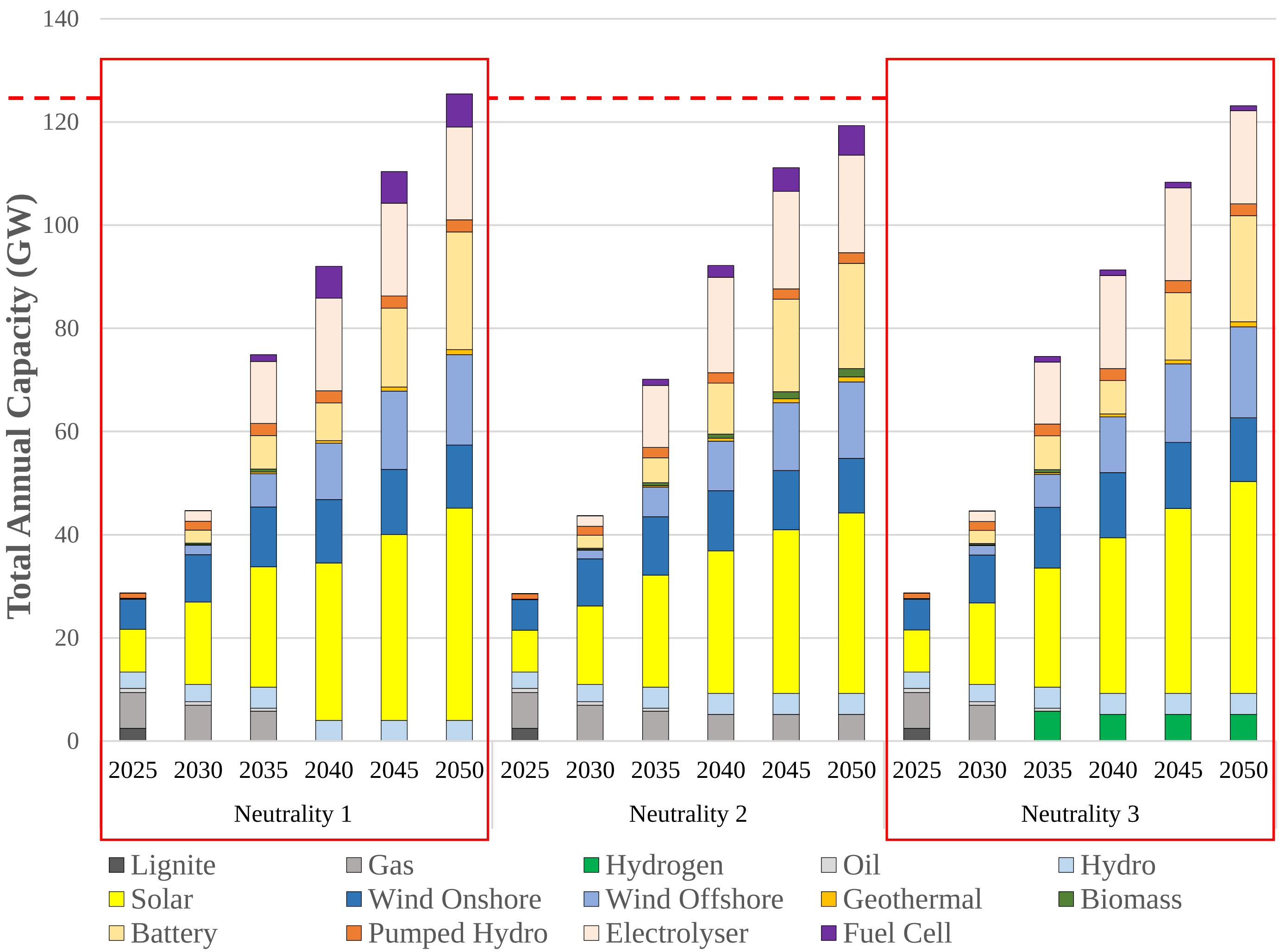
Long-term capacity planning prior to flexibility assessment

2030: ~27 GW VRE
2040: ~54 GW VRE
2050: ~**71 GW** VRE

NECP target: **69.5 GW**

Neutrality 1 and **Neutrality 3** scenarios …

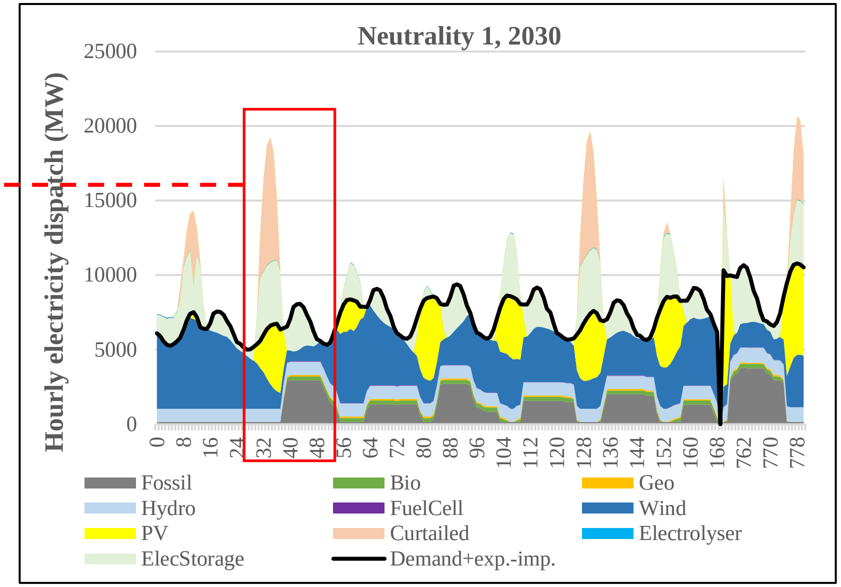
… **result** in the **achievement** of the **national VRE capacity targets** by **2050**

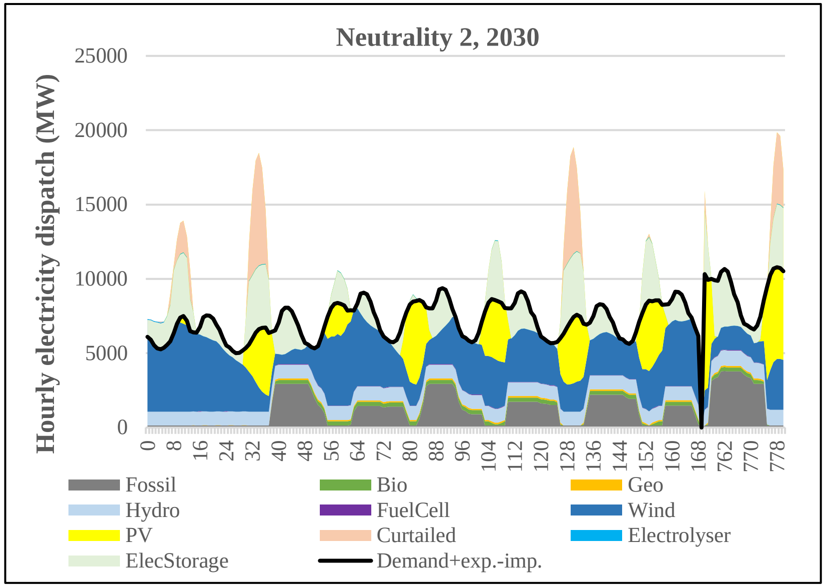


Funded by the European Union

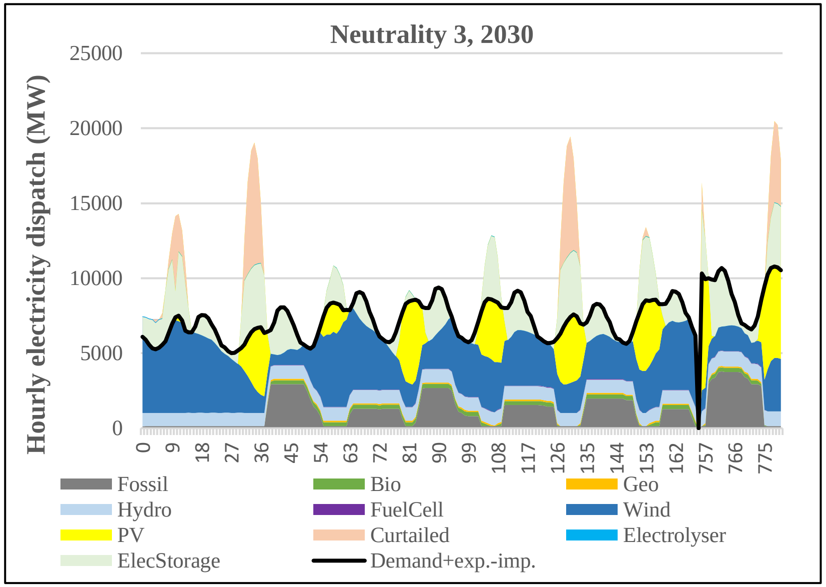
FlexTool Flexibility assessment for 2030

Daily dispatch





Scenario	Peak net load (MW)	Curtailment (% of VRE gen.)	Loss of load (% of annual demand)
"Neutrality 1"	8,182	8.9	0
"Neutrality 2"	8,195	7.7	0
"Neutrality 3"	8,176	8.7	0



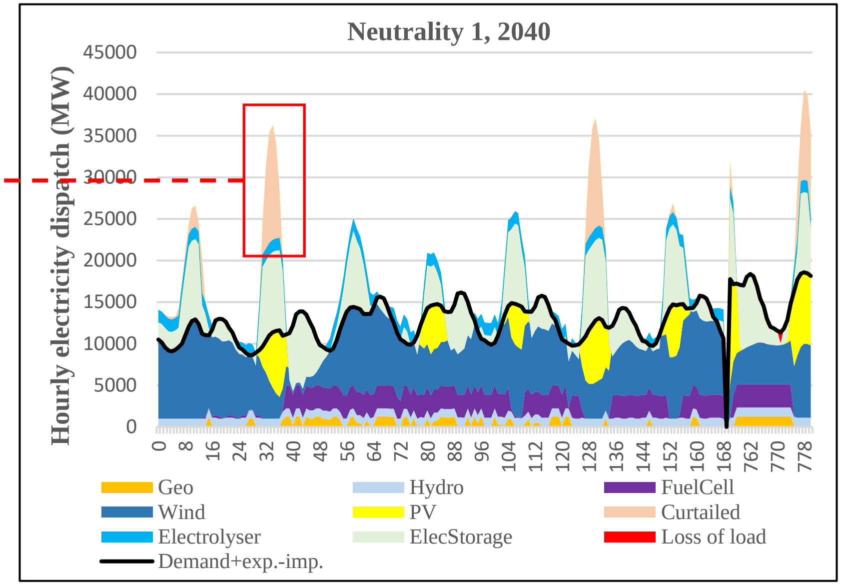
The flexibility assessment results are **similar** in **2030** since the decarbonisation pathways do not significantly differ by then.

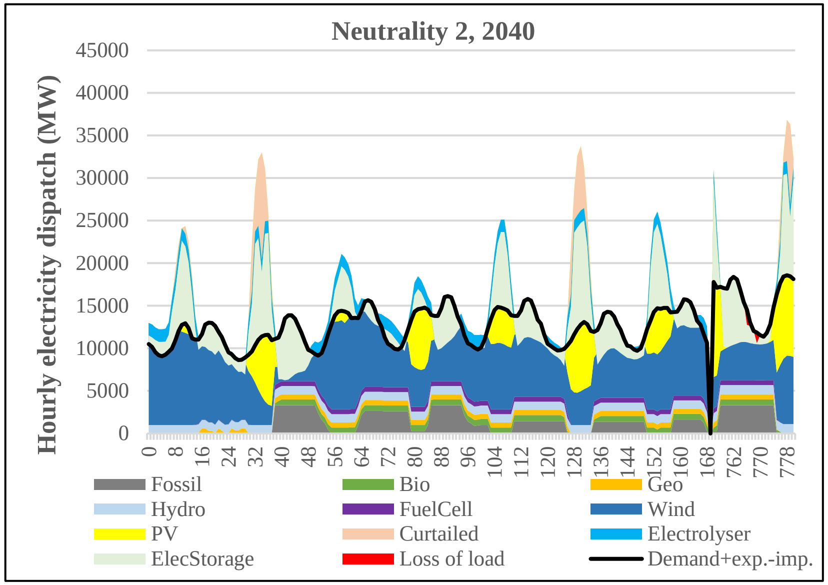
Funded by the European Union

Results (3/15)

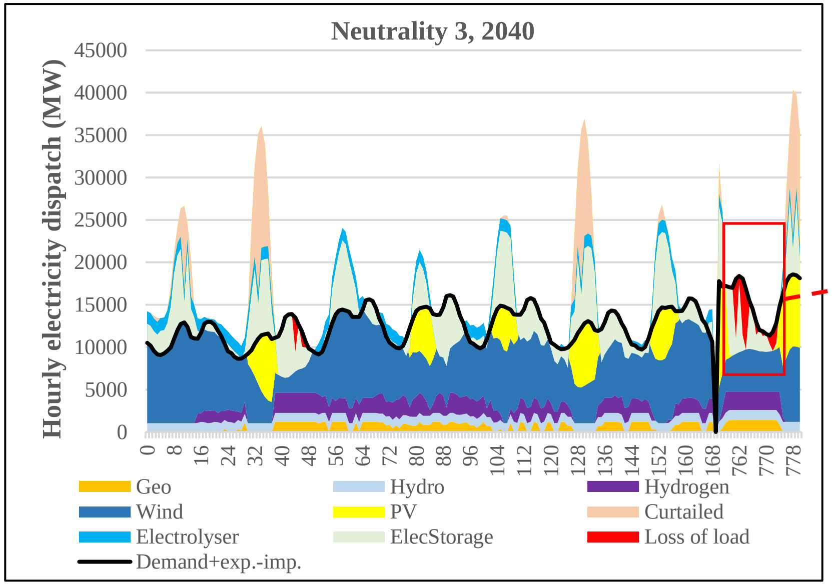
FlexTool Flexibility assessment for 2040

Curtailment





Scenario	Peak net load (MW)	Curtailment (% of VRE gen.)	Loss of load (% of annual demand)
"Neutrality 1"	12,635	6.9	0.08
"Neutrality 2"	13,117	4.1	0.13
"Neutrality 3"	12,555	9.3	1.42



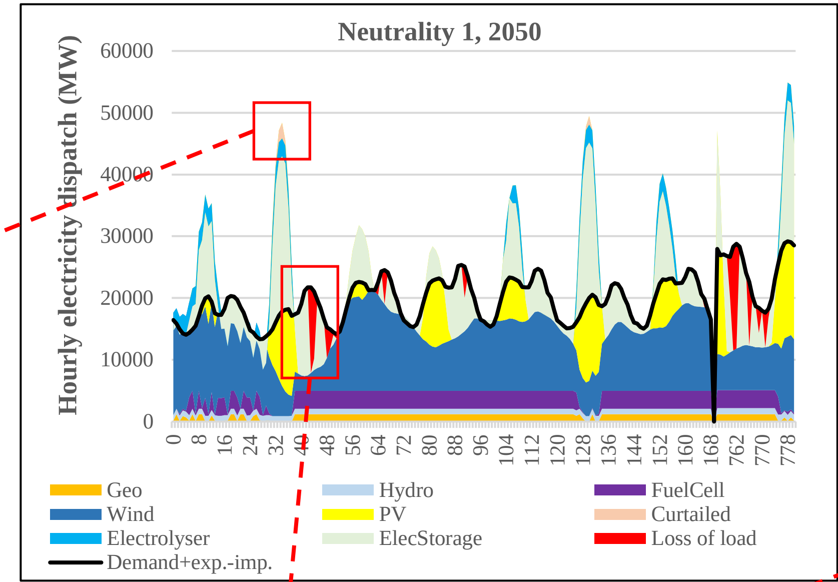
Losses of load are mainly detected in "***Neutrality 3***".

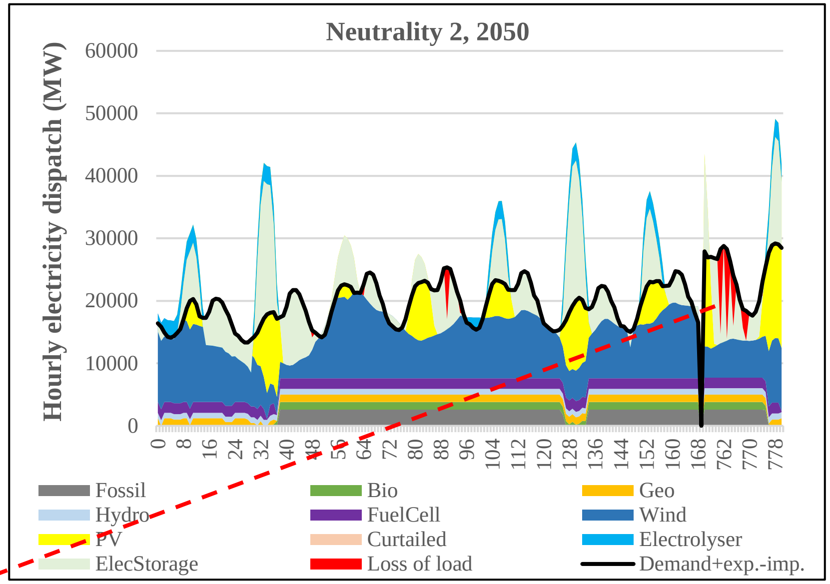
Funded by the European Union

IAM COMPACT

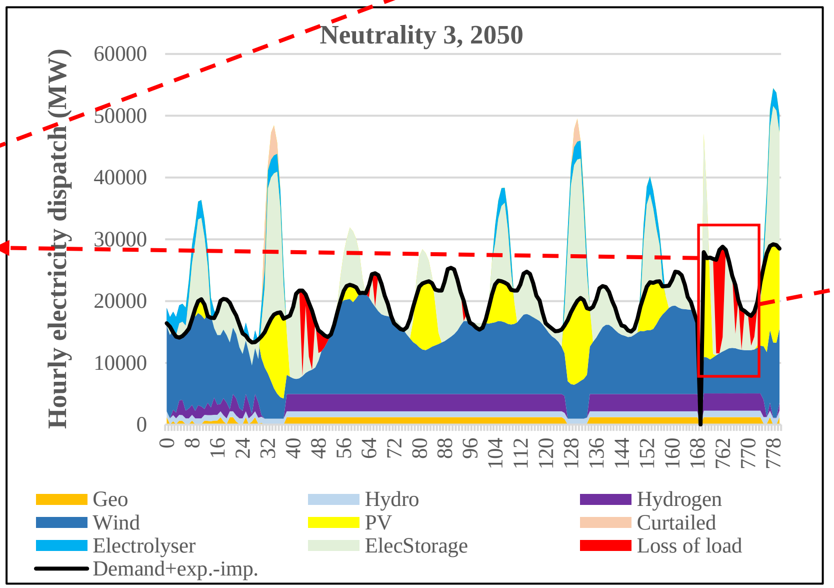
FlexTool Flexibility assessment for 2050

Curtailment is reduced towards **2050** due to the increased capacity of electricity storage and electrolysers.





Scenario	Peak net load (MW)	Curtailment (% of VRE gen.)	Loss of load (% of annual demand)
"Neutrality 1"	21,073	0.3	2.81
"Neutrality 2"	22,086	0	1.59
"Neutrality 3"	20,947	0.8	3.17



Losses of load are noticeable in all three scenarios.

Funded by the European Union

FlexTool

Insights from the flexibility assessment (**dispatch mode**): Additional **flexibility and capacity** is required after **2030** to prevent **loss of load**.

Considering the above ➔ FlexTool was used in **investment mode** to cover the arisen flexibility issues.

"Neutrality-Flex" scenarios	Peak net load (MW)	Curtailment (% of VRE gen.)	Loss of load (% of annual demand)
"Neutrality 1-2050"	20,114	1	0
"Neutrality 2-2050"	21,324	0.2	0
"Neutrality 3-2050"	19,873	1	0

Investment mode: The **VRE** and **storage capacity** additions eliminate loss of load and significantly decrease peak net load (~1GW across all scenarios) in 2050.

A **second round of runs** incorporating the flexibility insights in terms of additional investments ("*Neutrality-Flex*" scenarios) is performed using **OSeMOSYS-GR**.

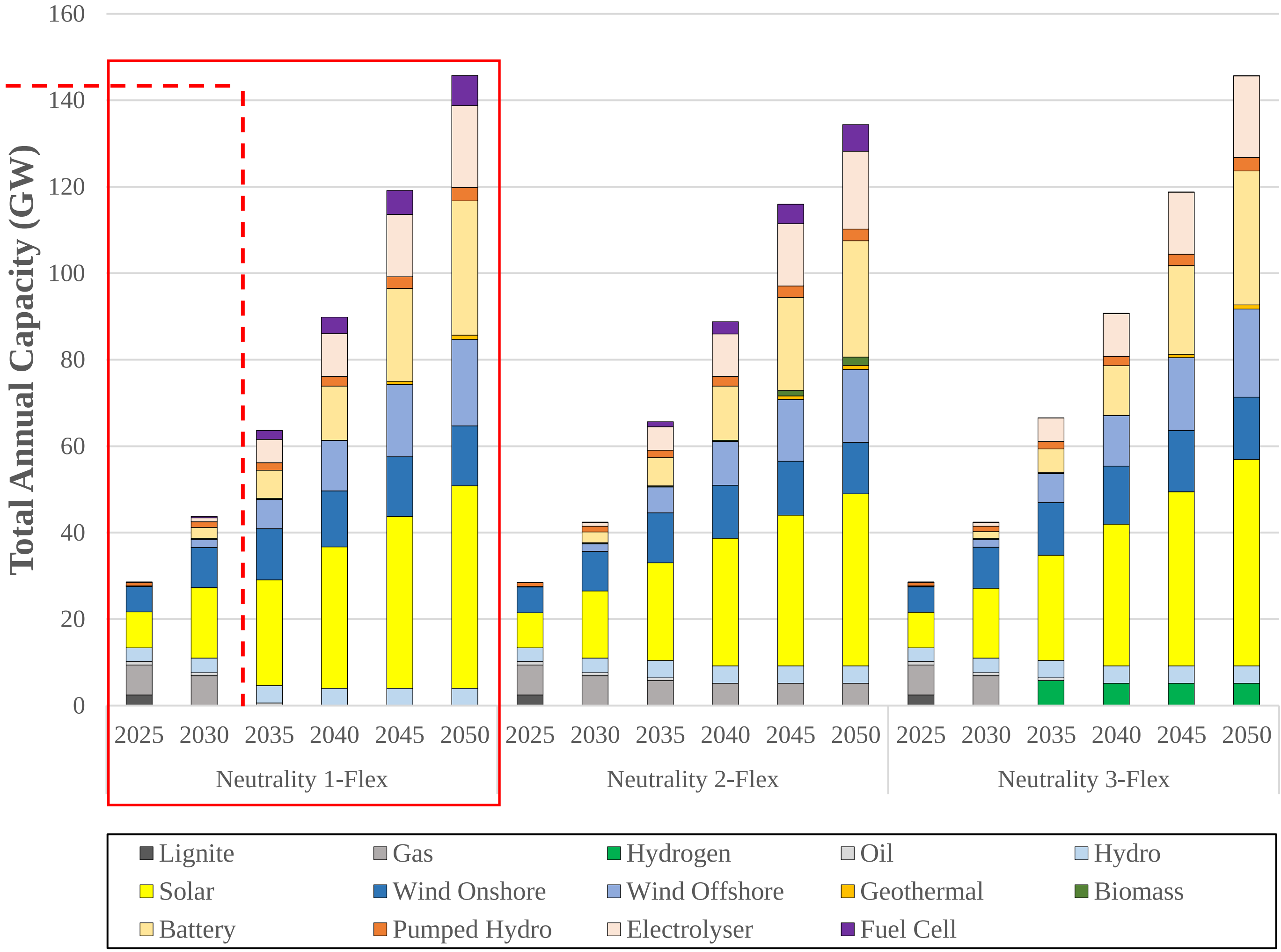
Funded by the European Union

IAM COMPACT

OSeMOSYS-GR
Linear Optimization Energy Planning Model

Long-term capacity planning after flexibility assessment

Neutrality 1-Flex scenario allows the phaseout of natural gas by **2033**.



Funded by the European Union

IAM COMPACT

OSeMOSYS-GR
Linear Optimization Energy Planning Model

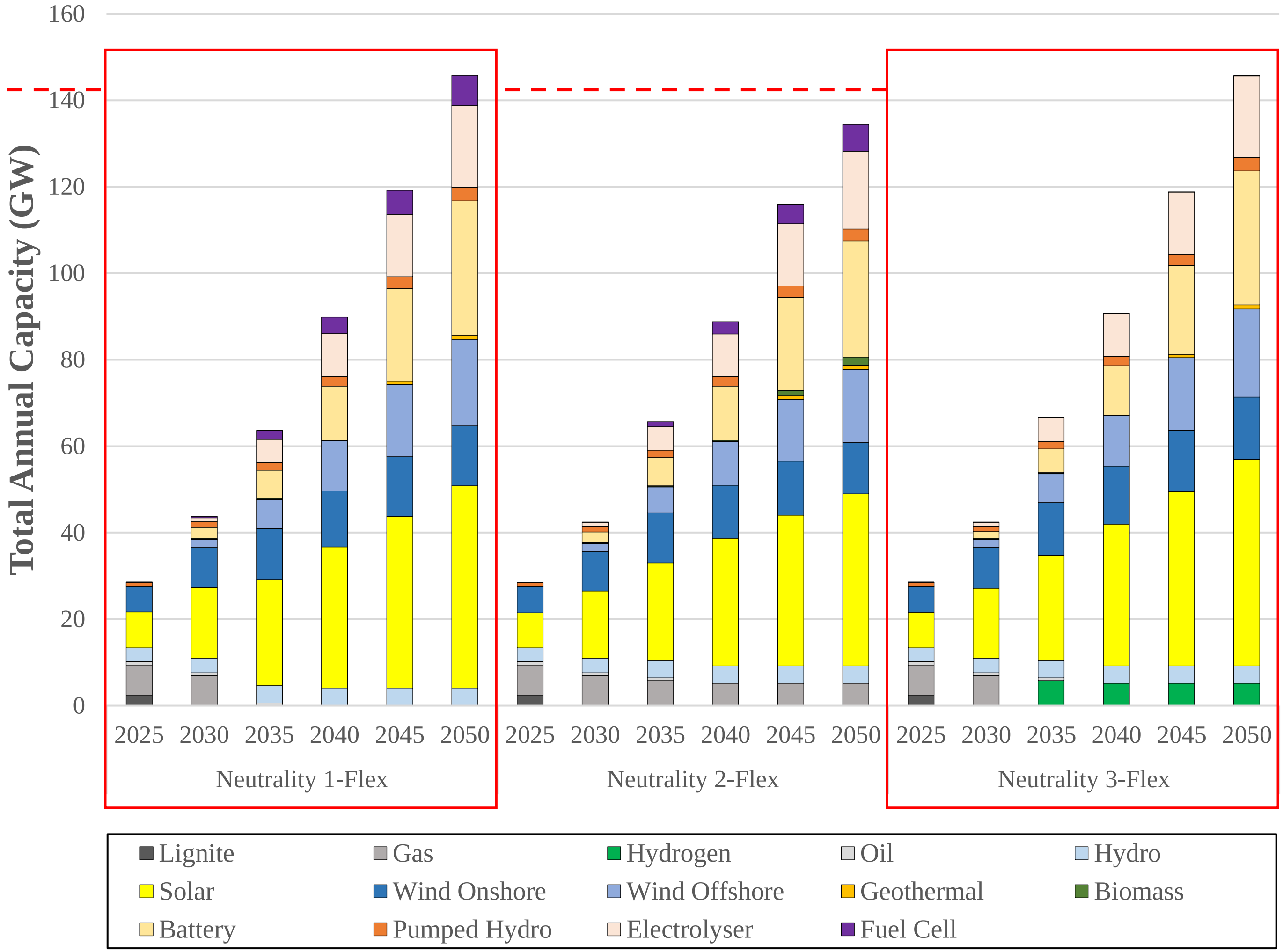
Long-term capacity planning after flexibility assessment

2030: ~27 GW VRE
2040: ~57-58 GW VRE
2050: ~**81-82.5 GW** VRE

NECP target: **69.5 GW**

Neutrality 1-Flex and **Neutrality 3-Flex** scenarios ...

... overshoot the NECP target by 11.5-13.0 GW



Funded by the European Union

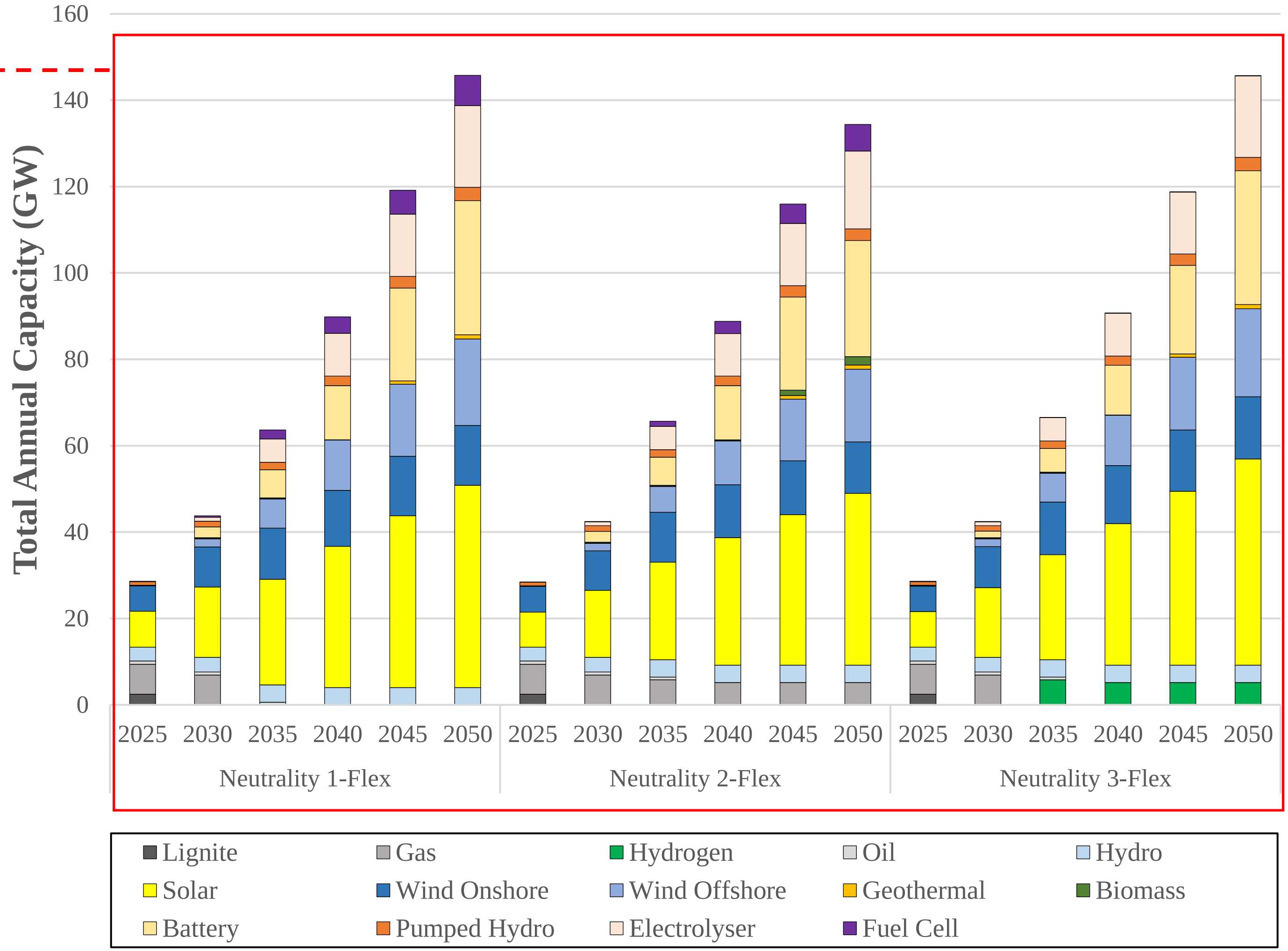
OSeMOSYS-GR
Linear Optimization Energy Planning Model

Long-term capacity planning after flexibility assessment

Battery & **pumped storage** capacity grows to **29.5-34.1 GW** by **2050**

Electrolyser capacity grows to **18.1-18.9 GW** by **2050**

Total capacity of **flexibility solutions** amounts to **47.6-53 GW** by **2050**

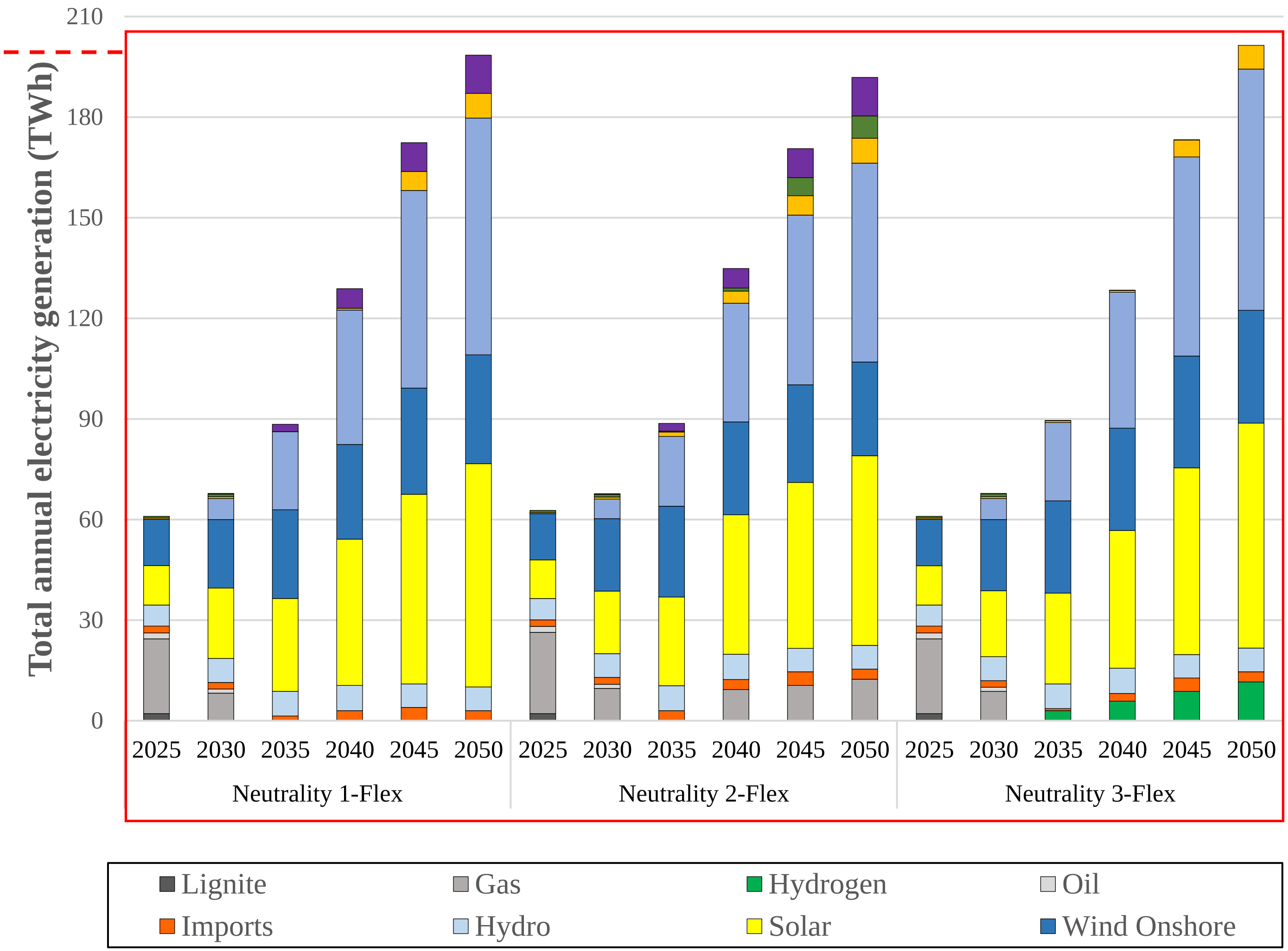


Funded by the European Union

Long-term capacity planning after flexibility assessment

2030: ~81-83% of total annual power generation from RES and hydrogen

NECP target: **81.5%**



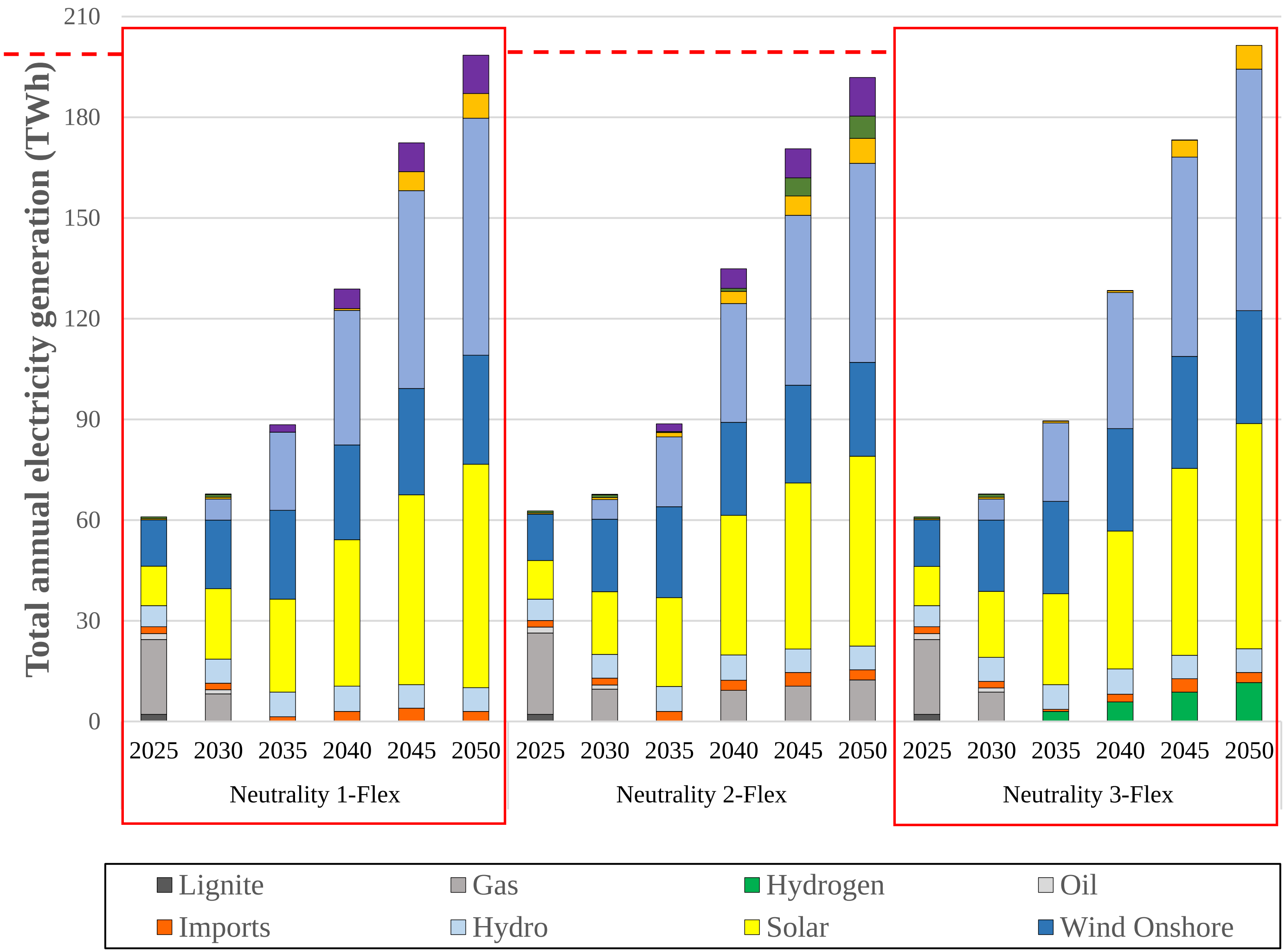
Funded by the European Union

Long-term capacity planning after flexibility assessment

Neutrality 1-Flex and **Neutrality 3-Flex** scenarios

2050: ~98.5% of total annual power generation from RES and hydrogen

NECP target: **98.3%**



Funded by the European Union

IAM COMPACT

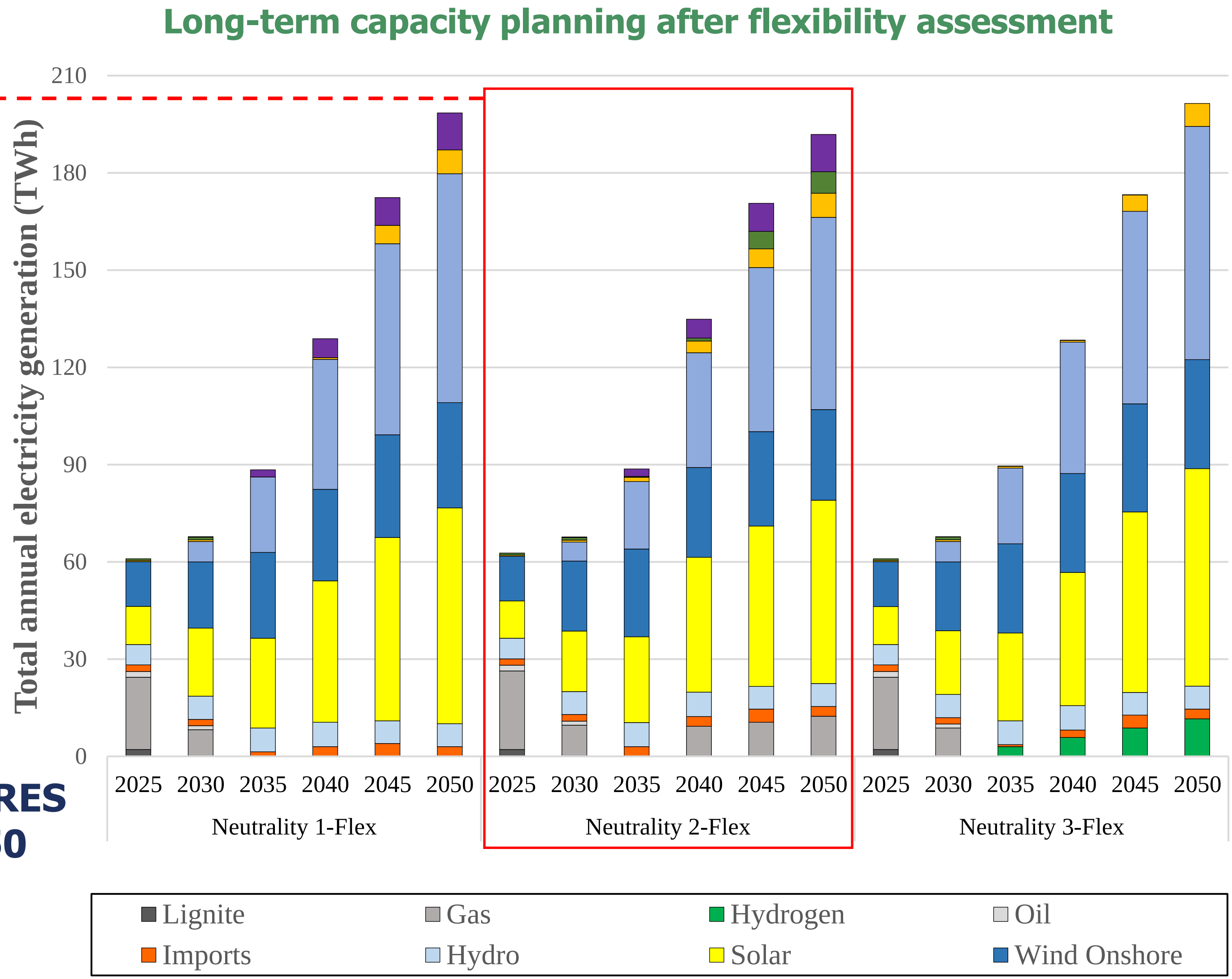
OSeMOSYS-GR
Linear Optimization Energy Planning Model

Neutrality 2-Flex
scenario …

2050: ~92% of total annual power generation from RES and hydrogen

NECP target: **98.3%**

… cannot result in the **achievement** of the **national RES penetration targets** by **2050**



Funded by the European Union

IAM COMPACT

OSeMOSYS-GR
Linear Optimization Energy Planning Model

Flexibility solutions provided by Flextool investment mode ➔ Feasible system sizing

Electricity generation (TWh)	2030	2035	2040	2045	2050
"Neutrality 1"	78.8	106	131	159.8	177.9
"Neutrality 1-Flex"	67.8	88.4	128.8	172.4	198.5
"Neutrality 2"	76.6	105.1	135	159.4	174.5
"Neutrality 2-Flex"	67.7	88.6	134.9	170.6	191.8
"Neutrality 3"	78.7	103	131.1	160.1	178.7
"Neutrality 3-Flex"	67.7	89.5	128.4	173.2	201.4

Curtailment reduction → 2040

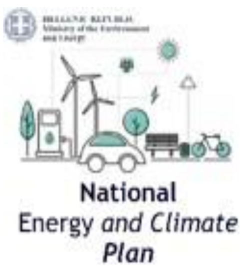
Loss of load reduction → 2050

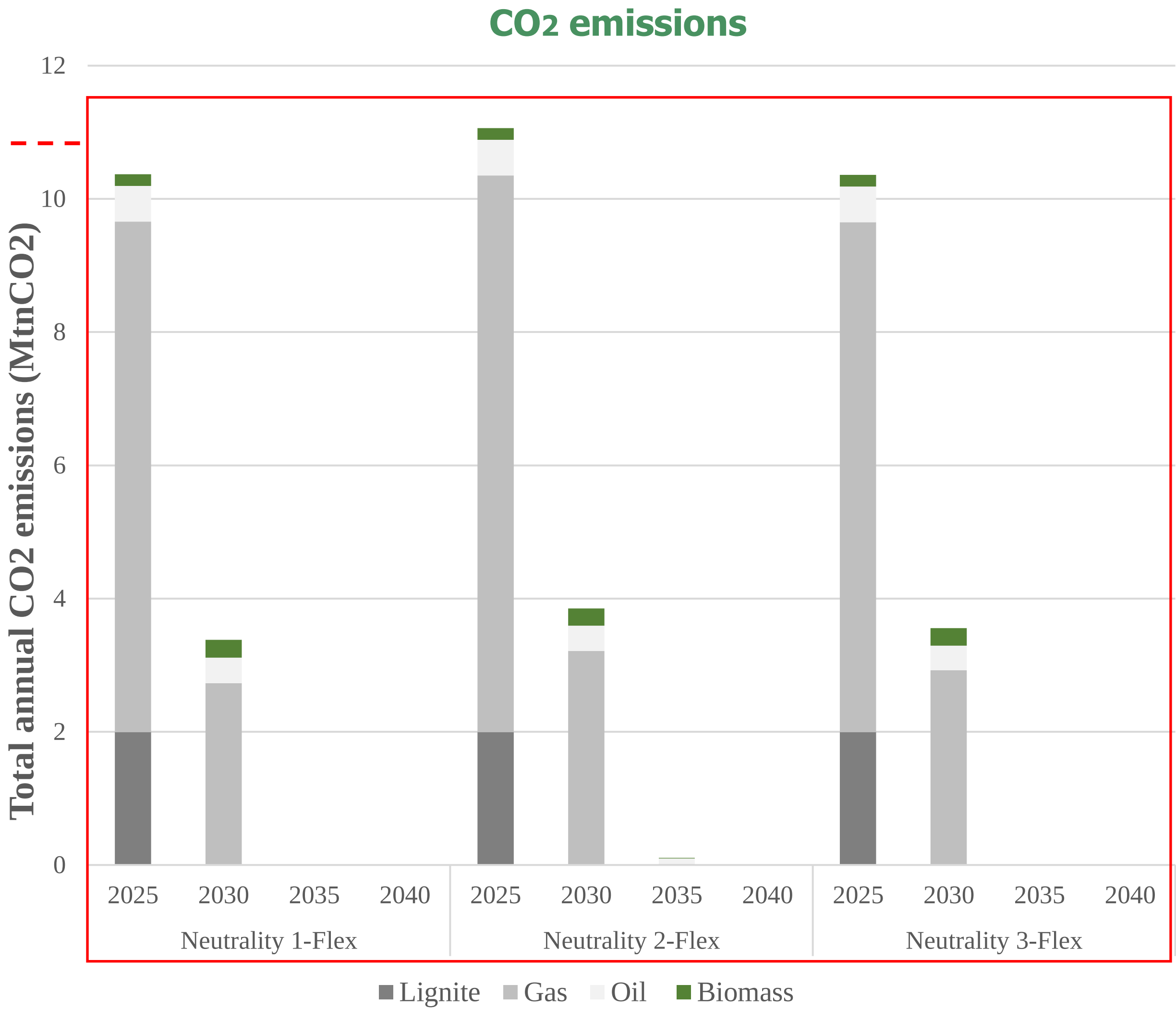
Funded by the European Union

OSeMOSYS-GR
Linear Optimization Energy Planning Model

The CO2 emission reduction by **2030** compared to the 2005 levels is **93.4-94.2%** in the "*Neutrality-Flex*" scenarios.

NECP target: **89.7%**



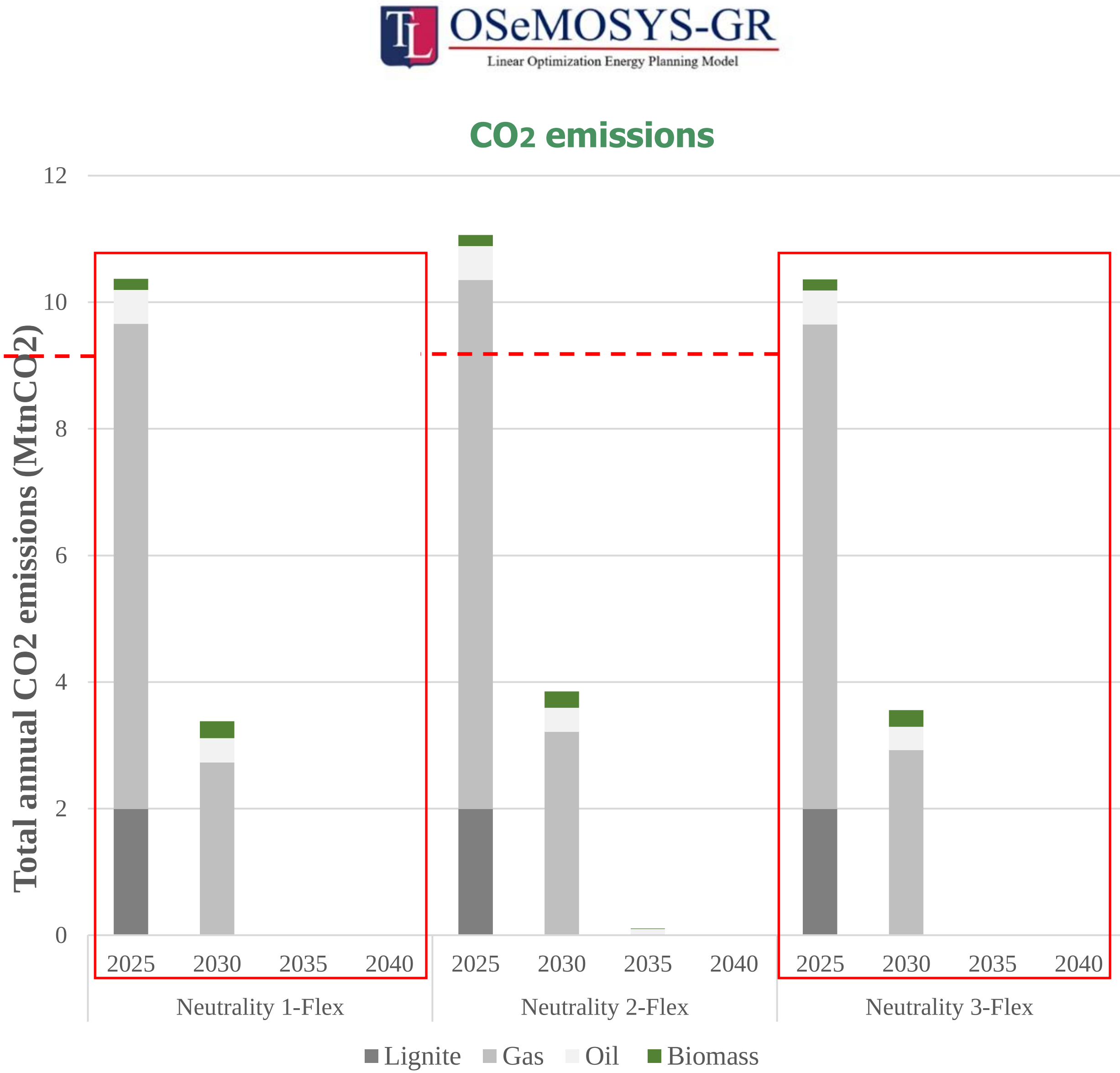


Funded by the European Union

Neutrality 1-Flex and **Neutrality 3-Flex** scenarios …

… **result** in the **achievement** of the **carbon neutrality target** by **2035**, **five years earlier** than the **revised draft NECP target (2040).**

This finding is consistent with the **revised final NECP target (2035)**.



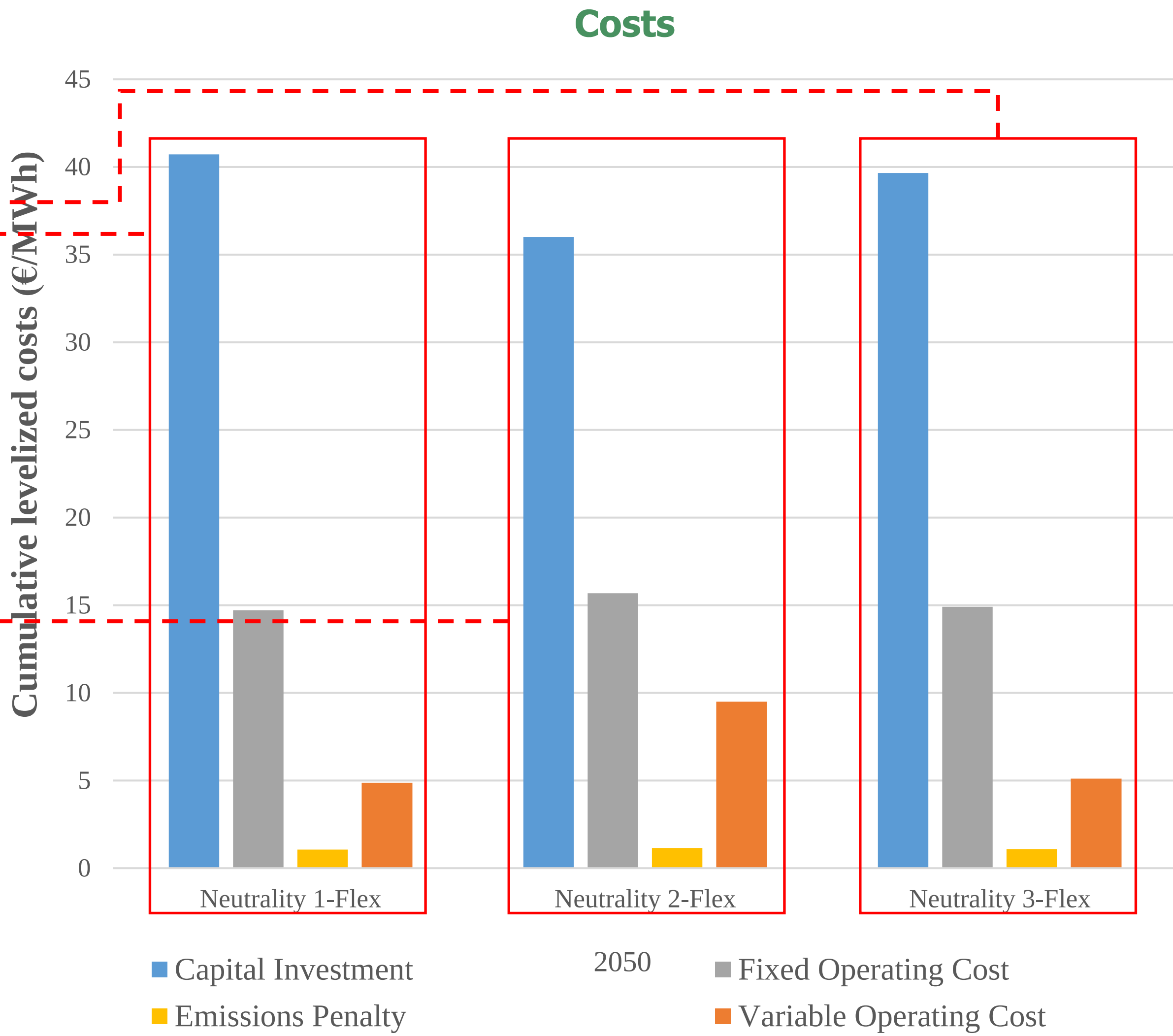
Funded by the European Union

OSeMOSYS-GR
Linear Optimization Energy Planning Model

Neutrality 1-Flex and Neutrality 3-Flex: larger capital investment requirements (**40.7** and **39.7 €/MWh**) due to higher adoption rate of VRE and storage

Neutrality 2-Flex: higher variable operating cost expenditures (**9.5 €/MWh**) due to continuation of gas-fired electricity generation

All scenarios: similar total levelized cost **(60.8-62.3 €/MWh)**

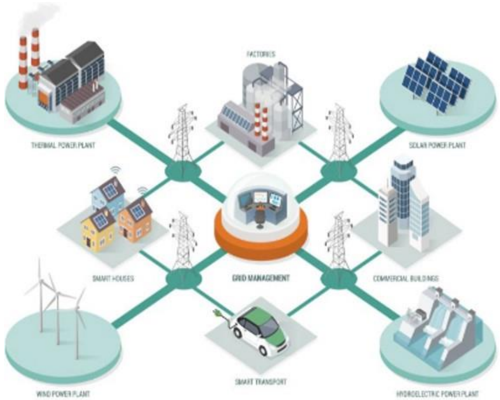


Funded by the European Union

Funded by the European Union

We see that …

…exploring long-term decarbonisation pathways should **combine long-term capacity planning** with **short-term operational assessment** to provide feasible solutions.



Funded by
the European Union

We see that …

…there is **path dependency on natural gas** in Greece **at least until 2033**, which could either result in a **lock-in effect** or lead to **stranded assets** (i.e., risk that investments in new natural gas power plants may not be profitable).

Funded by
the European Union

We see that …

…switching to **hydrogen** can be an alternative for newly built natural gas power plants to avoid becoming stranded assets.

…**gas power plants that can switch to hydrogen** could be prioritised in terms of fossil-fuel investments.

Funded by
the European Union

Publication

Bidirectional soft-linking of a Capacity Expansion Model with a Production Cost Model to evaluate the feasibility of transition pathways to carbon neutrality in the power sector

Nikos Kleanthis[1], Vassilis Stavrakas[1,*], Alexandros Flamos[1]

[1] *Technoeconomics of Energy Systems laboratory (TEESlab), Department of Industrial Management and Technology, University of Piraeus, Karaoli & Dimitriou 80, Piraeus 18534, Greece.*

ARTICLE INFO

Keywords:
Carbon neutrality
Capacity Expansion Models
Energy system modelling
Flexibility assessment
OSeMOSYS
Production Cost Models

ABSTRACT

Energy system models have supported well-informed decision-making processes in Europe over the past few decades. However, the vision of climate neutrality requires an additional level of detail that comes with designing an energy system based on intermittent renewables; many models that have already been applied to explore decarbonisation pathways, though, lack the necessary time resolution to capture the integration of variable renewable energy, or are not open source, raising concerns of transparency and scientific reproducibility. In this article, we address this gap by introducing a bidirectional soft-linking approach between two open-source tools- the Capacity Expansion Model, OSeMOSYS, and the Production Cost Model, FlexTool- to generate long-term scenarios and evaluate their short-term feasibility. More specifically, our approach allows the optimisation of power sector investments over a 30-year period and its hourly operation at different snapshots, thus evaluating the integration of variable renewable energy more accurately. To test our approach, we apply it to the power sector in Greece, to study the capacity and flexibility requirements of the transition to carbon neutrality and the economic impacts of reducing reliance on gas. Our results provide insight into the conditions under which emission and electricity capacity and generation targets can be attained. Modelling outcomes demonstrate that there is a path dependency on natural gas in Greece at least until 2033, while there is potential to achieve carbon neutrality much earlier than 2040 if significant investments in renewable energy materialise. Finally, cost comparisons reveal that switching to hydrogen could be, not only an effective solution for new gas plants to avoid becoming stranded assets, but also the most economically efficient alternative for a green transition in the power sector.

ENCLUDE
Energy Citizens for Inclusive Decarbonization

At high impact scientific journal

Status:
Under minor revision

Funded by the European Union

Next steps and further research (1/2)

Manias et al. (2024). Report on the decarbonization potential of energy citizenship at the national and the EU levels: Deliverable 5.4 Energy Citizens for Inclusive Decarbonization (ENCLUDE). Zenodo. https://doi.org/10.5281/zenodo.12686859

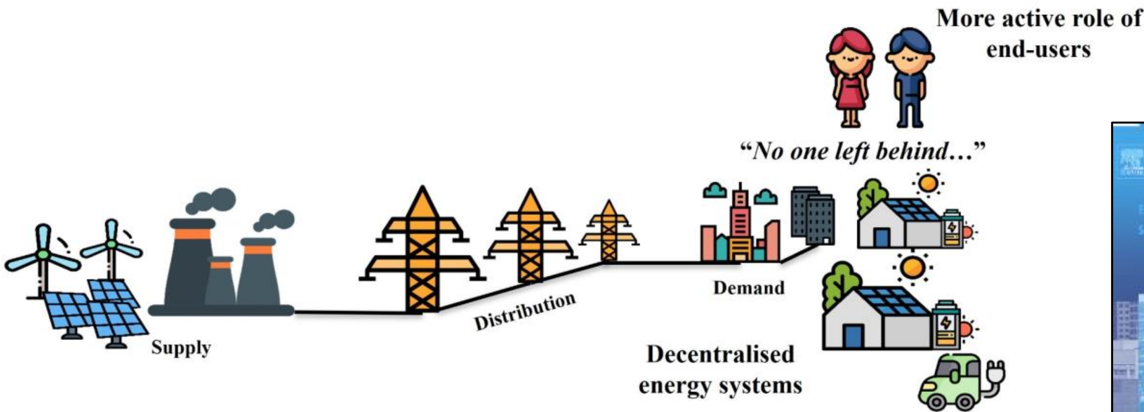
ENCLUDE
Energy Citizens for Inclusive Decarbonization

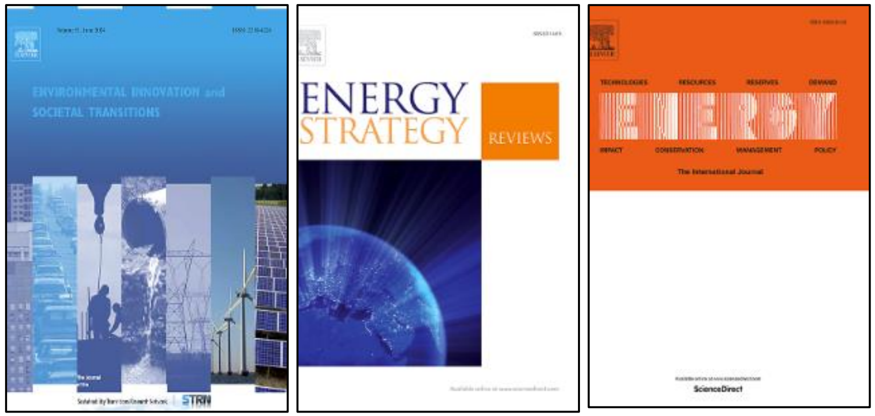
Citizen preference-led energy system planning alternatives under various future-world evolutions: Coupling transformative scenario design with energy system modelling towards 100% renewable-based energy systems

Nikos Kleanthis, Vassilis Stavrakas*, Alexandros Flamos

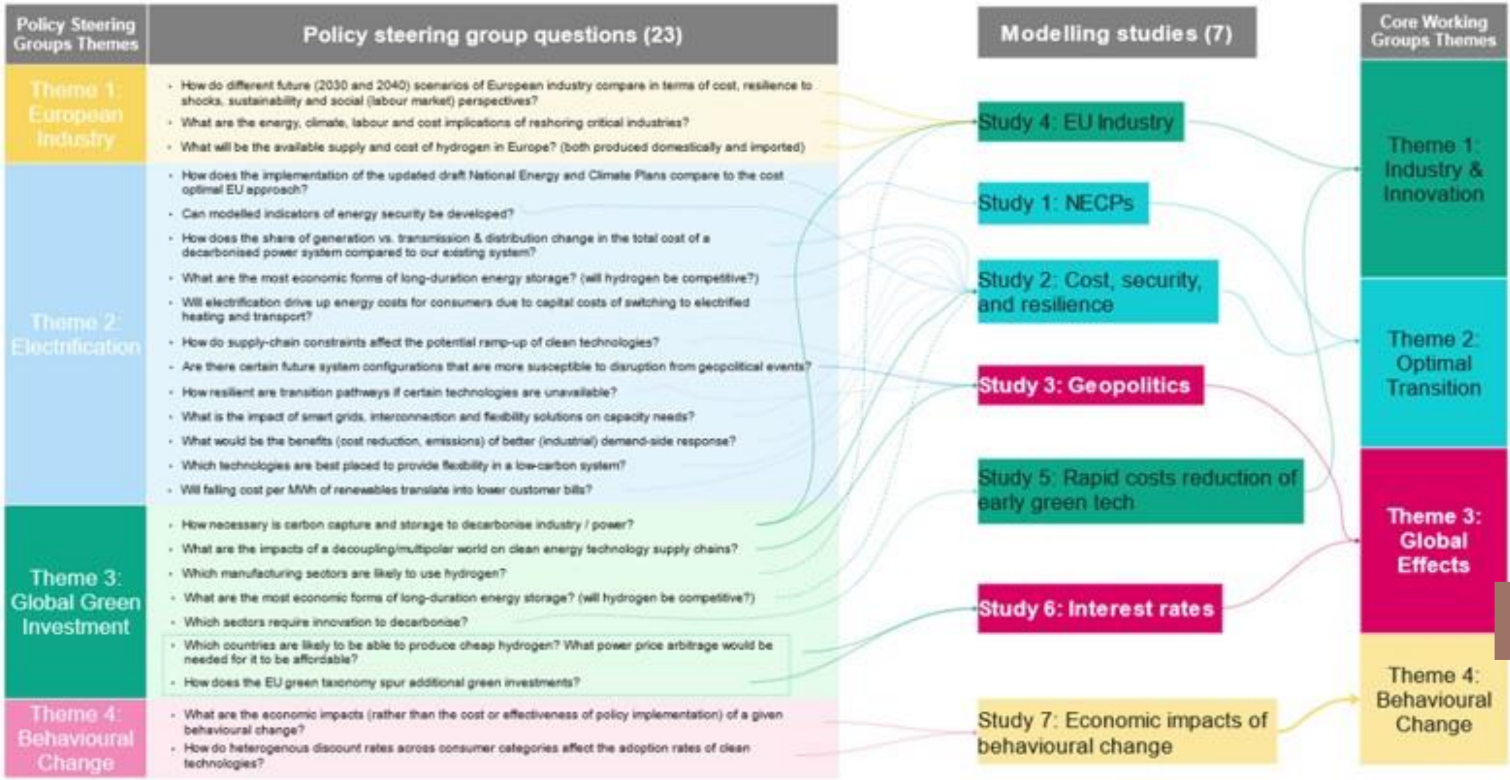
[1] Technoeconomics of Energy Systems laboratory (TEESlab), Department of Industrial Management and Technology, University of Piraeus, Karaoli & Dimitriou 80, Piraeus 18534, Greece.

?





Funded by the European Union



How does the cost of capital of different energy technologies influence decarbonisation pathways?

Funded by the European Union

aflamos@unipi.gr
vasta@unipi.gr
kleanthis@unipi.gr

Scan us for more info!

TEESlab – Technoeconomics of Energy Systems laboratory

@TEES_Lab

https://teeslab.unipi.gr/

Funded by the European Union

IAM COMPACT

Thank you!

Mr. Nikos Kleanthis
kleanthis@unipi.gr

Dr. Vassilis Stavrakas
vasta@unipi.gr

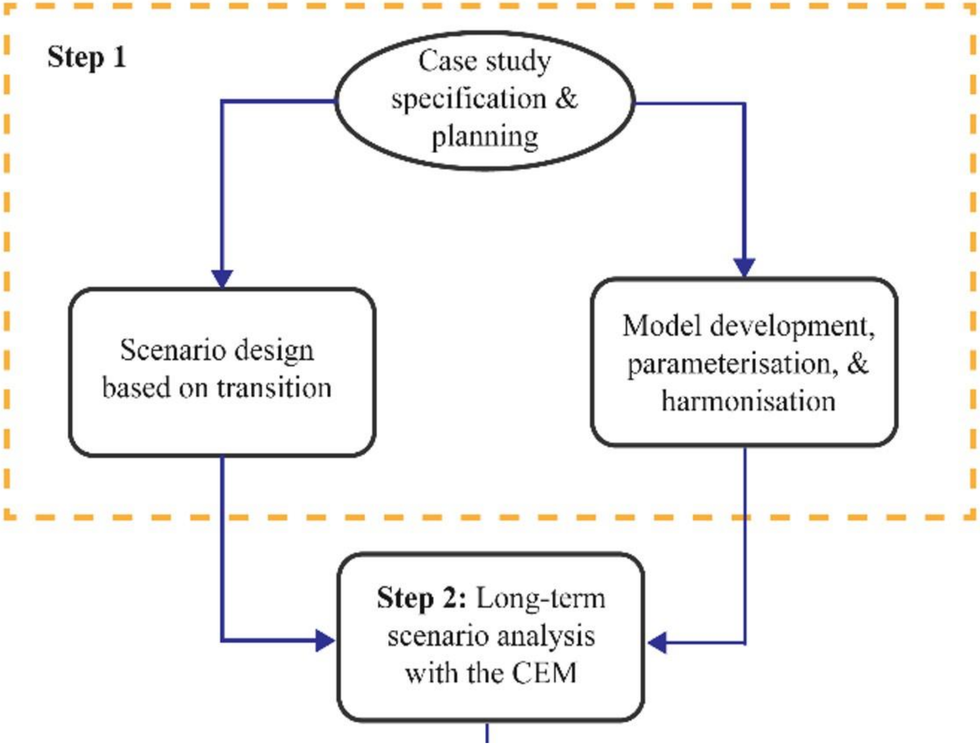
Prof. Dr. Alexandros Flamos
aflamos@unipi.gr

#iam-compact

iam_compact   iam-compact   iam_compact

Annex 1: Methods step by step

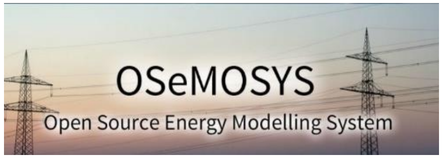
Funded by
the European Union



Step 1: *Case study specification, scenario design, and model parameterisation*

- Most recent **policy documents** & political **announcements**
- Case study **specifications** transcribed to modelling **scenarios**
- Modelling ensemble **designed** to accurately depict the system's **properties** & **characteristics**

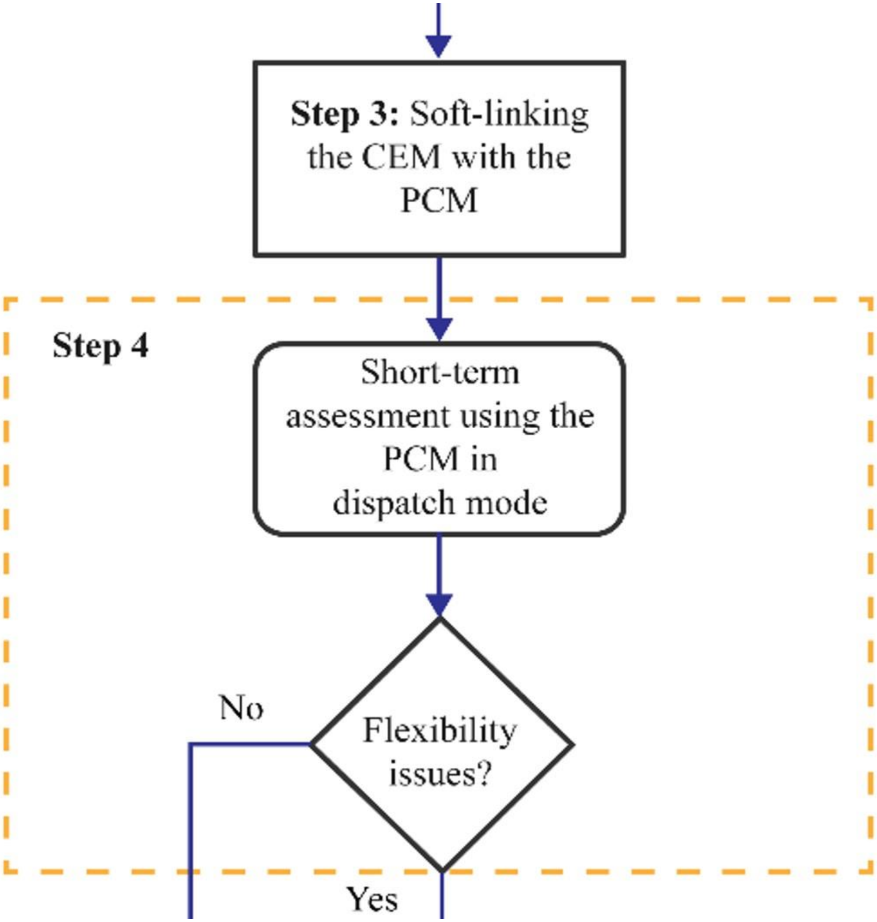
Step 2: *Long-term scenario analysis with the Capacity Expansion Model*



Run different long-term transition scenarios over the time horizon under study.

Establish a **set of baseline results** to **evaluate** the **power system's future behaviour**.

Funded by the European Union



Step 3: *Soft-linking the Capacity Expansion Model with the Production Cost Model*

OSeMOSYS
Open Source Energy Modelling System

IRENA International Renewable Energy Agency
FlexTool

Long-term output data of installed capacities by technology

Step 4: *Short-term assessment of flexibility using the Production Cost Model: Identifying issues*

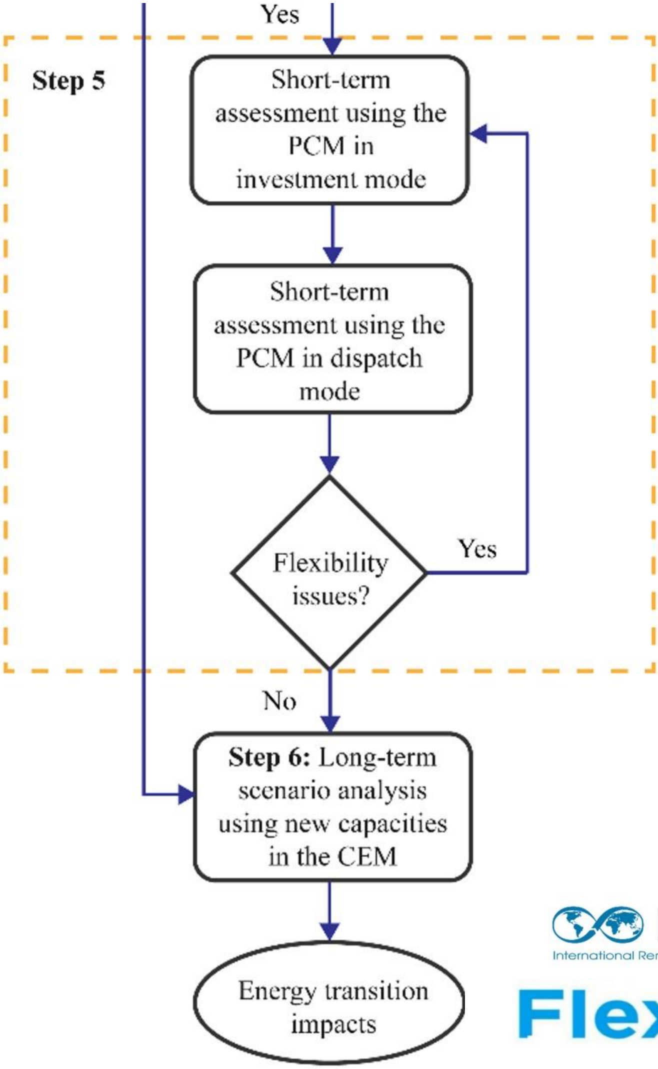
IRENA International Renewable Energy Agency
FlexTool

- Run in **dispatch** mode for different **milestone** years, i.e., 2030, 2040, 2050

- **Fixed capacities**, to conduct **periodic feasibility** analysis of short-term scenarios

- **Assess** the system's performance at various stages using **key indicators** to evaluate the feasibility of the scenarios, as **loss of load**, **curtailment**, etc.

Funded by the European Union



Step 5: *Short-term assessment of flexibility using the Production Cost Model: Solving issues*

IRENA International Renewable Energy Agency

FlexTool

- Additional simulations to solve any **remaining flexibility issues** (from the short-term assessment)

- **Investment mode** is used to provide the **required additional investments** in **VRE** & **electricity storage** to resolve the remaining issues, esp. in **2050**

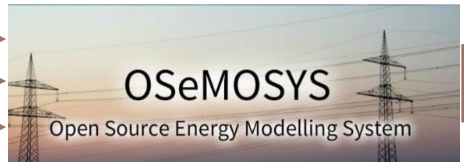
- Another round of iterations in dispatch mode to validate that the calculated investments **solve** the **flexibility issues** by **2050**

Step 6: *Refined long-term scenario analysis with the Capacity Expansion Model*

IRENA International Renewable Energy Agency

FlexTool

Additional investments in flexibility



Final electricity mix by 2050

&

Trade-offs between investment costs, emissions & flexibility

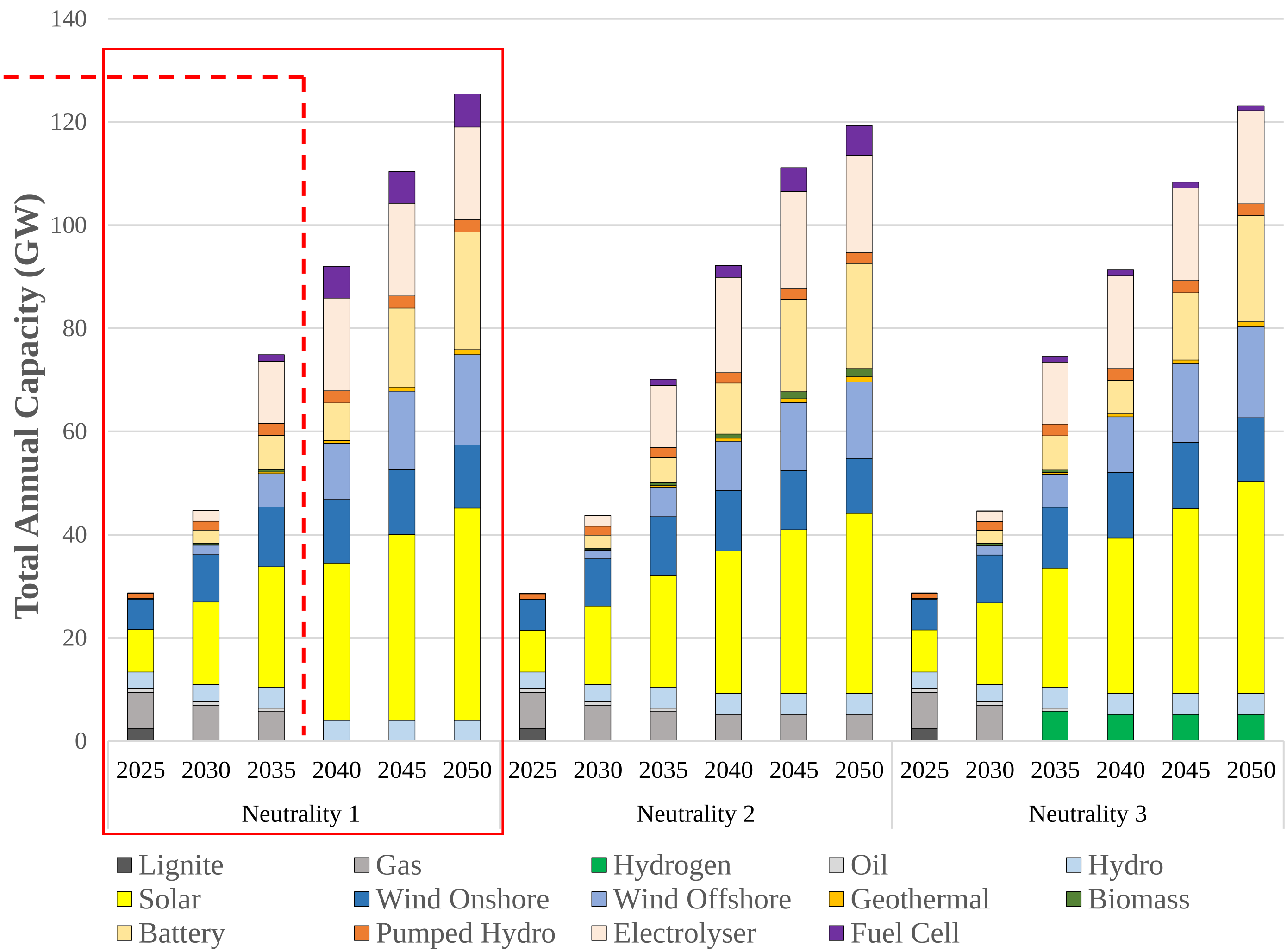
Funded by the European Union

Annex 2: Additional Results

Funded by
the European Union

Neutrality 1 scenario leads to the phaseout of natural gas by **2037**.

Long-term capacity planning prior to flexibility assessment



Funded by the European Union

IAM COMPACT

OSeMOSYS-GR
Linear Optimization Energy Planning Model

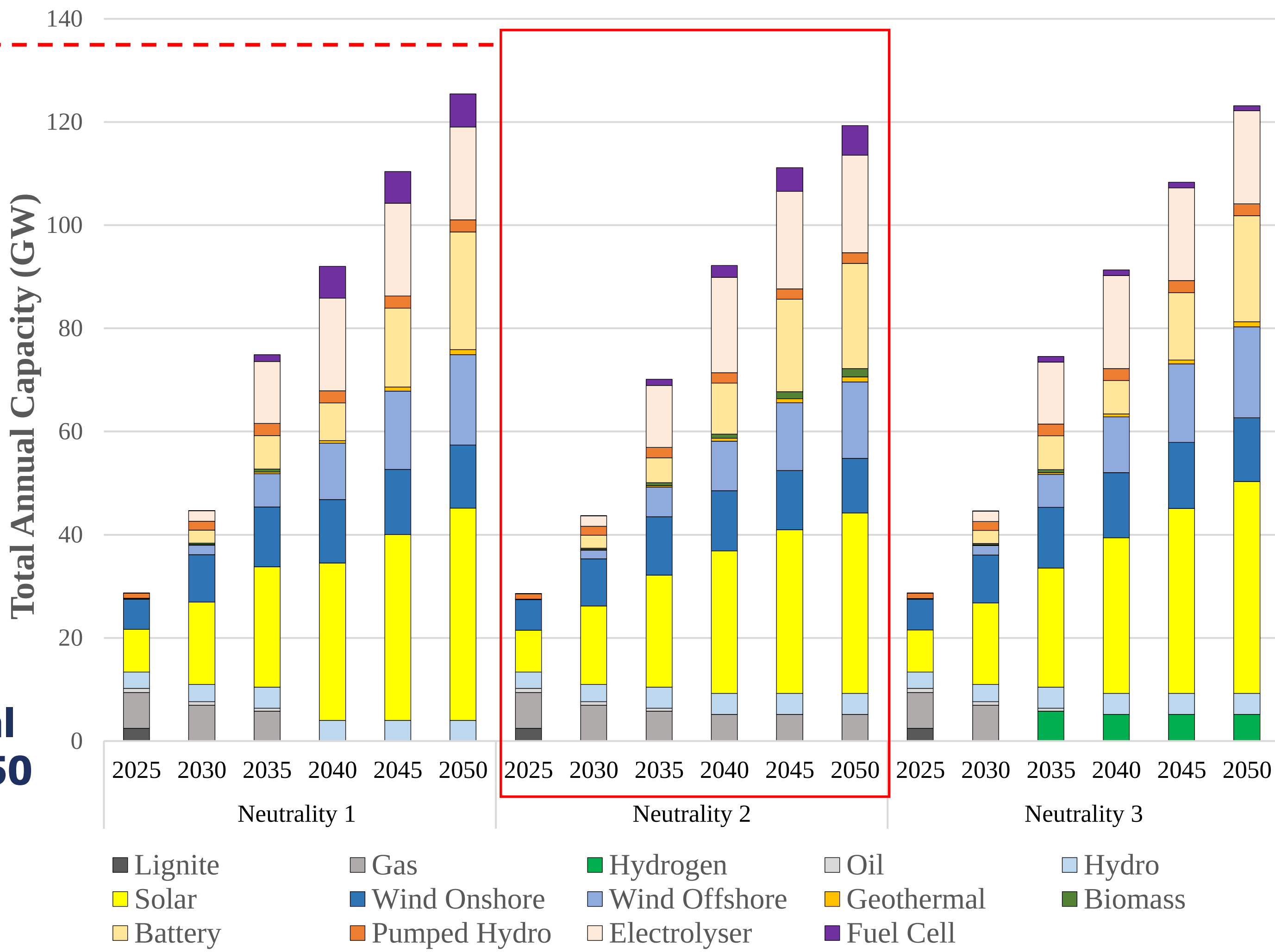
Long-term capacity planning prior to flexibility assessment

2050: ~**61 GW** VRE

NECP target: **69.5 GW**

Neutrality 2 scenario …

… **cannot result** in the **achievement** of the **national VRE capacity targets** by **2050**



Funded by the European Union

IAM COMPACT

OSeMOSYS-GR
Linear Optimization Energy Planning Model

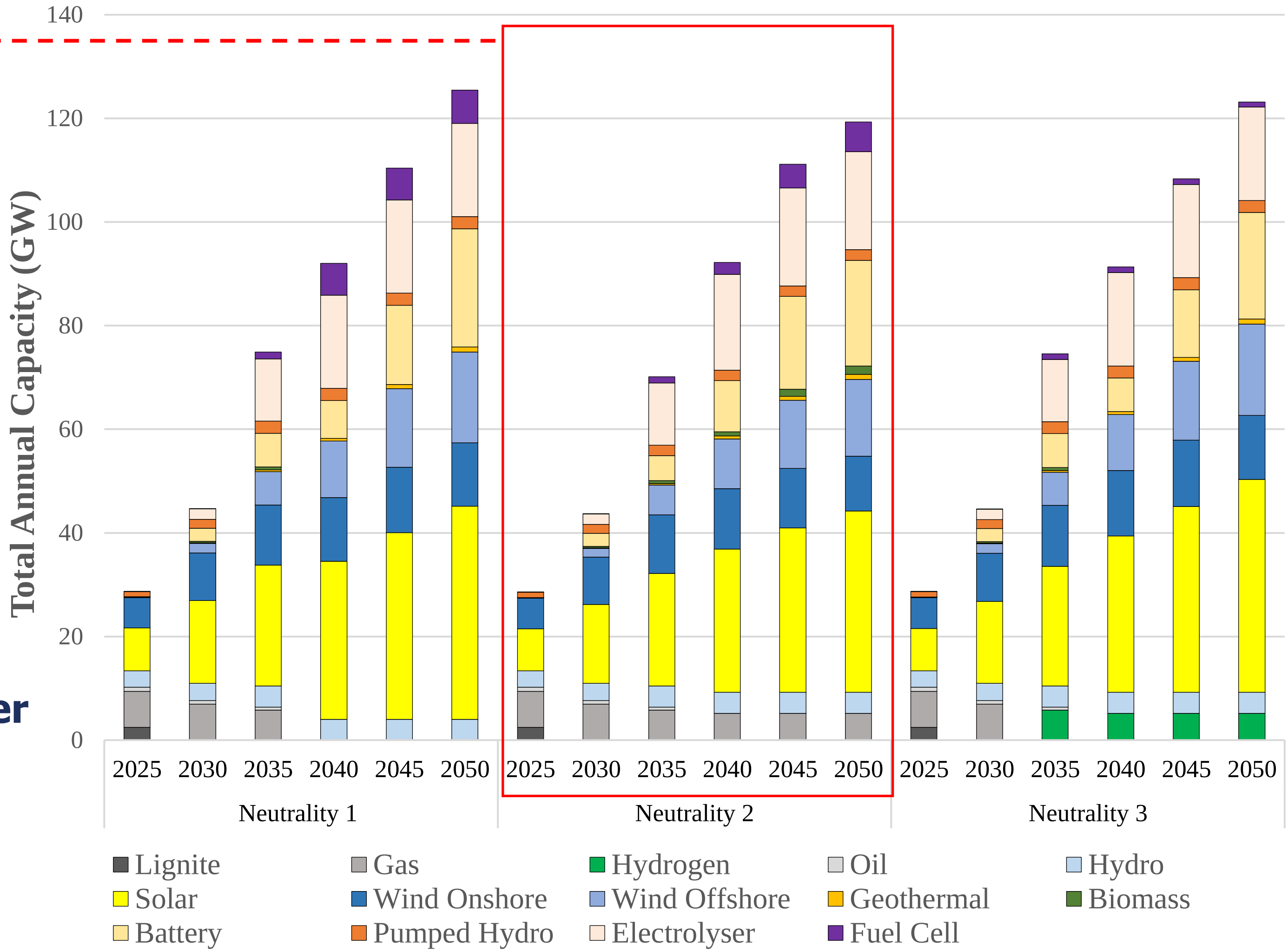
Long-term capacity planning prior to flexibility assessment

2050: ~**61 GW** VRE

NECP target: **69.5 GW**

In **Neutrality 2** scenario, …

… the lower installed VRE and flexibility is **offset** by the **higher baseload capacity**.



Funded by the European Union

IAM COMPACT

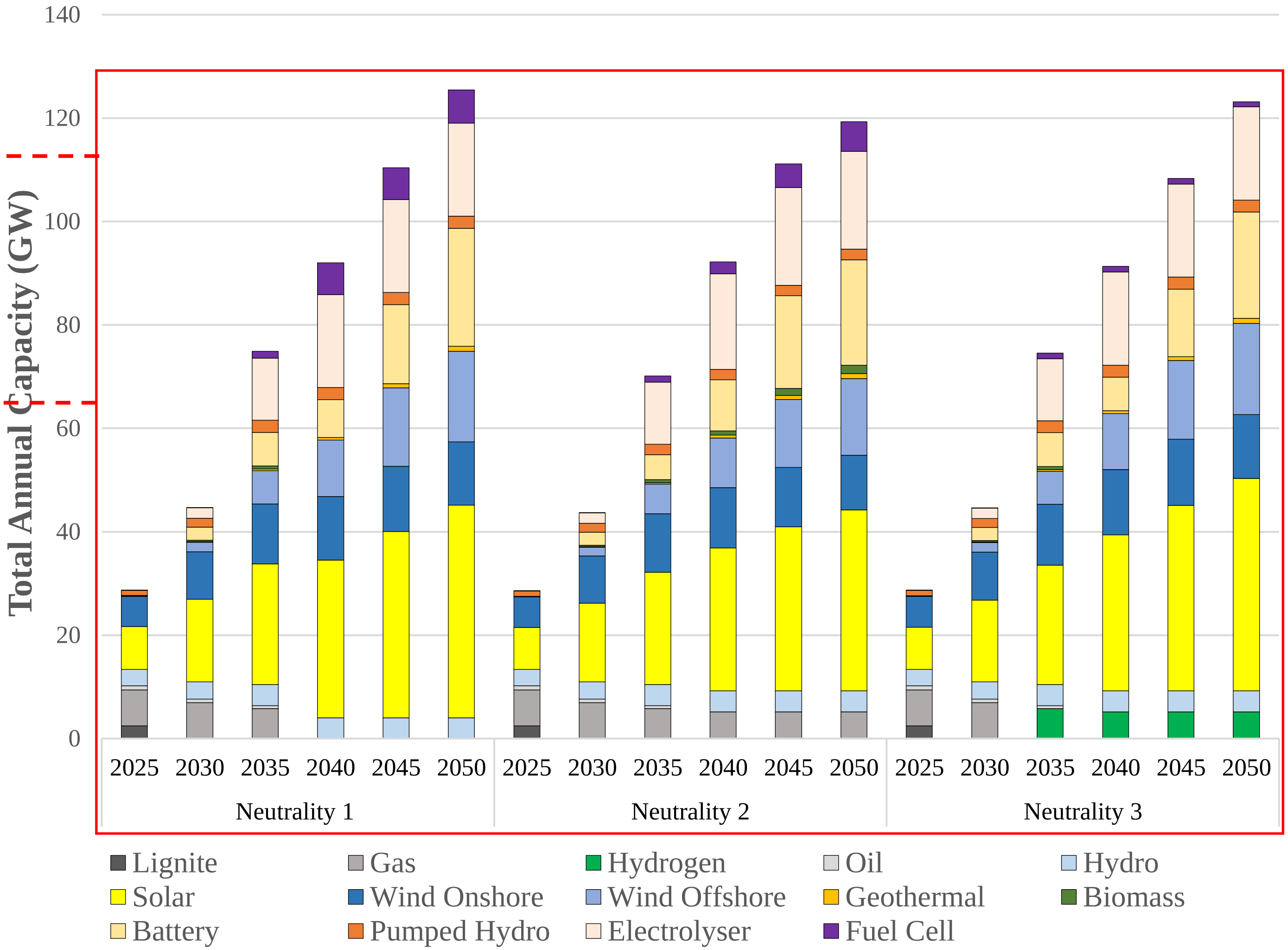
OSeMOSYS-GR
Linear Optimization Energy Planning Model

Long-term capacity planning prior to flexibility assessment

Battery & **pumped storage** capacity grow to **22.4-25.1 GW** by **2050**

Electrolyser capacity grows to **18-18.9 GW** by **2050**

Total capacity of **flexibility solutions** amounts to **40.4-44 GW** by **2050**



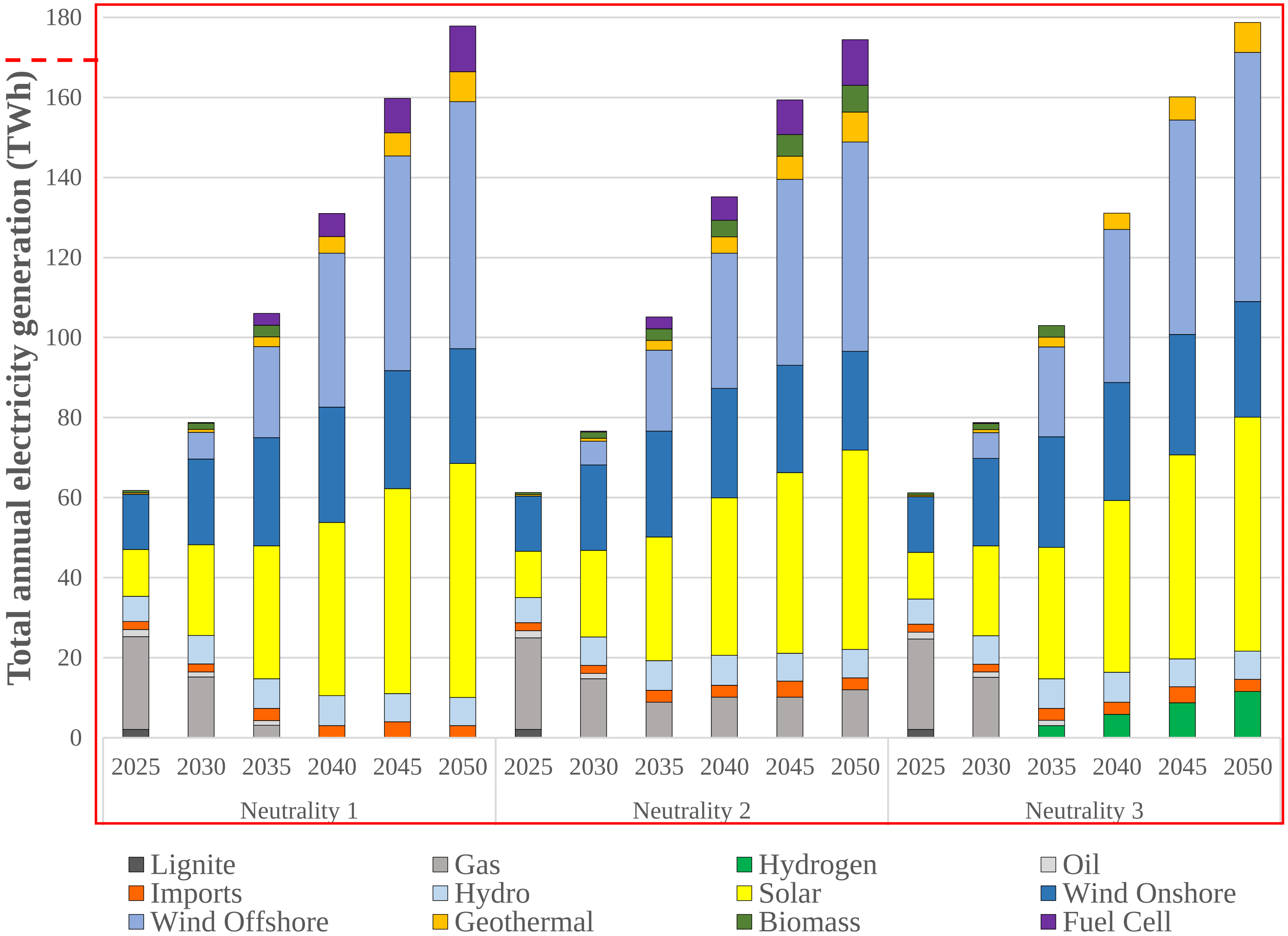
Funded by the European Union

OSeMOSYS-GR
Linear Optimization Energy Planning Model

Long-term capacity planning prior to flexibility assessment

2030: ~76.5% of total annual power generation from RES and hydrogen

NECP target: **81.5%**



The ambitious **2030 NECP target cannot be captured** by any of the scenarios, thus a **more frontloaded capacity expansion** is required.

Funded by the European Union

IAM COMPACT

OSeMOSYS-GR

Linear Optimization Energy Planning Model

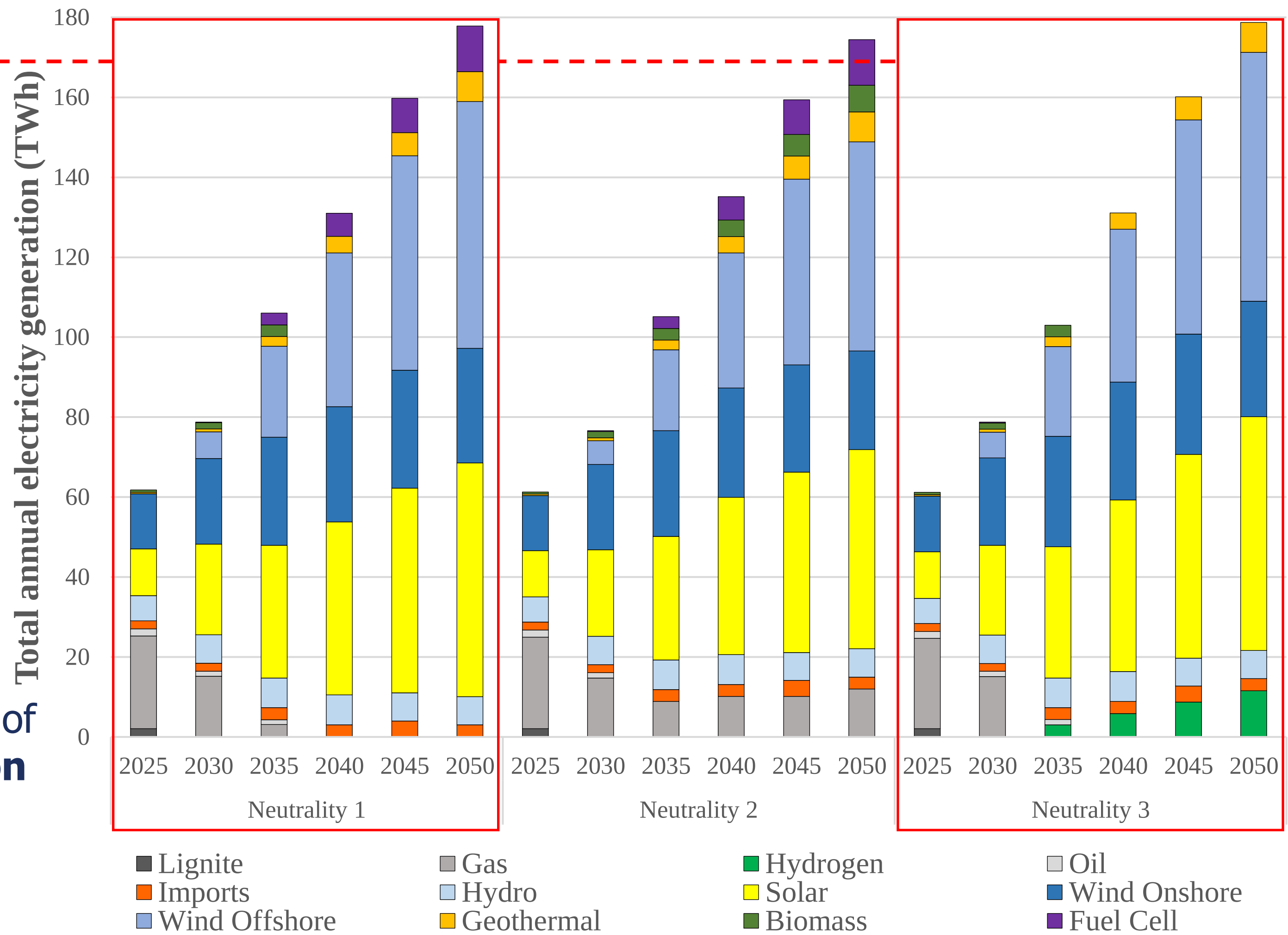
2050: ~98.3% of total annual power generation from RES and hydrogen

NECP target: **98.3%**

Neutrality 1 and **Neutrality 3** scenarios …

… **result** in the **achievement** of the **national RES penetration targets** by **2050**

Long-term capacity planning prior to flexibility assessment



Funded by the European Union

IAM COMPACT

OSeMOSYS-GR
Linear Optimization Energy Planning Model

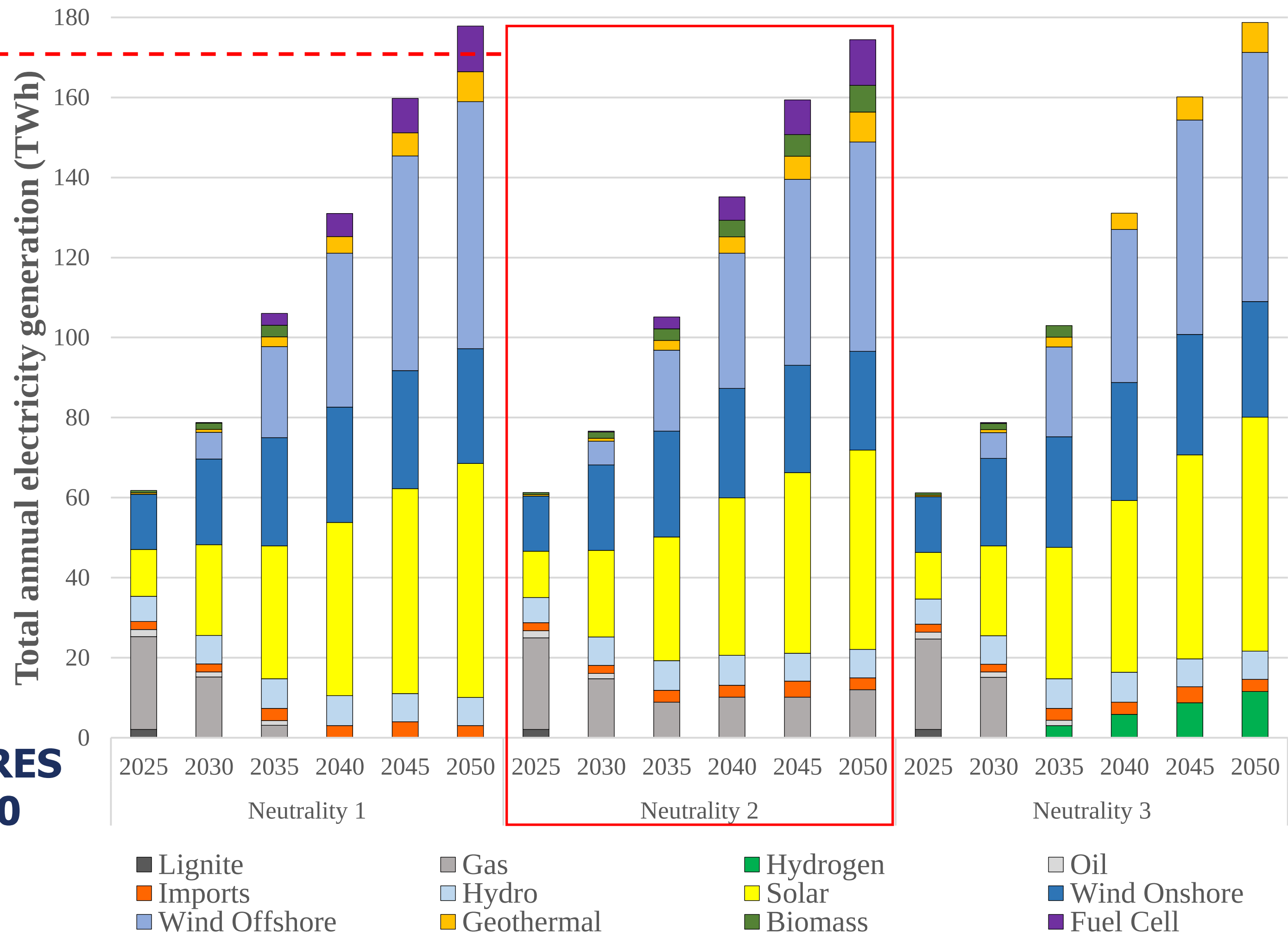
Long-term capacity planning prior to flexibility assessment

2050: ~91.4% of total annual power generation from RES and hydrogen

NECP target: **98.3%**

Neutrality 2 scenario …

… cannot result in the **achievement** of the **national RES penetration targets** by **2050**



Funded by the European Union

Long-term capacity planning prior to flexibility assessment

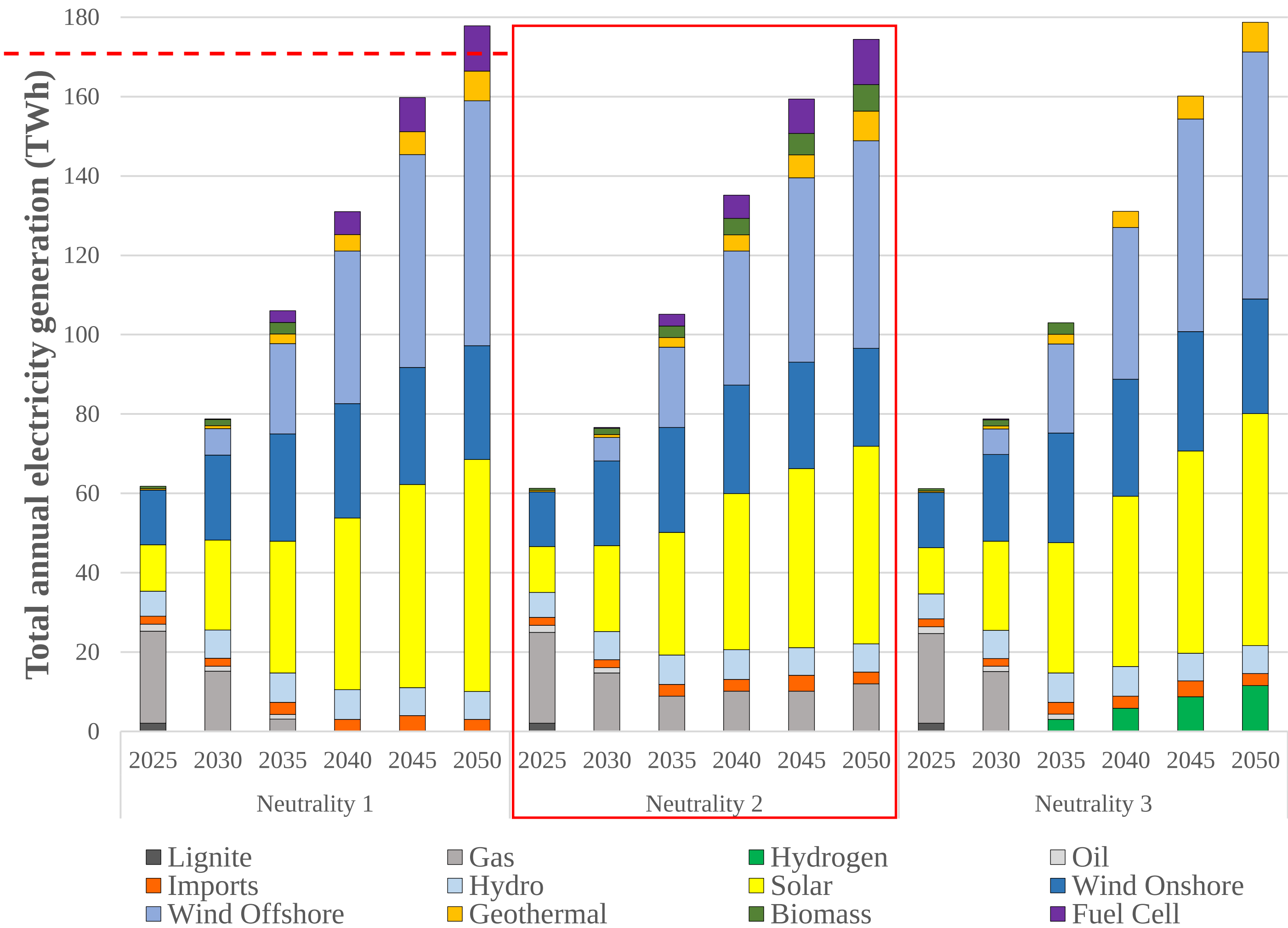
2050: ~6.9% of total annual power generation from gas

Baseload in **2030**: gas and hydro

Baseload in **2040** and **2050**: includes also geothermal and hydrogen.

Neutrality 2 scenario …

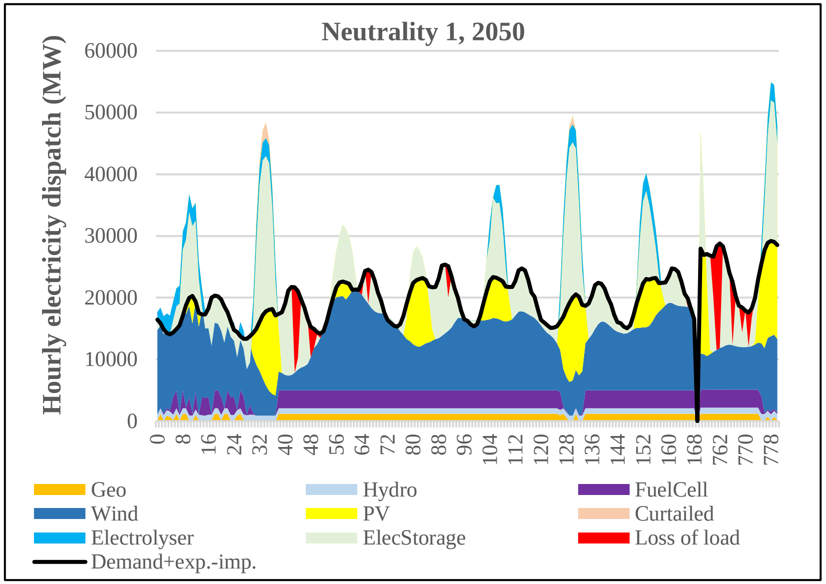
… results in a more **diversified electricity mix**

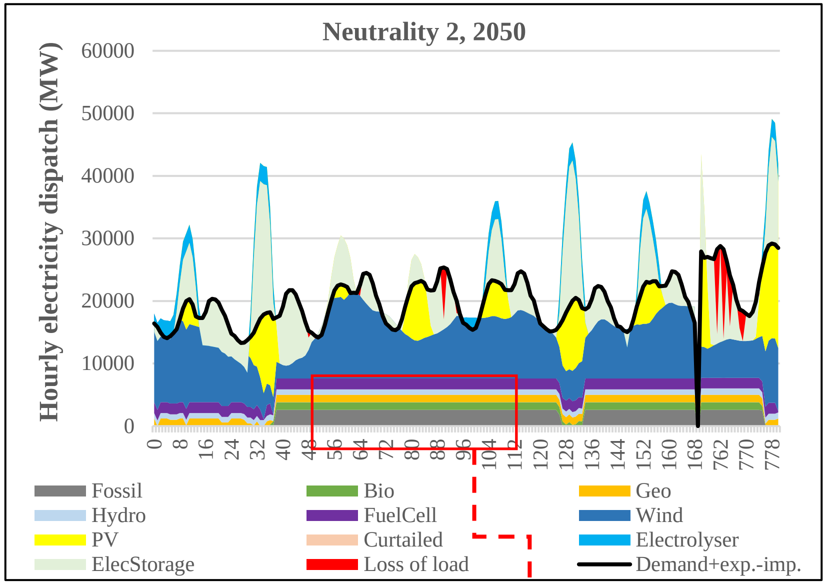


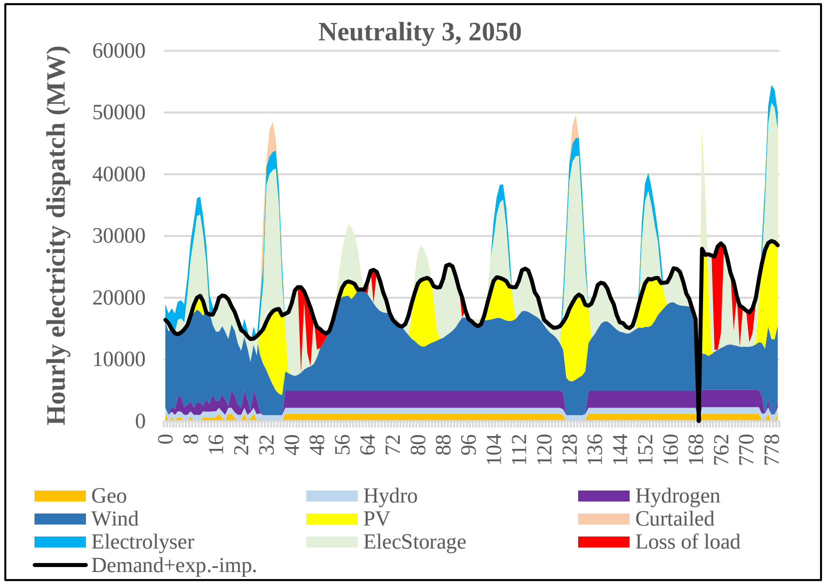
Funded by the European Union

FlexTool Flexibility assessment for 2050

"**Neutrality 3**" has additional losses due to the less efficient use of hydrogen for electricity generation (because of the lower efficiency of power plants compared to that of fuel cells).







Scenario	Peak net load (MW)	Curtailment (% of VRE gen.)	Loss of load (% of annual demand)
"Neutrality 1"	21,073	0.3	2.81
"Neutrality 2"	22,086	0	1.59
"Neutrality 3"	20,947	0.8	3.17

"**Neutrality 2**" performs better due to the operation of gas and biomass plants that provide additional flexibility, thus mitigating the need for storage.

Funded by the European Union

IAM COMPACT

OSeMOSYS-GR
Linear Optimization Energy Planning Model

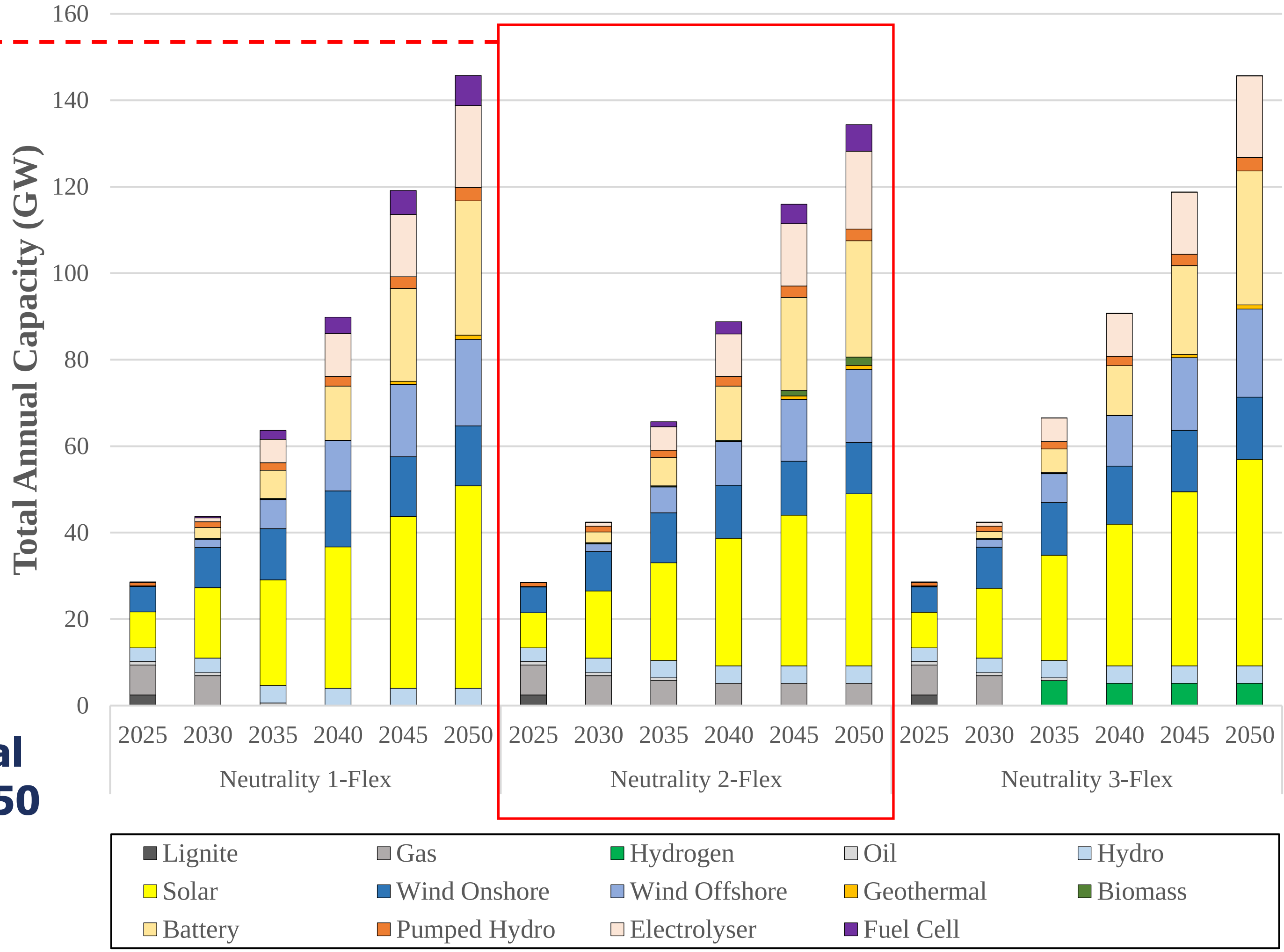
Long-term capacity planning after flexibility assessment

2050: ~**68.5 GW** VRE

NECP target: **69.5 GW**

Neutrality 2-Flex
scenario …

… almost results in the **achievement** of the **national VRE capacity targets** by **2050**



Funded by the European Union