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Research Paper

Design and Optimization of the Turkish Green Supergrid: Multi-Commodity Network Planning from Altai to the Danube

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ABSTRACT

This study investigates the techno-economic feasibility of the Turkish Green Supergrid, which extends from the Altai Mountains to the Danube and encompasses the members of the Organization of Turkic States (OTS). The main objective of the study is to demonstrate, using a multi-vector optimization model, how Central Asia's high renewable energy potential and existing natural gas infrastructure can be integrated with Europe's decarbonization goals (Green Deal). In the study, a 6-node energy network stretching from Nur-Sultan to Edirne was modeled using the Mixed-Integer Linear Programming (MILP) method. The model was run under three different scenarios—Fully Green (S0), Transition Process (S1), and Business As Usual (S2)—to minimize annual costs. The simulations simultaneously optimize electricity (HVDC), hydrogen, and natural gas flows. Simulation results revealed that the annualized capital expenditures (CAPEX) for the backbone infrastructure remained consistent across scenarios, stabilizing at approximately 0.68 billion €/year . It was determined that 8503 MW of electrolyzer capacity needed to be installed at the Edirne (Thrace) node to meet European export demand. The conversion (repurposing) of existing natural gas pipelines (TANAP, etc.) to carry hydrogen and the strengthening of the Trans-Caspian crossing have been identified as the most critical components of the project. The Turkish Green Supergrid is not just an energy transmission project, but a strategic necessity for regional energy security and green transformation. The findings prove that this infrastructure is a No-Regret investment and creates a resilient energy corridor for Europe and OTS countries against geopolitical uncertainties.

Keywords: Green supergrid; Hydrogen economy; MILP optimization; Trans-Caspian corridor; Organization of Turkic States.

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1. Introduction

In the context of combating global climate change, decarbonizing energy systems has become one of the greatest engineering and policy challenges of the 21st century. In particular, the European Union's Green Deal objectives and the search for energy supply security have increased the importance of alternative and clean energy corridors [1]. In this context, work on strategic lines connecting Asia's vast renewable energy resources to Europe's demand centers has gained momentum.

At the heart of these strategic lines are the countries located along the historic Silk Road route and united under the Organization of Turkic States (OTS) (Figure 1) [2]. The OTS is an international organization that aims to promote political, economic, and cultural cooperation in the Eurasian region, with Türkiye, Azerbaijan, Kazakhstan, Kyrgyzstan, and Uzbekistan as members, and Hungary, Turkmenistan, and the TRNC as observers. In terms of energy diplomacy, the OTS is a natural bridge connecting the hydrocarbon wealth of the Caspian basin and the enormous wind/solar potential of Central Asia to Western markets.

Expanding the hydrogen transportation infrastructure is critical. Current standards are open to improvement [3], but hydrogen's physical properties complicate the conversion of existing networks [4-6]. Therefore, transitional solutions (inhibitors, optimized supply chains) gain importance [7-9]. Türkiye, with its infrastructure and potential, can become a regional hydrogen hub [10-13, 6], the market transformation provided by TANAP will contribute to this process [14, 15].

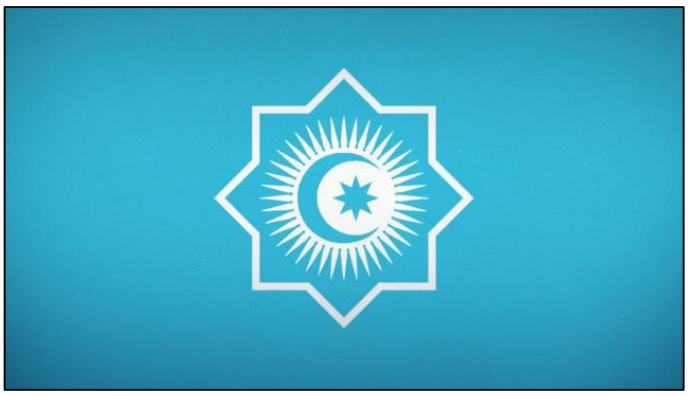


Figure 1. Flag of the Organization of Turkic States

While historical data indicates immense potential, recent climate projections suggest spatial restructuring and potential variability in Caspian wind resources [16, 17], necessitating stochastic planning approaches. The region is an ideal laboratory for wave physics studies [18]. The conversion of offshore infrastructure to hydrogen is being rapidly researched; dozens of GW in the Netherlands and cost-focused production models in China are at the forefront [19, 20].

Cross-border trade in South Asia could increase the share of renewables and emission reductions [21-23], but fairness issues may arise in Northeast Asia [24]. Stochastic planning models have been developed for high-renewable systems [25]. Integrated system optimization (electricity-gas [26], multi-vector community systems [27, 28]) increases operational efficiency and reduces costs. This forms the basis for an integrated, cross-sector energy architecture [29-37].

However, realizing this potential requires navigating complex geopolitical and material challenges. The Trans-Caspian route traverses a delicate security environment, necessitating robust diplomatic protocols to protect critical infrastructure. Furthermore, the transition to a renewable-heavy system implies a surge in demand for critical minerals (copper, lithium, rare earth elements), linking energy security to mineral supply chains [38]. Addressing these risks is as crucial as the technical optimization of the grid.

MILP models provide fast and optimal solutions for shared production and microgrid optimization [39-43]. Other studies highlight fuel savings through platonization [44], ecological corridor optimization [45], and the suitability of Türkiye and Romania for investment in the New Silk Road countries [46].

While existing literature extensively covers the European Hydrogen Backbone and North African energy corridors, there is a significant gap regarding the quantitative analysis of the Trans-Caspian route. Previous studies have largely focused on geopolitical aspects or single-vector (only gas) transport. This study contributes to the literature by (1) proposing a multi-vector (electricity, gas, hydrogen) optimization model specifically for the OTS geography, (2) quantifying the investment requirements for the Altai to Danube line under carbon-constrained scenarios, and (3) analyzing the operational feasibility of repurposing the Southern Gas Corridor for green hydrogen.

2. Methodology

In this study, a mathematical optimization approach was adopted to determine the optimal design and operating strategies of the proposed energy corridor. The problem is formulated as a Mixed-Integer Linear Programming (MILP) model to minimize the total annualized cost (TOTEX), comprising Capital Expenditures (CAPEX) for new transmission and generation assets, and Operational Expenditures (OPEX) including fuel costs and carbon taxes [40-42]. The optimization was performed using MATLAB with the YALMIP interface, utilizing the IBM CPLEX solver to handle the large-scale Mixed-Integer Linear Programming (MILP) problem efficiently [47].

In an energy network, each node (N) plays a critical role in terms of production, conversion, or transmission. The Turkish Green Grid has been modeled based on six main nodes stretching from east to west in terms of geographical continuity and resource diversity (Table 1): Nur-Sultan (Kazakhstan), Turkmenbashi (Turkmenistan), Baku (Azerbaijan), Erzurum, Konya, and Edirne (Türkiye).

The Edirne node is defined as the connection point to the European grid (ENTSO-E) and the main export gateway. For each node, 2035 projected demand data, hourly solar and wind capacity factors (CF) from the COPERNICUS database, and existing installed capacity data have been integrated into the system [48-53].

When these six nodes are connected to each other via HVDC + hydrogen transmission lines, the system enables the surplus solar-hydrogen energy from the east to be transported to consumption centers in the west, while electricity, data, and carbon certificates flow in the opposite direction.

In the mathematical model, three fundamental variables are defined for each node: (1) production capacity, (2) energy type conversion coefficient, (3) network connection matrix. These variables are solved using a multi-objective optimization algorithm $\min(C_{total}, E_{CO_2})$, $\max(S_{reliability})$ [41, 42].

Equation 1 is used in the study for the general weighted objective of minimizing total cost. Here, λ_{CO_2} represents the carbon price and $S_{security}$ represents the supply security indicator [41, 42].

$$\min Z = \sum_i c_i^{inv} x_i + \sum_{n,p,t} c_{n,p,t}^{op} g_{n,p,t} + \lambda_{CO_2} \sum_{n,p,t} \varepsilon_p g_{n,p,t} - \beta S_{security} \quad (1)$$

The constraints in the study are shown in Table 2 [4, 18, 19, 26, 28, 31, 39-42, 54-56].

To assess the robustness of the grid design, three distinct policy scenarios were defined:

- *S0 (Full Green)*: A strict decarbonization scenario where fossil gas usage is prohibited, forcing a 100% renewable supply.
- *S1 (Transitional)*: A realistic transition scenario where existing gas power plants are subject to a phase-out constraint (limited to 20% capacity factor) and a carbon tax of €150/ton is applied.
- *S2 (Business-as-Usual)*: A baseline scenario with no carbon tax and unrestricted gas usage, representing the current policy trajectory.

In the S1 scenario, the carbon tax of €150/ton is modeled as a shadow price reflecting the EU's Carbon Border Adjustment Mechanism (CBAM) compliance costs for exports. The 20% capacity factor limit for gas plants assumes their role shifts to peak-shaving and backup services rather than baseload generation. Furthermore, while demand is projected for 2035, the renewable generation profiles are based on historical meteorological data to preserve realistic weather correlations.

Table 1. Node points and technical justifications

Node point	Role	Reasons
Nur-Sultan (Kazakhstan) – North Central Asia Hub	High wind and solar potential + HVDC connection start	• Average wind speed of 6–7 m/s in northern Kazakhstan • 4.5–5.5 kWh/m^2.day of sunshine • Extensive infrastructure, metallurgical industry (hydrogen usage potential) • Flexibility of connection with Russian and Chinese lines
Turkmenbashi (Turkmenistan) – Eastern Production Node	Solar + natural gas-based conversion + green hydrogen production	• 3000+ hours of sunshine per year • Low population density in the Karakum region (suitable for large PV areas) • Starting point for Caspian transit pipelines and cable lines
Baku (Azerbaijan) – Caspian Integration Hub	Energy conversion center (hydrogen–ammonia–electricity integration)	• Caspian Sea offshore wind potential (5–8 m/s) • Natural harbor and existing oil-gas infrastructure • Connection to Europe via TANAP • Can be transformed into a digital control center for energy exports
Erzurum–Kars (Türkiye) – Western Transit Hub	Central Asia–Anatolia HVDC and pipeline convergence point	• Intersection of TANAP, BTK railway, and fiber optic lines • High altitude → geothermal and hydro potential • Most suitable region for establishing Türkiye's eastern HVDC converter station
Konya–Karapınar (Türkiye) – Western Production Node	Solar energy + battery storage + grid balancing	• 5.6 kWh/m^2.day solar radiation (among the highest in Türkiye) • 1 GW+ PV production field available • Central geographic location for grid balancing
Edirne–Tekirdağ (Türkiye) – European Exit Node	Energy export + European interconnection	• Physical transition point to the ENTSO-E system • High demand density around the Marmara region • Suitable for hydrogen–ammonia export port infrastructure

Table 2. Constraints

Constraint	Equation	Equation number	Note
Node energy balance	$\sum_{l\in in(n)} y_{l,p,t} + g_{n,p,t} + \sum_s disch_{n,s,t} + imp_{n,p,t} = d_{n,p,t} + \sum_{l\in out(n)} y_{l,p,t}(1 + loss_{l,p}) + \sum_s ch_{n,s,t} + E^{EL}_{n,t}$	(2)	$E^{EL}_{n,t}$; electricity consumption for the electrolyzer, if hydrogen production occurs
Line capacity	$0 \le y_{l,p,t} \le cap^{exist}_{l,p} + cap^{new}_{l,p} x_l$	(3)	If the line is a pipeline, $p = g$; if HVDC, $p = e$
Storage dynamics	$s_{n,s,t+1} = s_{n,s,t}(1-\mu_s) + ch_{n,s,t}\eta_{ch,s} - \frac{disch_{n,s,t}}{\eta_{disch,s}}$	(4)	μ_s; self-discharge
	$0 \le s_{n,s,t} \le Cap^{stor}_{n,s}$	(5)	
Electrolyzer – H_2 relationship	$h_{n,t} = \eta^{EL} E^{EL}_{n,t}$	(6)	kg or MWh-eq
	$0 \le E^{EL}_{n,t} \le Cap^{EL}_{n}$	(7)	Must be LHV-based
Pipeline repurpose and H_2 transportation	$if\ \ rep_l = 1\ \ then\ \ cap^{H_2}_l = \alpha_l cap^{pipe}_l$	(8)	α_l; conversion factor
Emissions constraints	$\sum_{n,p,t} \varepsilon_p g_{n,p,t} \le EmissionLimit_{scenario}$	(9)	*S0 – Full-Green*; natural gas/oil use is not permitted (zeroed). *S1 – Transitional*; existing gas/oil infrastructure is used, carbon pricing and CCUS options are available. *S2 – BAU (Business-as-usual)*; hydrocarbons can be used freely (reference comparison).
Security reserve	$g_{n,local,t} \ge \gamma_n d_{n,t}$	(10)	γ_n; safety factor

The economic analysis of the system was calculated using Equations 11-13 [57].

$$NPV = -\sum_i c^{inv}_i x_i + \sum_{y=1}^{Y} \frac{(Revenue_y - Opex_y)}{(1+r)^y} \quad (11)$$

$$LCOE = \frac{\sum c^{inv}_i CRF + \sum Opex}{\sum_t generation_t} \quad (12)$$

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (13)$$

3. Results and Discussions

The optimization results reveal a striking similarity in the physical infrastructure requirements across all three scenarios. The total annualized system cost stabilized at approximately €0.68 billion for both the Transitional (S1) and Full Green (S0) scenarios. This indicates that the investment in the Trans-Caspian backbone is a "no-regret" decision; the infrastructure is economically justified regardless of the speed of the green transition.

A consistent finding across all simulations is the massive deployment of electrolyzers at the Edirne node. To meet the high export demand of Europe (simulated as a pull-factor), the model installed 8,503 MW of electrolyzer capacity in the Thrace region. This transforms Edirne from a passive transit point into an active energy conversion hub, aggregating renewable electrons from Central Asia and converting them into green molecules (hydrogen) for the European grid (Figure 2). The model's selection of Edirne for massive electrolyzer capacity (8.5 GW), despite the option to repurpose pipelines, is driven by two factors: (1) Fresh water availability in the Thrace region is higher compared to the arid production zones in the Caspian steppes, reducing desalination costs. (2)

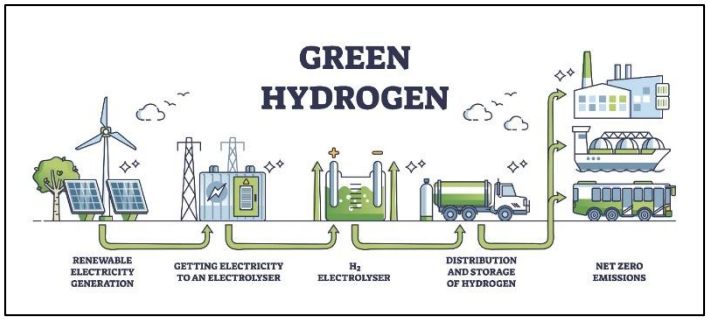


Figure 2. Edirne node

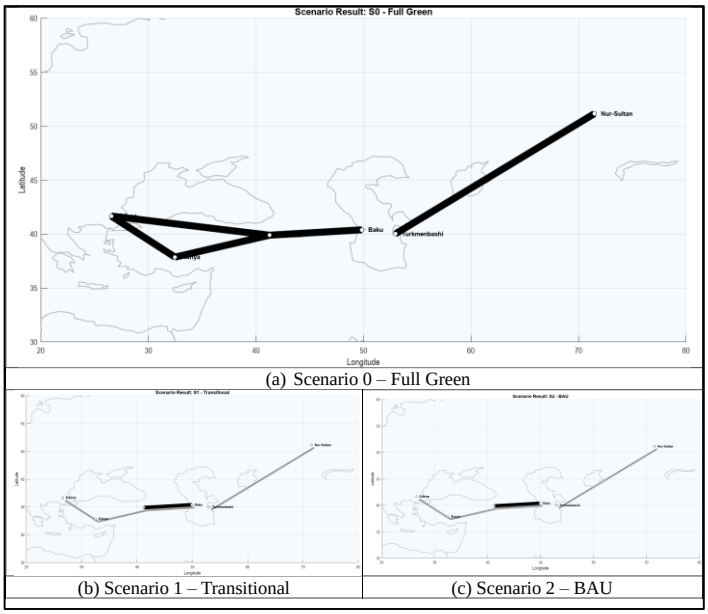
Producing hydrogen at the demand center (European border) allows the HVDC backbone to operate at higher efficiency for direct electricity exports when needed, offering operational flexibility. However, the repurposing of TANAP remains vital in the S1 scenario for transporting hydrogen produced from transitioning natural gas assets (blue hydrogen) or smaller-scale green hydrogen pilots in the east, creating a hybrid transmission model.

Figure 3 shows the spatial distribution and energy flow directions of the proposed Turkish Green Supergrid. The size of the nodes on the map is proportional to the newly installed renewable energy capacity (MW) in the relevant region. Black lines represent high-voltage direct current (HVDC) transmission lines, while gray lines represent existing natural gas pipelines. As seen on the map, energy flow is concentrated from east (Nur-Sultan, Turkmenbashi, Baku) to west (Edirne). In particular, the Hazar Sea crossing and the increased line thickness over Anatolia indicate that the system maximizes its backbone capacity to meet the high export demand in Edirne. This topology confirms that Central Asia is the source production center and Turkey is a strategic bridge and transformation center (Hub), as well as the strategic importance of the Caspian Sea crossing and the transmission line over Anatolia (TANAP route). The fact that the physical infrastructure requirement remains unchanged even if scenarios change proves that these investments are No-Regret in nature.

In other words, this infrastructure must be established regardless of whether future policy is fully green or mixed. While the physical maps (topology) of S1 and S2 appear similar, their operational characteristics differ significantly (Figure 4-6):

- In S1 (Transitional), due to the carbon tax and phase-out constraints, gas plants operate as peaker units, filling the gaps only when solar and wind generation is insufficient. This hybrid operation proves that the existing gas infrastructure is vital for the system's reliability during the transition period.
- In S2 (BAU), existing gas power plants in Baku and Turkmenistan operate as baseload generators due to low marginal costs.

Figure 4 represents the S0 scenario, where fossil fuel use is completely banned. As seen in the graphs, the entire energy demand is met by wind, solar, and storage discharge (green areas). There is no fossil gas support (gray area). In this scenario, it has been observed that battery storage systems play a critical role in managing seasonal fluctuations in renewable energy production, particularly in high-demand nodes such as Edirne and Konya. While technically feasible, the S0 scenario requires significantly higher installed power investment compared to S1 and S2 and strains system flexibility.



(a) Scenario 0 – Full Green

(b) Scenario 1 – Transitional

(c) Scenario 2 – BAU

Figure 3. Optimized network topology and geographic flow map of the Altay- Danube energy corridor

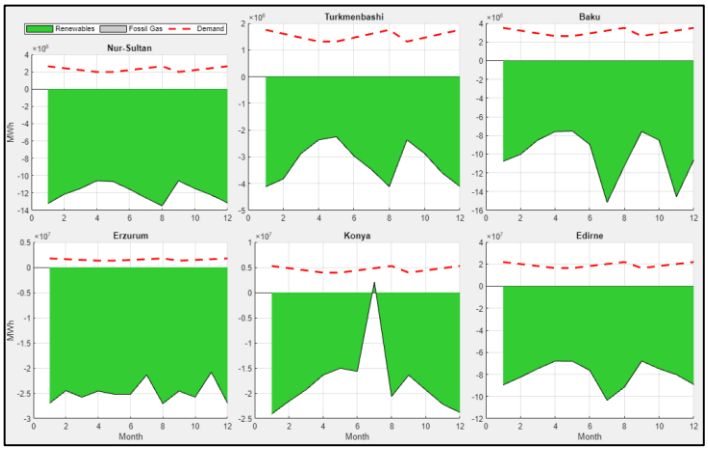


Figure 4. 100% renewable energy production-consumption balance under scenario S0 (Fully green)

Figure 5 shows the production dynamics in scenario S1, where natural gas capacity is constrained (20% usage quota) and a carbon tax is applied. Compared to Figure 6 (S2), it is clear that in the S1 scenario, renewable energy sources (green areas) have risen to become the system's main energy provider. Here, natural gas (gray areas) functions not as a base load power plant, but only as a Balancing/Peaker Plant that comes online when wind and solar production cannot meet demand. This hybrid operating regime prevents the existing gas infrastructure from becoming stranded assets while ensuring the system meets its decarbonization targets. The graphs confirm that the S1 scenario is the optimal transition strategy, both ensuring supply security and supporting the green transition.

Figure 6 presents the production profile in the S2 scenario, where no carbon tax is applied and there are no natural gas restrictions. Examining the graphs, it is seen that Fossil Gas production, shown in gray, is used as a continuous Base-load source throughout the year. Renewable energy production (Wind and Solar), shown in green, is

added to gas power plants to meet total demand. While this operating strategy ensures the preservation of existing infrastructure (low CAPEX), it results in high carbon emissions and operating costs (OPEX) due to continuous fossil fuel consumption. The peak gas usage, especially during winter months (months 1 and 12), demonstrates that the system's dependence on fossil fuels continues in the S2 scenario.

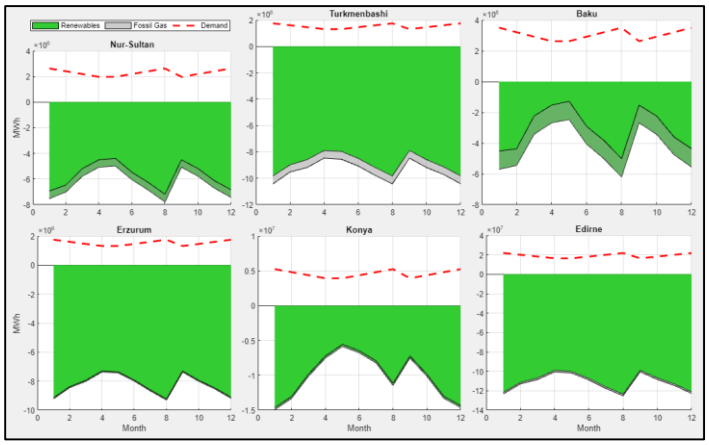


Figure 5. Node-based monthly energy balance and hybrid operation strategy for scenario S1 (Transition)

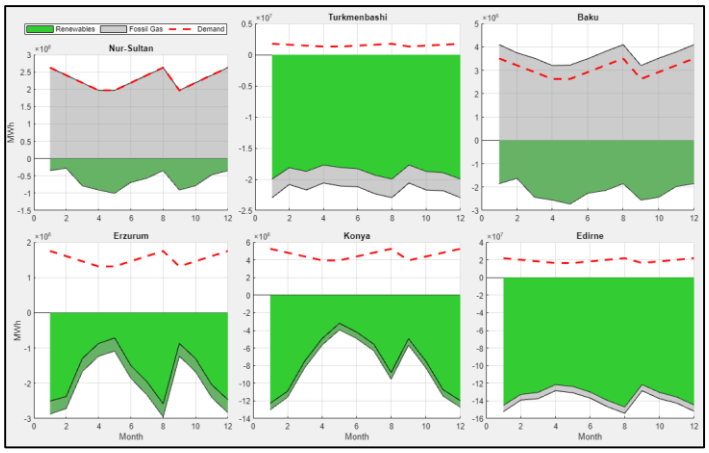


Figure 6. Node-based monthly energy balance and resource allocation for the S2 (Business as usual) scenario

The results align with the broader European Hydrogen Backbone initiative but extend it eastward. The identification of the Caspian Sea wind potential and Central Anatolian solar potential as the primary feeders for the European hydrogen market is a novel finding. The fact that the model prioritizes repurposing pipelines over building new HVDC cables in the S1 scenario suggests that the "blending" of hydrogen into the TANAP line should be an immediate priority for policymakers. Unlike studies focusing solely on North Sea wind, this study highlights the distinct advantage of the OTS corridor: the complementarity of resources (high wind potential in the Northern Caspian/Kazakhstan regions and high solar irradiance in the Southern/Turkmenistan regions) which balances the grid naturally.

Financing a cross-border infrastructure of this magnitude requires a multi-layered capital structure. A specific 'Energy Transition Fund' under the umbrella of the Organization of Turkic States (OTS) could act as a guarantor. Furthermore, blending concessional financing from development banks (World Bank, EBRD) with private equity via Public-Private Partnerships (PPP) reduces the cost of capital. For the S1 scenario, framing the project as a 'security of supply' asset allows access to strategic geopolitical funds from the EU.

4. Conclusions

Analyses conducted on the Turkish Green Supergrid model show that the renewable energy potential of Central Asia and Türkiye is an indispensable resource for Europe's decarbonization goals. The most striking result of the study is that infrastructure requirements are independent of political scenarios. Whether a fully green future is targeted or a natural gas-supported transition process is planned, strengthening the Trans-Caspian transit and investing in multi-gigawatt scale electrolyzers in the Thrace region is a robust requirement across all modeled technical scenarios. The model has proven that a hydrogen capacity of 8503 MW would transform the region into a strategic hub in global energy trade.

In light of the model findings, the following recommendations have been developed for policymakers and investors:

I. To ensure energy flow between Turkmenistan (Solar/Gas) and Azerbaijan (Wind), the high-capacity transmission lines (HVDC or H_2 Pipeline) indicated by the model should be immediately taken into the planning phase.

II. To meet the 8.5 GW capacity requirement identified in the simulation, Edirne and its surroundings should be declared a Special Hydrogen Industrial Zone. This zone should have a hybrid infrastructure that provides physical integration with both the electricity grid (TEİAŞ/ENTSO-E) and the natural gas network (TANAP/TAP).

III. The findings show that modifying existing natural gas pipelines (TANAP, etc.) to carry hydrogen (repurposing) is more economical than building new pipelines from scratch. Therefore, as envisaged in the S1 scenario, a legal basis should be prepared for blending applications (mixing H_2 into natural gas).

IV. The risk for investors is not the choice of technology but delay. Since the infrastructure is the same in every scenario, financing models should be designed to be flexible, starting with Transition Fuel (Natural Gas) and continuing with Green Hydrogen.

Nomenclature

AC	: Alternating current
$CAPEX$	: Capital expenditure (€ or $)
$CCUS$	: Carbon capture, utilization and storage
C_{op}	: Operational cost (€/MWh)
CRF	: Capital recovery factor
CO_2	: Carbon dioxide
D	: Demand (by node, time series)
E	: Energy
EL	: Electrolyzer
η	: Efficiency
GHG	: Greenhouse gas
H_2, h	: Hydrogen
$HVDC$	: High voltage direct current
$LCOE$	: Levelized cost of energy
LHV	: Lower heating value

LP	: Linear program
$MILP$	: Mixed integer linear program
NPV	: Net present value
OC	: Operating cost
P	: Power (MW)
R	: Renewable production profile (kW or MWh)
SOE	: State of energy
t	: Time index (hour)
x	: Investment decision variable (binary/continuous)
y	: Operation (flow) variable
$ch_{n,s,t}$, $disch_{n,s,t}$	: Storage filling/discharging (MWh)
$rep_l \in \{0,1\}$	: Decision to convert the pipeline to hydrogen transport
ε_p	: Emission factor per fuel (tCO_2/MWh)
$loss_l$	: Transmission line loss rate
g	: Natural gas
e	: Electricity
l	: Line

Conflict of Interest Statement

The authors must declare that there is no conflict of interest in the study.

CRediT Author Statement

Mert Ökten: Conceptualization, Supervision, Writing-original draft, Validation, Data curation, Formal analysis

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