# Hydrogen-Enabled Sector Coupling in Turkiye's Energy Transition: Integrated Modeling with GENeSYS-MOD

*Gokhan Kirkil*
*Center for Energy and Sustainable Development*
*Kadir Has University*
Istanbul, Turkey
gokhan.kirkil@khas.edu.tr

*Oluremi Success Oyejide*
*Center for Energy and Sustainable Development*
*Kadir Has University*
Istanbul, Turkey
oluremi.odebode@stu.khas.edu.tr

*Saiqa Dilawaiz*
*Department of Electrical and Electronics Engineering*
*Kadir Has University*
Istanbul, Turkey
saiqadilawaiz@stu.khas.edu.tr

*Bimbo Lawrence Damitan*
*Department of Administrative Sciences*
*Kadir Has University*
Istanbul, turkey
bimbo.damitan@stu.khas.edu.tr

***Abstract*—As a part of the Man0EUvRE project, this study investigates the role of hydrogen-based storage and power conversion in supporting Turkiye's long-term energy transition and its emerging contribution to the wider European energy system. Using a soft-linked modeling framework combining GENeSYS-MOD-Europe with a high-resolution national version of GENeSYS-MOD-Turkiye, we analyze scenarios in which renewable electricity, hydrogen production, seasonal storage, and cross-sectoral hydrogen use evolve through 2050. The model incorporates recent national policies, including Turkiye's Hydrogen Strategy and National Energy Plan, while remaining consistent with European decarbonization pathways and anticipated hydrogen trade dynamics. Our results show that hydrogen significantly enhances system flexibility, enabling renewable electricity to supply a substantially larger share of final energy demand by mid-century. Hydrogen integration into power, industry, and heating sectors contributes to improved renewable integration, reduced curtailment, and lower fossil fuel dependency compared to current system configurations. These findings highlight the strategic role of hydrogen-enabled sector coupling for both Turkiye and Europe, demonstrating how coordinated multi-scale modeling can inform robust energy planning and cross-border system integration.**

***Index Terms*—Energy system modeling, GENeSYS-MOD, power-to-hydrogen pathways, decarbonization strategies**

## I. INTRODUCTION

The global shift towards climate neutrality presents a dual challenge for developing economies, which must sustain economic growth while meeting increasingly strict emission standards. Situated at the crossroads of Europe and Asia, Turkey faces growing domestic energy demand alongside pressing international climate obligations. After ratifying the Paris Agreement, Turkiye set a 2030 target to reduce emissions by 41% from business-as-usual levels, with peak emissions projected for 2038 and net-zero greenhouse gas emissions by 2053 [1], [2]. Meeting these targets requires rapid scaling of renewable energy and comprehensive transformation across electricity generation, industry, transport, and heating.

The 2022 National Energy Plan outlines substantial expansion of solar and wind capacities by 2035 [1], [3], driving extensive variable renewable energy (VRE) deployment. However, managing intermittent supply and seasonal energy requirements beyond the capacity of short-term battery storage demands long-duration storage and cross-sectoral integration solutions. Hydrogen has emerged as a key enabler in this regard, serving both as an industrial feedstock and a storage medium that connects energy sectors while reducing emissions in hard-to-decarbonize industries [4]. The European Union similarly recognizes hydrogen as essential for continental decarbonization, requiring joint infrastructure development and cross-border energy trade [5], with offshore renewable-based production increasingly viable for export-oriented markets [6].

In response, Turkiye's Ministry of Energy and Natural Resources published its national Hydrogen Technologies Strategy and Roadmap in 2023, targeting 5 GW of electrolyzer capacity by 2035 and 70 GW by 2053, with green hydrogen serving both domestic decarbonization and European export objectives [3]. Academic literature increasingly supports this direction: decentralized hydrogen valleys can enhance industrial decarbonization when matched to local demand [7], and hydrogen in energy communities improves system resilience, though economic feasibility depends on system design [8]. At a broader scale, studies using the OSeMOSYS framework show that domestic electrolysis can reduce emissions and import dependency in Turkiye, while others highlight its geopolitical potential as an energy hub between Asian supply corridors and European demand centers [9], [10], [11]. However, no

Project is funded by the national funding agency TUBITAK.

comprehensive framework has yet linked Turkiye's national energy system with European transition processes [9], [12].

This study addresses that gap using a soft-linked modeling framework connecting Turkiye's GENeSYS-MOD national implementation with the Man0EUvRE project's GENeSYS-MOD European platform. Four transition scenarios — GoRES, NECP Essentials, REPowerEU++, and Trinity — representing varying levels of policy ambition, technological progress, and regional cooperation are examined. The central question is: How can hydrogen-enabled sector coupling support Turkiye's decarbonization while enabling integration with the European energy system under alternative transition scenarios? The study provides policy-relevant insights into how coordinated hydrogen strategies can shape both Turkiye's domestic transition and its role in the evolving European energy system.

## II. SCENARIOS

Researchers use the GENeSYS-MOD energy system modeling framework to study Turkiye's energy system development over extended periods through multiple exploratory scenarios. The EU EnVis-2060 scenario framework generates these scenarios, which examine different ways European countries will transition their energy systems until 2060. The study uses identical scenario narratives to maintain research alignment with European modeling activities while evaluating hydrogen-enabled sector coupling impacts on Turkiye's energy system. The scenarios combine qualitative narratives with quantitative modeling assumptions. The qualitative narratives describe possible developments in social acceptance, technological innovation, political commitment to climate policy, and geopolitical cooperation. The elements proceed to convert into quantitative parameters, which GENeSYS-MOD uses to determine renewable energy deployment rates and hydrogen production capacity and technology cost developments and carbon emission constraints and energy demand projections. The scenarios enable researchers to study various energy transition routes, which affect hydrogen implementation and sector coupling in Turkiye through their qualitative-to-quantitative conversion. The four scenarios considered in this study are briefly described below.

The GoRES scenario is the most ambitious decarbonization pathway. The level of public acceptance, the speed of technological development, and the effectiveness of climate policies create the conditions for a large-scale transformation towards renewable energy systems. The level of renewable electricity generation is significantly higher, providing the necessary conditions for the large-scale development of green hydrogen production through the application of the electrolysis method. Hydrogen is central to the new energy system, enabling sector coupling and decarbonization of industry and heavy transport.

The NECP Essentials scenario is seen as a development path that is largely guided by existing policy engagements and national energy strategies. The development of the energy system occurs as described in the national energy and climate plans, with a moderate expansion of renewable energy technologies and a gradual improvement in energy efficiency. Hydrogen technologies emerge in industrial processes and energy storage, but large-scale deployment remains limited by moderate technological progress and investment levels.

The REPowerEU++ scenario is based on a higher level of political engagement and determination on energy security and decarbonization, especially because of global geopolitical challenges. Higher investment levels in renewable energy and hydrogen infrastructure enable a faster integration of green hydrogen into the energy mix. Hydrogen plays a role in sector coupling with electricity, industry, and transport, enabling higher levels of emission reductions and providing higher energy security.

The scenario of EU Trinity is characterized by limited technological innovation, fragmented policy coordination, geopolitical instability, and limited public support for transformative climate policies, which affects the pace of renewable energy technology deployment, including emerging innovations such as green hydrogen. Under the EU Trinity scenario, the role of hydrogen is limited within the energy mix of Turkiye, including sector coupling and the pace of decarbonization.

Once the scenario narratives are defined, the qualitative assumptions are translated into quantitative inputs for the GENeSYS-MOD model. This includes adjustments to parameters such as technology costs and efficiencies, renewable resource availability, emission constraints, and energy demand projections. The modeling framework enables systematic evaluation of hydrogen-based sector coupling pathways in Turkiye under different energy transition scenarios.

## III. METHODOLOGY

The research evaluates hydrogen-driven sector coupling in Turkiye using the open-source linear energy system model GENeSYS-MOD. The model determines cost-optimal investment and operational pathways under projected future conditions while satisfying system constraints and policy targets across electricity, hydrogen, natural gas, industry, transport, and buildings. In line with the European Union EnVis 2060 scenarios, GENeSYS-MOD considers around 160 technologies covering energy supply, conversion, trade, and storage options in Fig .1 The study employs two structurally consistent model instances: a European-wide model and a geographically detailed Turkish national model. The Turkish model cover the period 2018–2060 with five-year investment intervals and hourly resolution of the 484th hour, which gives 18 time steps per year to capture renewable variability and electrolysis operation. Hydrogen infrastructure expansion is represented until 2053 in accordance with national net-zero targets. All optimizations were performed using the Gurobi solver (version 13.0.0 build v13.0.0rc1) within the GENeSYS-MOD framework on a workstation equipped with an Intel Xeon processor (24 logical processors, 160 GB RAM). The Turkish model typically converges within minutes, whereas the larger European model, which includes multiple countries and cross-border trade, requires more time, running into a few hours.

Spatially resolved wind and solar resources are used to model renewable electricity generation subject to national technical potential limits. Hydrogen production is represented through alkaline and PEM electrolysis technologies, alongside short-term and seasonal hydrogen storage systems that reduce renewable curtailment and enable inter-seasonal balancing. Hydrogen can substitute fossil fuels in industry and transport, be reconverted to electricity when economically favorable, and be blended into natural gas networks within existing infrastructure limits (15–20% by volume). Hydrogen deployment is determined endogenously through system cost optimization. The Turkish and European model instances are connected through an iterative soft-linking procedure. First, the European model determines hydrogen import demand and marginal import costs under decarbonization constraints. These values are transferred to the Turkish model, which optimizes domestic hydrogen production, storage, exports, and capacity expansion. The resulting export quantities and marginal supply costs are then returned to the European model to update trade parameters. This process is repeated until traded volumes and marginal prices converge within 1% between successive iterations, typically requiring 13 iterations. The soft-linking approach reduces computational complexity by avoiding simultaneous co-optimization of the full European system.

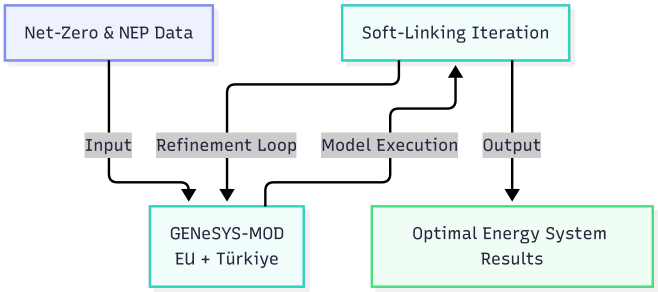

Fig. 1. Inputs and outputs of the energy system model GENeSYS-MOD

## IV. RESULTS

Renewable electricity generation and demand increase substantially across all scenarios in Fig. 2, mainly driven by photovoltaics and onshore wind, while hydropower and geothermal remain relatively stable. GoRES achieves the highest renewable output by 2060 due to rapid solar and wind expansion and strong electricity demand from electrolysis, transport, and industry. NECPEssentials follows a similar but more balanced transition with lower electrolysis demand. REPowerEU++ also shows strong renewable growth after 2040, though at lower levels than GoRES because of slower electrification and hydrogen integration. Trinity exhibits the slowest transition, with weaker solar and wind deployment and no electricity demand from electrolysis, indicating limited green hydrogen production and weaker sector coupling. Electricity demand in transport and industry increases across all pathways, while bidirectional trade flows, typically imports, support system balancing.

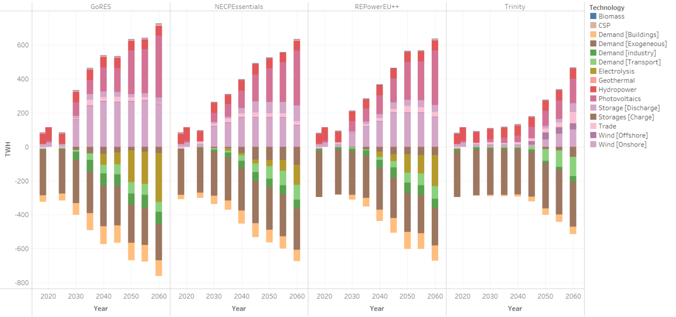

Fig. 2. Development of renewable electricity generation (positive) and consumption (negative) in Turkiye.

Fig. 3 shows distinct hydrogen development pathways across the scenarios, reflecting different decarbonization strategies and technology choices. Trades appear as both imports (positive bar) or exports (negative bar) across all scenarios in varying magnitudes. GoRES achieves the strongest green hydrogen transition, driven entirely by rapidly expanding electrolysis after 2040, supporting transport, industry, and methanation, while becoming a net hydrogen exporter by 2060. NECPEssentials follows a similar but more moderate pathway, with lower electrolysis deployment and greater hydrogen integration in buildings and power generation. REPowerEU++ demonstrates gradual hydrogen expansion, mainly serving industry and methanation, alongside declining imports as domestic production increases. In contrast, Trinity represents the least decarbonized pathway, relying heavily on fossil-based SMR and large non-EU hydrogen imports, especially in 2060 due to limited renewable expansion and the absence of electrolysis. Although such imports are technically feasible within GENeSYSMOD, they may be unrealistic in practice because of infrastructure, geopolitical, energy security, and economic constraints. Hydrogen use in Trinity is concentrated in methanation and buildings, with the highest storage requirements by 2060. In buildings in Fig. 4, hydrogen penetration remains limited in GoRES, where electrification and heat pumps dominate decarbonization. In NECP Essentials and REPowerEU++, hydrogen blending into the natural gas network increases after 2040 and approaches 15–20% in policy-consistent cases, reducing fossil gas consumption relative to 2020 levels.

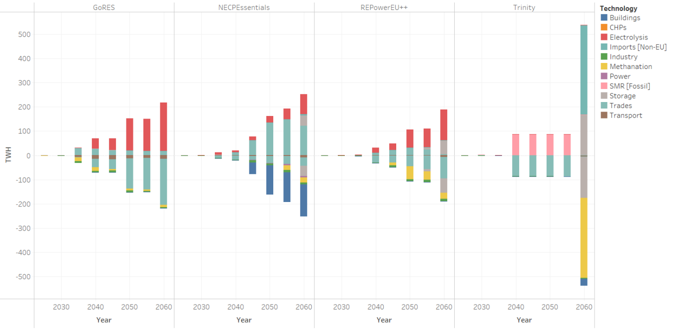

Fig. 3. Development of hydrogen production (positive) and use (negative).

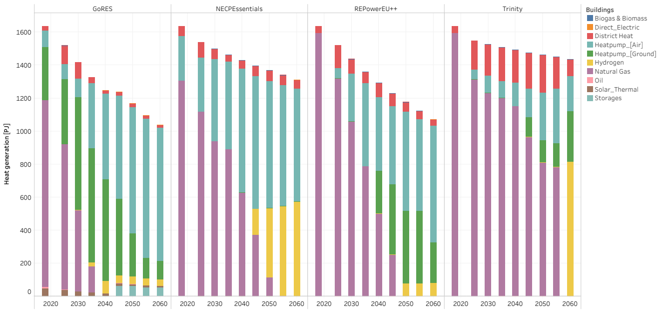

Fig. 4. Development of building heat supply.

Trinity shows later but more pronounced hydrogen use in buildings due to slower electrification progress. Industrial process heat in Fig. 5 reflects varying decarbonization ambition and hydrogen integration across scenarios. Fossil gas dominates initially in all scenarios but gradually declines as low-carbon technologies expand. GoRES achieves the fastest transition, with hydrogen becoming a major industrial heat source after 2030 alongside strong electrification and synthetic gas deployment. NECPEssentials follows a similar but more gradual pathway, while REPowerEU++ demonstrates a balanced and moderate transition with later hydrogen penetration. Trinity remains largely fossil-dependent through 2060, with limited hydrogen uptake and greater reliance on conventional fuels and synthetic gases.

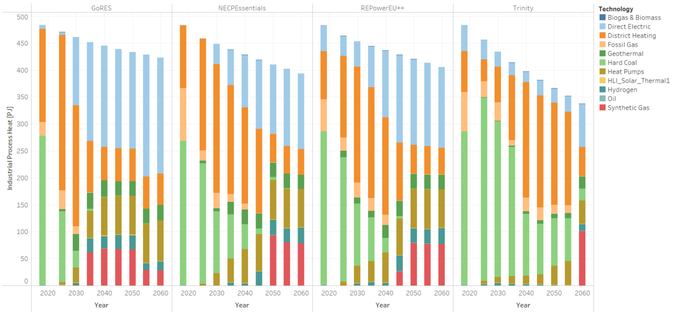

Fig. 5. Development of hydrogen for industrial process heat generation from 2018- 2060.

In transport in Fig. 6, hydrogen deployment is strongest and earliest in GoRES, expanding after 2035 and reaching the highest volumes by mid-century, particularly in passenger mobility. NECP Essentials shows modest growth until 2050 followed by accelerated uptake toward 2060. REPowerEU++ remains comparatively moderate, whereas Trinity reflects delayed adoption with a stronger orientation toward freight applications. Across scenarios, hydrogen use in transport remains secondary to electrification but contributes to diversification of decarbonization strategies. Hydrogen storage capacity expands after 2035 in all scenarios in Fig. 7. GoRES and NECP Essentials show steady growth in seasonal storage, reaching approximately 0.11–0.14 PJ by 2060. REPowerEU++ attains slightly higher levels due to increased trade-driven system balancing needs. Trinity displays a delayed but sharper increase after 2050, reaching roughly 0.18 PJ by 2060, indicating the requirement for stronger buffering in a pathway characterised by later infrastructure build-up and higher import dependence. Storage deployment closely follows electrolysis scale and renewable variability, highlighting hydrogen's role in long-term system balancing.

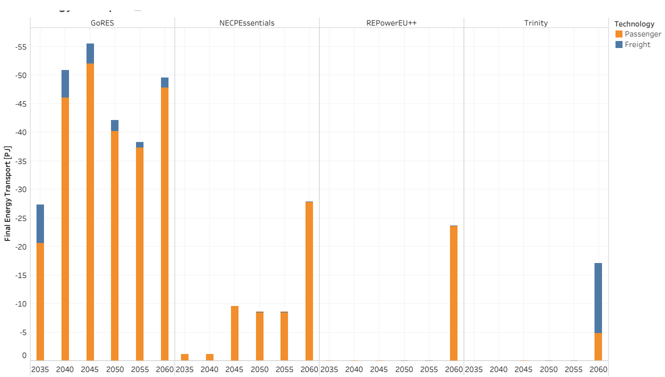

Fig. 6. Development of hydrogen for final energy transport.

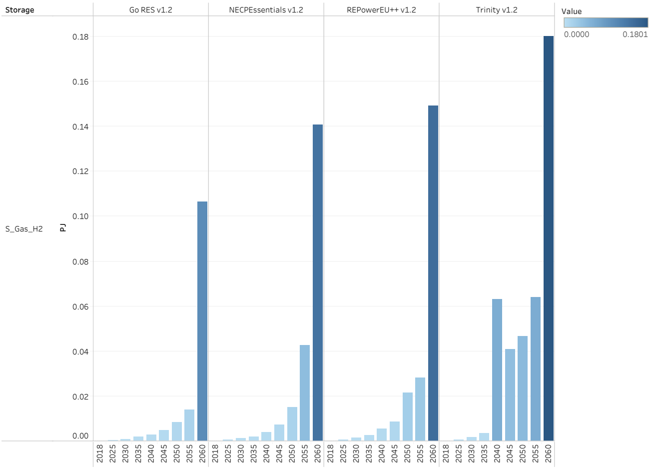

Fig. 7. Hydrogen storage level.

## V. DISCUSSION

The comparison between scenarios shows that renewable electricity growth after 2030 determines both hydrogen deployment and system-wide decarbonization. The renewable capacity development in GoRES and NECP Essentials from their early stages enables various processes, which include electrolysis and sector coupling and fossil fuel replacement. The slower pace of renewable energy development in Trinity limits the production of green hydrogen while extending the period of fossil fuel dependence. The process of producing hydrogen through electrolysis links together different renewable energy sources because it uses excess electricity while decreasing the need to stop production during peak times. Hydrogen exports through the soft-linking framework create extra value for the system because they enable better cross-border system connections with European demand. The hydrogen production methods which depend on fossil fuels in Trinity create a danger that they will prevent the achievement of decarbonization targets in the future. The field deployment patterns show the existing structural differences between sectors. Industrial heat substitution emerges as the most robust hydrogen application across ambitious pathways, while building-sector use depends strongly on electrification assumptions and infrastructure constraints. The adoption of transport services depends on both technology development and government regulations.

High-renewable systems use seasonal hydrogen storage to establish operational stability. The systems that expand electrolysis capability begin to develop their storage systems incrementally, while systems that delay their transitions need to increase their storage capacity rapidly during their subsequent decades to ensure operational stability. Hydrogen plays a vital role in Turkiye's transition because its impact depends on when renewable energy sources expand, when electrolysis technology becomes the main production method, and when energy systems establish links to European markets. These findings indicate that achieving the 2053 net-zero vision depends on early renewable deployment and coordinated hydrogen integration, both domestically and with European markets.

While this framework provides valuable insights, GENeSYS-MOD employs a linear, deterministic optimization structure with perfect foresight. Consequently, the pathways are interpreted as cost-optimal benchmarks rather than predictions, as real-world investments face uncertainty in technology costs, policy continuity, financing conditions, and future demand. The five-year investment periods also permit large stepwise capacity additions, meaning that ambitious renewable and electrolyser deployment pathways may place significant pressure on manufacturing capacity, supply chains, permitting processes, grid integration, land availability, and skilled labour. In addition, although the soft-linking approach captures cross-border hydrogen trade through iterative volume and price exchanges, it does not endogenously model the physical infrastructure required to realise these flows, such as pipelines, ports, storage terminals, or related sociopolitical barriers. Thus, the modelled pathways are best understood as strategic long-term transition scenarios rather than directly implementable policy roadmaps. Future work could improve robustness through stochastic optimization, higher temporal and investment resolution, and explicit infrastructure feasibility modelling.

## VI. CONCLUSION

This research shows how hydrogen-enabled sector coupling functions as a vital component of Turkiye's energy transition while it interacts with European energy systems. The four transition scenarios GoRES and NECP Essentials and REPowerEU++ and Trinity show that hydrogen deployment methods and storage facilities and sectoral integration capabilities depend on the speed at which renewable electricity expands. The results demonstrate how integrated modeling frameworks which connect national and European energy systems function as vital elements for research. The study assesses hydrogen's impact on decarbonization through its measurement of sectoral adaptability and export capacity which produces valuable information for decision-makers who want to enhance renewable energy implementation and hydrogen infrastructure development and international energy collaboration. The coordinated hydrogen strategies will help Turkiye to achieve its energy transition goals while providing essential support for European energy security and developing effective strategies for future low-carbon development.

## VII. ACKNOWLEDGEMENT

Authors acknowledge the support from the Clean Energy Transition Partnership through the Man0EUvRE project, co-funded by the European Union and TÜBİTAK.

## REFERENCES

[1] Ministry of Energy and Natural Resources (ETKB), *Turkiye National Energy Plan*, Ankara, 2022.

[2] Republic of Turkiye, *The Second Nationally Determined Contribution (NDC 3.0)*, UNFCCC, 2025.

[3] Ministry of Energy and Natural Resources (ETKB), *Turkiye Hydrogen Technologies Strategy and Roadmap*, Ankara, 2023.

[4] M. Yue et al., "Hydrogen energy systems: A critical review of technologies, applications, trends and challenges," *Renewable and Sustainable Energy Reviews*, vol. 146, 2021.

[5] M. van der Spek et al., "Perspective on the hydrogen economy as a pathway to reach net-zero $CO_2$ emissions in Europe," *Energy & Environmental Science*, vol. 15, 2022.

[6] S. Ramakrishnan et al., "Offshore green hydrogen production from wind energy: Critical review and perspective," *Renewable and Sustainable Energy Reviews*, vol. 195, 2024.

[7] E. A. Bekele et al., "Hydrogen valleys to foster local decarbonization targets: a multiobjective optimization approach", *Applied Energy*, vol. 402, 2025.

[8] N. Velaz-Acera et al., "The Role of Hydrogen in Energy Communities," *Hydrogen*, vol. 7, no. 1, 2026.

[9] M. Barani et al., "European Energy Vision 2060," Proc. EEM, 2024.

[10] H. Tetik and G. Kirkil, "The Role of Hydrogen in the Energy Mix: A Scenario Analysis for Turkiye Using OSeMOSYS," *Energies*, vol. 17, 2024.

[11] İ. Hilali et al., "The hydrogen perspective for Turkiye... Can Turkiye become hydrogen hub?" *International Journal of Hydrogen Energy*, vol. 75, 2024.

[12] S. Mathisen et al., "Energy and climate plans in energy system modeling scenarios," in *Proc. 21st Int. Conf. on the European Energy Market (EEM)*, IEEE, 2025.