Strategic Development of Croatia's Transmission System within the European Energy Transition

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***Abstract*—Croatia's transmission system is a relatively small, but quite specific case on the EU's southeastern margin. It is strongly interconnected and functions as a transit corridor for regional power flows. Its elongated north–south "croissant" geographic shape creates pronounced spatial mismatch: peak consumption is concentrated in the north, while most of existing generation and new connection requests are located in the south and along the coast, where tourism drives strong seasonal demand variations. Additional challenge is a large number of diversified islands with large seasonal demand variation and expected further electrification of transport and service sectors without significant power generation on the site. With a 400 kV backbone largely built in the 1960–70s, the system is increasingly constrained by N-1 security margins, high voltages, and cross-border flow transits and interactions under rising renewable penetration and electrification. This paper presents a transferable transmission planning experience that links national targets and connection queues to binding grid constraints and a prioritized investment portfolio combining new internal 400 kV corridors, reinforcement of interconnections, and evaluation of a potential submarine HVDC link to neighboring Italy, while explicitly accounting for permitting, financing, and climate driven resilience risks. It makes the planning logic explicit, showing how development trajectories and the grid connection requests translate into a short list of binding constraints and a staged investment portfolio.**

Keywords—transmission planning, interconnected power systems, RES integration, N-1 security, investment sequencing, HVDC interconnection, energy storage, grid resilience

I. Introduction And Contributions

The European energy transition is accelerating renewable energy sources (RES) integration, electrification of end-use sectors, and cross-border power exchanges, placing unprecedented requirements on transmission system security, flexibility, and resilience. In this context, transmission planning must increasingly balance long lead-time infrastructure investments with fast-changing generation and demand patterns, permitting constraints, and climate-driven stress on assets.

Croatia provides a compact but representative study case for these challenges. It is a relatively small power system located on the EU's southeastern margin, yet it is strongly interconnected and often operates as a transit corridor for regional flows. Its elongated north–south geography creates a persistent spatial mismatch: the main load center is in the north around capital Zagreb, while a large share of RES potential and new connection requests are concentrated in the south and coastal areas. In addition, tourism drives strong seasonal demand variation, including peaks on the coast and islands. Most of Croatia's 400 kV backbone was constructed during the 1960–70s, and a growing share of operating conditions is now shaped by N-1 margins, high voltages and cross-border exchanges.

While many elements of Croatia's development plans are publicly available, the planning logic that connects national targets and the connection pipeline to binding grid constraints and investment sequencing is rarely made explicit [1]. What is new in this paper is an explicit, replicable "driver - scenario - constraint - measure - sequencing" logic that connects National Energy and Climate Plan (NECP) trajectories [2] and connection queues to binding grid constraints and then to investment prioritization under uncertainty. This paper addresses that gap and contributes:

- A replicable planning logic that converts national targets and connection queues into a small set of stressed scenarios and constraint checks.
- A driver-to-constraint-to-measure mapping that explains why specific corridors, transformers, and controllability measures become priority.
- An uncertainty and sequencing (permitting, financing, climate stress) that explains when each investment is ready to "go" vs "conditional".
- A clarified role of a Croatia–Italy HVDC option—strategic for controllability and regional value, but not a substitute for internal reinforcements.

The paper is organized as follows: Section II summarizes the system context and dominant stressors; Section III presents the planning framework and constraint mapping; Section IV discusses the investment portfolio and sequencing; Section V evaluates the role of the HVDC option; and Section VI concludes with transferable lessons learned.

II. Croatian Transmission System Context And Planning Stressors

Due to its specific geographical position and shape, Croatia's power system comprises power plants, transmission and distribution network elements located in different climatic zones and geographical areas.

The total installed capacity of all power plants in Croatia is currently ~6.5 GW. Of this, about 2.5 GW comes from hydropower, 1.2 GW from wind power, and around 1.4 GW from solar power, with the remainder coming from other generation technologies. The average daily demand typically ranges between 2.2 GW and 2.8 GW, with peak load reaching up to about 3.4 GW [1].

Transmission network in Croatia is quite specific on European scale. As shown on the Figure 1, its transmission

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system rests on a meshed 400 kV backbone consisting of two longitudinal branches, following strange country shape, complemented by 220 kV corridors and a dense 110 kV level.

Croatia has more than 1200 islands and islets which is quite challenging task in ensuring security of supply, particularly during summers months and high touristic season.

Strong cross-border interconnections provide gigawatt-scale exchange capability and are central to security of supply and market integration. Under normal conditions the grid meets the N-1 security criterion, with critical substations arranged to ride through the loss of a single element without load shedding.

On heavily loaded interfaces, along with rapid RES integration, Croatian TSO increasingly applies preventive and corrective measures, topology optimization, transformer tap control, dynamic thermal line ratings (DLR), and redispatching to preserve margins during stressed periods.

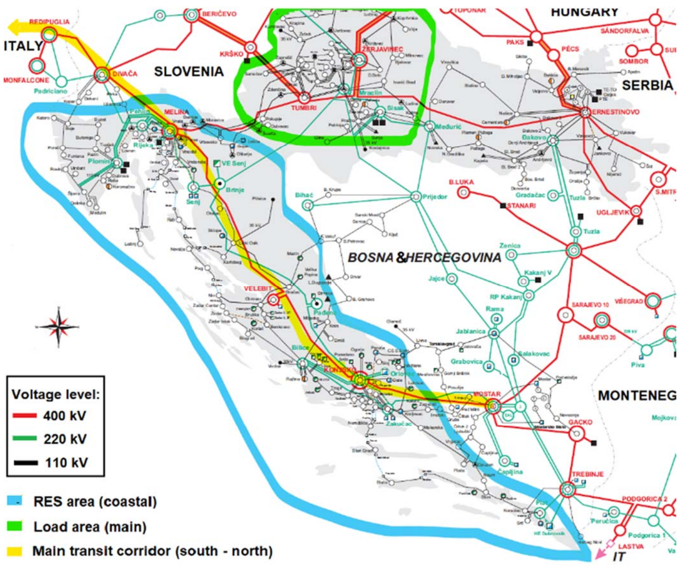

Fig. 1. Croatian transmission network

Network congestion is seasonal. In summer, touristic coastal demand combined with high solar and wind injections can saturate local 110 kV, where voltage and reactive power control become binding. In winter, electrification of heating lifts evening peaks at the coastal area, tightening margins on north–south trunks and around key 400/220/110 kV nodes supplying large urban loads. High export from the east of Europe can also stress east–west transit through Croatia.

Several elements recur as operational "hot spots". On the 400 kV backbone and 400/110 kV interfaces, the Zagreb ring (substations Žerjavinec, Tumbri, Mraclin) sees tight transformer margins at winter peaks and high east–west transit. For example, loss of a 400/110 kV transformer there is a critical contingency. The Ernestinovo area (eastern area) faces constraints during high export from eastern countries. The Konjsko–Melina 400 kV corridor is pivotal for supplying coastal areas and evacuating RES. A single-circuit trip under summer peaks shifts stress to 220/110 kV coastal interfaces. Around Vodnjan/Melina (Istria–Kvarner), 110 kV network runs near limits in summer. On 220/110 kV coastal rings, the Rijeka–Istria area and Split area frequently approach thermal voltage limits when RES output coincides with high loads. Coincident grid trips can sharply reduce evacuation capacity.

Mitigation combines routine operations, preventive reconfiguration, Q/U scheduling (incl. 220 kV SVC in SS Konjsko), dynamic line rating (DLR), short-term redispatch and targeted curtailment, with targeted reinforcements of 400/220/110 kV corridors toward RES and load zones. Scaling storage and demand response for ancillary services, and standardizing "connect-and-manage" practices, are key to maintaining security during rising RES and electrification.

Moreover, the network is significantly older than EU average, with 50% of the network out of its lifetime [1]. It assumes significant investments need in the revitalization and modernization to ensure system reliability.

Climate resilience is an additional binding driver of transmission development. The Mediterranean region is assessed as particularly exposed to climate change. For transmission assets, these hazards cause acute disturbance risks and chronic stress (reduced thermal margins during heat, accelerated aging of equipment, storm-driven faults, icing and salt pollution in exposed corridors, and wildfire-related outages). Therefore, both planning and operation must integrate resilience measures, climate change related standards, corridor management, hardening of critical substations, redundancy for coastal supply and island connections, and emergency and restoration procedures, consistent with the broader technical literature on climate impacts on power systems.

III. Planning Framework: From NECP Targets And Connection Requests To Grid Constraints

A. *Planning Inputs*

Inputs considered in Croatian planning include:

- NECP key targets (capacity and energy shares by technology and timeframe) [2].
- Connection requests (RES, storage, new loads), by location and simultaneity [1].
- Cross-border exchange patterns (Croatia as transit country with sensitivity to neighboring dispatch) [3].
- Climate and resilience stressors (heat, storms, wildfire risk) affecting ratings, outage probabilities and restoration time [1].

In practice, NECP targets [2] enter planning only after spatial and temporal disaggregation: allocate expected RES additions to connection zones and allocate demand growth to load centers (Zagreb and coastal tourism peaks); translate these into a few stressed snapshots (summer peak + high RES + high transit; winter peak + low RES + high transit etc.); and run N-1, voltage/reactive, short-circuit and controllability screens to identify the first binding element (corridor, transformer group, interface or voltage pocket). The planning decision is then driven by the binding constraint (thermal vs voltage vs controllability), not by policy compliance metrics.

The focus therefore shifts from "connecting capacity" to identifying where injections and demand growth translate into binding thermal, voltage and controllability constraints.

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Connection requests provide the second quantitative boundary condition. In the latest Network Development Plan (NDP) [1], projects with signed grid connection agreements total ~1.9 GW, with ~2.5 GW in the grid study phase and a further 5–6 GW in earlier stages of interest, including nearly 1 GW of BESS requests submitted in 2025. Since not all projects will be realized, the pipeline is treated probabilistically, shaping reinforcement timing and prioritization.

As explained above, cross-border exchanges are a first-order input for Croatia. Interconnection capacity (≈13 GW) is several times larger than the peak load, so internal loading can be driven as much by neighboring dispatch as by domestic generation. Scenarios therefore include "high transit" cases and sensitivity to regional market outcomes. ENTSO-E TYNDP 2024 [3] also indicates additional interconnection needs toward 2040 involving Croatia (e.g., toward Slovenia, Bosnia and Herzegovina, and Serbia), reinforcing the importance of cross-border-driven constraints.

Climate impacts are reflected via derating thermal-margin assumptions, outage-risk sensitivity for exposed corridors, and restoration constraints. The resulting logic is illustrated in Fig. 2, linking these drivers to stressed scenarios, constraint checks, and corresponding planning measures.

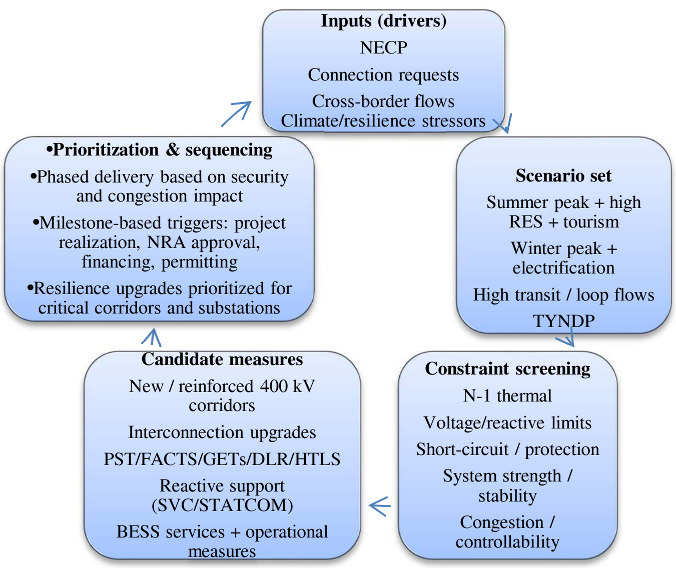

Fig. 2. Planning framework used to translate NECP and connection-pipeline drivers into stressed scenarios, binding constraints and a prioritized transmission investment portfolio

B. *Constraint Mapping*

For each representative scenario (Fig. 2), the planning process identifies the binding limitations that determine reinforcement needs and the appropriate mix of capacity expansion and controllability measures. Constraints are screened in five categories, as follows.

Security and thermal margins (N-1): Candidate corridors and transformer groups are assessed under the loss of a single critical element, and binding constraints are those that produce thermal overloads or unacceptable post-contingency loading. In Croatia, these often emerge on the north–south 400 kV backbone and on 400/110 kV interfaces supplying major load centers during winter peaks, as well as on corridors toward the coastal regions (Dalmatia, Dubrovnik area, islands, Istria etc.).

Voltage and reactive-power adequacy: Voltage profiles and reactive reserves are evaluated under high-RES output and high coastal demand, where weak 110/220 kV interfaces and long radial supplies can make reactive support and control binding. Coastal and island areas are screened for voltage stability margins and the availability of dynamic reactive sources.

Short-circuit level and protection constraints: New generation and large load connections can exceed equipment ratings or require protection-system upgrades, so screening checks include substation fault levels, breaker capability, and protection selectivity, particularly at cluster connection nodes.

System dynamic performance: With rising inverter-based resources, scenarios are reviewed for conditions where low short-circuit strength or reduced inertia may constrain operations, triggering needs for grid-forming capability, operational limits, or specific network reinforcements.

Congestion and controllability under cross-border flows: due to strong interconnections, internal corridor loading is sensitive to neighboring dispatch and transits. Therefore, the mapping distinguishes constraints best addressed by added transfer capacity (e.g. new 400 kV line) from those mitigated by controllability measures (e.g., operational remedial actions).

TABLE 1. DRIVER-TO-CONSTRAINT MAPPING USED IN CROATIA TRANSMISSION PLANNING

Target / request (input)	System effect	Binding grid constraint	Typical planning response
Coastal PV/wind growth +summer tourism peak	High injections +high coastal load; north–south transfers & transits	N-1 thermal on key 400 kV corridor; 400/110 kV and 220/110 kV interface loading; voltage/reactive limits	New/strengthened 400 kV corridor(s); transformer/DSO interface upgrades; reactive support (SVC/STATCOM); operational redispatch/curtailment
Winter peak growth (electrification) around Zagreb + transit flows	Higher evening peak in north + east–west transit	Transformer N-1 margins at 400/110 kV nodes; 110 kV supply constraints	400/110 kV reinforcement; substation upgrades; topology measures; GETs/DLR/HTLS and congestion management
High cross-border exchanges (Croatia as transit)	East–west loading sensitive to neighbors' dispatch	Congestion and controllability limits; loop flows; interface constraints	PST/FACTS; coordination with neighboring TSOs; HVDC assessment; remedial action schemes
New large loads (data centers) / new connection pockets	Concentrated demand or generation at specific nodes	Short-circuit, voltage, transformer capacity, local thermal limits	Substation strengthening; new transformers; protection upgrades; staged connection rules ("connect-and-manage")
Climate stress (heat, storms, wildfires, icing/winds)	Derating, higher fault rates, slower restoration	Reduced thermal margins; higher outage probability of exposed corridors	Resilience-based refurbishment; vegetation/fire management; redundancy for critical corridors; climate-informed planning criteria

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The resulting constraint profile (which constraints bind, where, and in which season) provides the basis for the investment portfolio and sequencing discussed in Section IV and for the role of the HVDC option discussed in Section V.

Although parameter values are Croatia-specific, the driver-to-constraint mapping in Table 1 and the planning logic in Fig. 2 are transferable to other small, strongly interconnected systems with spatial load–generation mismatch and pronounced seasonality.

Section IV applies this framework to justify the investment portfolio and sequencing in the Network Development Plan [1].

IV. Investment Portfolio And Sequencing In Croatia's Network Development Plan

Croatia's Network Development Plan (NDP) [1] defines a phased program to expand and modernize the 400/220/110 kV network to integrate rapidly growing renewable generation and new loads while maintaining N-1 security under strong cross-border exchanges. Consistent with the planning framework in Section III (Fig. 2 and Table 1), the NDP is scenario-based (seasonal peak/minimum conditions, hydrology, high wind/PV dispatch, and alternative import/export patterns) and prioritizes reinforcements that address binding thermal, voltage, and controllability constraints. Because project realization, permitting, regulatory approval, and financing remain uncertain, the NDP also includes an implementation logic-sequencing that determines which measures must be delivered first and which can follow as system needs and project maturity become clearer.

A. *Portfolio Logic*

The investment portfolio comprises four complementary measure groups: new or reinforced 400 kV corridors to increase internal capability and relieve structural congestion; targeted upgrades of 400/220/110 kV interfaces and coastal supply zones to address seasonal voltage and local thermal limits; modernization of aging 220/110 kV assets (reconductoring and submarine cable replacement) to restore reliability and increase usable capacity and grid-enhancing controllability solutions to improve operational margins and optimize the timing and scope of reinforcements.

B. *Backbone Reinforcement: North–South 400 kV Axis*

A central NDP measure is a reinforced internal north–south 400 kV transfer axis to address Croatia's elongated geography and the Zagreb–coast load–generation mismatch. The proposed "spine" comprises the 2×400 kV OHLs Konjsko–Lika, Lika–Melina, and Lika–Tumbri lines and a new 400/(220)/110 kV Lika substation [1]. It is intended to relieve summer coastal constraints under tourism and high RES output, strengthen supply to Dalmatia/Kvarner, and improve N-1 margins on key northern 400/110 kV interfaces (Fig. 3) [1].

C. *Targeted Regional Reinforcements and Interface Upgrades*

Beyond the backbone axis, the NDP includes targeted reinforcements in areas with concentrated connection interest and recurring constraints. In the far south, a new 400 kV spur (tap on the Konjsko–Mostar corridor) is planned to strengthen supply and accommodate rising renewable interest near Dubrovnik [1].

More broadly, transformer upgrades and local 110/220 kV reinforcements increase hosting capacity in coastal zones where coincident high load and PV/wind output make thermal and voltage limits binding.

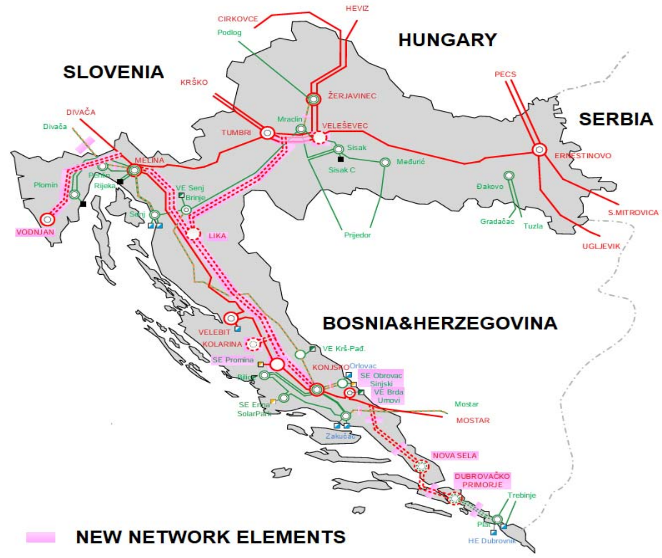

Fig. 3. Proposed topology of new 400 kV corridors for 2035 in the proposal of Croatian NDP 2025-2034 [1.]

D. *Modernization, Resilience-Oriented Refurbishment, And Grid-Enhancing Technologies*

Modernization is a major NDP component because many 220/110 kV assets are at or beyond nominal lifetime [1]. Planned actions include revitalizing 220/110 kV overhead lines and replacing aging 110 kV submarine cables to islands/coastal areas, improving reliability in the most exposed zones [1]. Where new corridors are constrained, HTLS reconductoring, dynamic thermal rating, and targeted reactive compensation (e.g., SVC/STATCOM where justified) increase usable capacity and support voltage control. In the Zagreb area, high fault levels and heavy interface loading require additional studies and advanced measures to manage short-circuit constraints.

E. *Implementation Sequencing Under Uncertainty*

Implementation sequencing defines the order and timing of measures, prioritizing actions that mitigate N-1 risks and have long lead times, while staging later reinforcements to match the maturity of connection requests and realized demand. Key uncertainties include RES realization, regulatory schedules, financing availability and climate stress on critical corridors.

In summary, Croatia's NDP combines internal 400 kV reinforcements, targeted interface upgrades, modernization & revitalization, and grid-enhancing technologies (HTLS, DLR etc.) to address the constraint profile identified in Section III. Because Croatia is both strongly interconnected and geographically elongated, solutions must manage not only capacity limits but also controllability under high transit and stressed seasonal conditions. Against this backdrop, Section V assesses the submarine HVDC option as a strategic controllability and interconnection measure, clarifying its limits and the additional planning insight.

V. Submarine HVDC Option

A potential Croatia-Italy interconnection project could represent a strategic opportunity to enhance regional energy security, market integration, and renewable energy utilization across the Adriatic Sea, due to its shallow waters and a relatively short distance. Given that the project is being evaluated as part of Med-TSO's Master Plan of interconnections [4] (association of Mediterranean TSOs), as an exploratory project planned for 2040, Croatian TSO HOPS, in cooperation with experts from Energy Institute Hrvoje Pozar (EIHP) conducted additional analyzes in the form of a pre-feasibility study with different case scenarios, completed at the end of 2025 [5.].

Study assesses the technical, market, economic-financial, spatial-environmental, and regulatory conditions for a potential - new ±525 kV HVDC submarine interconnection between Croatia and Italy with a 1000 MW transfer capacity. Two route variants are considered and examined: a southern route (Promina, HR – Fano, IT; ~235 km subsea) and a northern route (Vodnjan, HR – Porto Tolle, IT; ~112 km subsea). Both options comprise VSC converter stations at 400 kV and a bipolar submarine cable, with associated onshore connections.

The HVDC option is strategic because a VSC link adds controllable transfer capability and can help manage regional congestion patterns and stress events (e.g., import support during coastal peaks or export absorption during high RES). However, it is insufficient on its own: Croatia's dominant bottlenecks are primarily internal (north–south transfer and coastal interface constraints), so a 1 GW interconnection cannot substitute for the internal 400 kV "spine" reinforcements required to preserve N-1 margins and voltage adequacy.

The study [5] shows great potential for regional security and recommends advancing to a joint HR–IT phase, align with the Italian TSO, refine technical parameters and routing, quantify bilateral benefits, and structure EU co-funding, after which TSOs can take final strategic and investment decisions on technical, financial and timeline details.

VI. Conclusions And Transferable Lessons

Croatia's transmission system is entering a period of accelerated reinforcement and modernization driven by high RES growth, electrification, new large loads, and strong cross-border exchanges, while much of the 400 kV backbone and 220/110 kV assets are approaching end of life. Applying the planning framework in this paper indicates that the binding limitations are primarily internal (north–south transfer capability and coastal interfaces), but their severity is strongly affected by regional transit flows and seasonal demand patterns.

Key takeaway of this paper is that in small, strongly interconnected systems, the decisive planning step is not "how much RES will connect," but which constraint binds first under stressed seasonal and high-transit conditions, and how fast it can be relieved with a staged portfolio. Discussion-worthy implications is that internal transfer capability remains the prerequisite for successful market integration. Interconnections and HVDC help most when internal bottlenecks are already addressed. Uncertainty should be operationalized as sequencing gates (realization/ permitting/ finance/climate), not just acknowledged.

Transferable lessons for other small, strongly interconnected systems are: explicitly link policy targets and the connection pipeline to constraint categories (N-1 thermal, voltage, short-circuit, and controllability) using a small set of stressed seasonal and high-transit scenarios; complement corridor investments with controllability and voltage-support solutions where cross-border flows can dominate internal loading; and embed climate resilience (derating, outage exposure, restoration constraints) in both sizing and prioritization.

Delivery remains sensitive to RES realization, NRA and permitting timelines, and financing availability, underscoring the need for phased implementation, robust risk management, and proactive stakeholder engagement in line with European grid acceleration initiatives [6], [7].

This paper has a relevance beyond Croatia. Namely, the same planning logic applies to US regions where RES and new loads are geographically separated from major demand centers and a limited number of bulk corridors become binding. For example, CAISO's experience with north–south interface constraints [8], high variable renewables [9], and growing wildfire and heat exposure mirrors Croatia's need to combine new transfer capability with controllability and resilience measures. Similarly, New England's coastal peaks, interregional dependence, and offshore wind-driven reinforcements reflect the value of using stressed seasonal scenarios to map policy-driven build-outs to thermal, voltage, and deliverability constraints.

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