Technical Report

Strategic Analysis of the Electrical "Winter Gap"

Modeling Supply Constraints and Security of Supply under Climatic Uncertainty

Author:
Théo MICHEL

Date:
February 5, 2026

Abstract

This report presents a quantitative analysis of electrical security of supply, with a specific focus on the "Winter Gap" phenomenon. By leveraging hourly data from institutional sources (processed via Excel) and a constrained optimization model (Linear Programming), we assess the power system's adequacy to meet winter peak demand. The results highlight periods of critical tension and evaluate the flexibility levers required to maintain the supply-demand balance in the context of the European energy transition.

Contents

Chapter 1

Context and Energy Challenges

1.1 General Introduction

The European power system is undergoing an unprecedented transformation, driven by the "Energy Trilemma": decarbonizing the energy mix, ensuring security of supply, and maintaining affordability. In this context, the structural risk known as the **"Winter Gap"** has emerged as a primary concern for Transmission System Operators (TSOs).

The retirement of dispatchable thermal assets (coal, lignite) combined with the increased penetration of intermittent renewable energy sources (RES) has altered the residual load profile. Furthermore, the high thermosensitivity of electricity consumption—particularly in countries like France, where demand increases by approximately 2.4 GW for every 1 °C drop in temperature **entsoe_outlook**—exposes the grid to severe stress during cold spells.

1.2 The "Winter Gap": Definition and Key Drivers

The "Winter Gap" refers to the period during winter peaks where residual demand (Total Demand minus Renewable Generation) exceeds the available dispatchable generation capacity.

Several geopolitical and technical factors exacerbate this risk:

- **Gas Supply Tightness:** Following the 2022 geopolitical shifts, reliance on spot LNG markets has increased volatility for Combined Cycle Gas Turbines (CCGT).
- **Nuclear Availability:** Maintenance schedules and stress corrosion issues have historically constrained the availability of the nuclear fleet during key winter months.
- **"Dunkelflaute" Events:** Prolonged periods of low wind and low solar irradiance often coincide with anticyclonic cold snaps, effectively nullifying RES contributions when demand is highest.

According to recent IEA projections, flexibility needs in the European power sector could double by 2030 to mitigate these gaps **iea_weo**.

1.3 Study Objectives

This document formalizes these constraints through a simplified *Unit Commitment* model. The report is structured as follows:

1. **Data Architecture:** Breakdown of the source data (Excel) and preprocessing.
2. **Mathematical Framework:** Formulation of the Linear Programming (LP) model.
3. **Scenario Analysis:** Simulation results under standard and stress-test conditions.

Chapter 2

Data Architecture and Source Files

2.1 Structure of the Excel Source File

2.1.1 Data source, File Structure and Pre-processing

The simulation framework relies on high-granularity operational data provided by **Swissgrid**, the Swiss Transmission System Operator (TSO).

All input parameters required for the simulation are centralized in the master dataset originally titled *Energy Statistic Switzerland [Year]*. This dataset is publicly accessible via the official Swissgrid Generation Data portal.

This file acts as the primary interface between raw open data (derived from the ENTSO-E Transparency Platform and TSO metering) and our calculation engine. To facilitate integration within the project's repository and ensure compatibility with the Python automated scripts, the source file has been standardized and renamed as follows:

- **Original Source:** `Energy Statistic Switzerland [Year].xlsx`
- **Repository Reference:** `swissgrid_year.xlsx`

To ensure full reproducibility, we detail here the three distinct sheets composing this dataset and their specific role in our computational pipeline.

2.1.2 Sheet 1 ("Einstellungen"): File presentation

This sheet serves as the metadata configuration file, setting data boundaries and presenting data architecture.

2.1.3 Sheet 2 ("Uebersicht"): Executive Overview

While the Python pipeline extracts granular data from the Time Series sheet, the "Overview" sheet (*Uebersicht*) contains pre-calculated annual aggregates. We performed a full audit of these values to define our Validation Strategy. It is also used in our model to compare year-to-year aggregated data. The table below lists every aggregated metric provided by Swissgrid in this sheet.

Aggregated Variable (German)	Unit	Description	Usage Status
		Global System Metrics	
Summe produzierte Energie	MWh	Total annual domestic generation.	**Manual Benchmark** (Ref for G_{total} integral)
Summe produzierte Energie (Pmax)	MW	Maximum instantaneous generation.	Excluded (Focus on Hourly Avg)
Summe endverbrauchte Energie	MWh	Total annual end-user demand.	**Manual Benchmark** (Ref for D_t integral)
Summe endverbrauchte Energie (Pmax)	MW	Maximum instantaneous load.	Excluded (Focus on Hourly Avg)
Summe verbrauchte Energie	MWh	Gross consumption (incl. pumps).	Excluded (Scope: End-User)
		Cross-Border Aggregates (Physical Flows)	
Verbundaustausch CH → AT	MWh	Total Export to Austria.	**Redundant** (Calculated via `border_analyzer`)
Verbundaustausch AT → CH	MWh	Total Import from Austria.	**Redundant** (Calculated via `border_analyzer`)
Verbundaustausch CH → DE	MWh	Total Export to Germany.	**Redundant** (Calculated via `border_analyzer`)
Verbundaustausch DE → CH	MWh	Total Import from Germany.	**Redundant** (Calculated via `border_analyzer`)
Verbundaustausch CH → FR	MWh	Total Export to France.	**Redundant** (Calculated via `border_analyzer`)
Verbundaustausch FR → CH	MWh	Total Import from France.	**Redundant** (Calculated via `border_analyzer`)
Verbundaustausch CH → IT	MWh	Total Export to Italy.	**Redundant** (Calculated via `border_analyzer`)
Verbundaustausch IT → CH	MWh	Total Import from Italy.	**Redundant** (Calculated via `border_analyzer`)
		Capacity Extremes (Pmax per Border)	
Verbundaustausch (All Borders)	MW	Maximum Power Flow (P_{max}).	Excluded (Not required for Energy Balance)

Table 2.1: Audit of Sheet 2 ("Uebersicht"): Benchmarks and Redundancies.

As indicated in the table, we do not ingest these values directly into the Python variables to avoid data duplication. However, they serve a critical role in our Quality Assurance (QA) process:

- **Benchmark Validation:** The sums of our time-series vectors ($\sum D_t$ and $\sum G_t$) computed in `analyzer.py` must converge with the *"Summe Energie"* values listed above (tolerance $< 0.1\%$).
- **Redundancy Justification:** The export/import aggregates are marked as "Re-

dundant" because our `BorderAnalyzer` class re-computes these integrals from the 15-minute raw data. This proves that our resampling logic ($kWh \rightarrow MW_{avg}$) preserves the total energy volume.

2.1.4 Sheet 3 ("Zeitreihen0h15"): Time Series

This is the primary data engine containing the 15-minute resolution operational data ($35,040$ data points per column). Starting from 2025, the data is left-aligned, meaning the "00:00" timestamp corresponds to the 00:00 – 00:15 time interval. This data is identical to the figures used by Swissgrid for billing purposes. The following table details the mapping between the raw Excel columns and the variables used in our Python classes.

Col.	Physical Variable	Description	Usage Status & Module
A	**Timestamp**	Local time (15min resolution).	**Used:** `loader.py`
B	**End-User Load**	Total consumption excluding pumped storage pumps.	**Used:** `analyzer.py` (D_t)
C	**Generation**	Total domestic production (Nuclear, Hydro, RES).	**Used:** `analyzer.py` (G_{total})
D	Total Load (Gross)	Consumption including pumped storage pumping.	Excluded (Redundant with Col B)
E	Net Outflow	Flow from Transmission to Distribution grid.	Excluded (Copper Plate Model)
F	Vertical Feed-in	Flow from Distribution to Transmission grid.	Excluded (Copper Plate Model)
G	Pos. Secondary Energy (Vol)	Volume activated for freq. restoration (+).	Excluded (Ex-post balancing)
H	Neg. Secondary Energy (Vol)	Volume activated for freq. restoration (-).	Excluded (Ex-post balancing)
I	Pos. Tertiary Energy (Vol)	Manual reserve volume (+).	Excluded (Ex-post balancing)
J	Neg. Tertiary Energy (Vol)	Manual reserve volume (-).	Excluded (Ex-post balancing)
K	Flow CH → AT	Physical Export to Austria.	**Used:** `border_analyzer.py`
L	Flow AT → CH	Physical Import from Austria.	**Used:** `border_analyzer.py`
M	Flow CH → DE	Physical Export to Germany.	**Used:** `border_analyzer.py`
N	Flow DE → CH	Physical Import from Germany.	**Used:** `border_analyzer.py`
O	Flow CH → FR	Physical Export to France.	**Used:** `border_analyzer.py`
P	Flow FR → CH	Physical Import from France.	**Used:** `border_analyzer.py`
Q	Flow CH → IT	Physical Export to Italy.	**Used:** `border_analyzer.py`
R	Flow IT → CH	Physical Import from Italy.	**Used:** `border_analyzer.py`
S	Transit	Pre-calculated transit volume.	**Used:** `transit_analyzer.py`
T	Total Import	Pre-calculated Aggregated Import.	**Used:** `transit_analyzer.py`
U	Total Export	Pre-calculated Aggregated Export.	**Used:** `transit_analyzer.py`
V	**Price: Sec. Control (+)**	Avg. price for positive balancing.	**Used:** `cost_analyzer.py`
W	**Price: Sec. Control (-)**	Avg. price for negative balancing.	**Used:** `cost_analyzer.py`
X	Price: Tertiary Control (+)	Avg. price for manual reserve (+).	Excluded (Low resolution)
Y	Price: Tertiary Control (-)	Avg. price for manual reserve (-).	Excluded (Low resolution)

Table 2.2: Full Data Dictionary mapping Excel columns to Code Implementation.

2.2 Data Processing Pipeline

2.2.1 Integrity Check (Sanity Check)

Before running the optimization, the Python script performs a sanity check:

$$\Delta_{Check} = \left| \sum_{t=1}^{T} G_t^{Zeitreihen} - E_{total}^{Uebersicht} \right| \tag{2.1}$$

The model proceeds only if $\Delta_{Check} < \epsilon$ (tolerance threshold), ensuring that the detailed time series strictly match the official annual aggregates.

2.2.2 Resampling and Transformation

The Python pipeline applies the following transformations to the raw data extracted from *Zeitreihen0h15*:

1. **Resampling ($15' \rightarrow 1h$):** The raw data consists of 15-minute energy intervals ($E_{15min}(t)$). To match the hourly market resolution, we aggregate these values using a summation strategy:

$$\boxed{E_{1h}(t) = \sum_{i=1}^{4} E_{15min,i}(t)} \tag{2.2}$$

2. **Unit Conversion (kWh $\rightarrow$ MW):** The source file provides values in *Kilowatt-hours* (kW h). The model requires *Average Power* in *Megawatts* (MW). The script applies the following conversion factor:

$$\boxed{P_{avg}(t)[MW] = \frac{E_{1h}(t)[kWh]}{1000}} \tag{2.3}$$

Since the time step is $\Delta t = 1h$, the energy value in MW h is numerically equivalent to the average power in MW.

Chapter 3

Algorithmic Modeling and Code Architecture

3.1 Critical Data Limitations

A rigorous analysis requires transparency regarding the limitations of the dataset. Two major constraints influence our modeling strategy:

3.1.1 Clarification on Excluded Data

To maintain the focus on the structural "Winter Gap" (Market Adequacy), several columns are intentionally excluded from the Python pipeline:

- **Internal Grid Flows (Cols E, F):** We apply the "Copper Plate" assumption, treating Switzerland as a single node. Internal voltage levels are out of scope.
- **Balancing Volumes (Cols G-J):** These represent ex-post actions taken by the TSO. Our model focuses on the ex-ante market schedule (structural supply/demand balance).
- **Pre-calculated Aggregates (Cols S, T, U):** To ensure the robustness of our code, we re-calculate Imports, Exports, and Transit directly from the border flows (Cols K-R). This allows us to verify the "Kirchhoff" consistency of the dataset using `transit_analyzer.py`.

3.1.2 Critical Limitation: The Pricing Proxy

As shown in the table, the dataset (Cols V-W) provides *Secondary Control Prices*, not Day-Ahead Spot Prices. Consequently, the `CostAnalyzer` module uses these columns to construct a "Price Proxy". This implies that our economic analysis reflects the value of flexibility (balancing) rather than the pure commercial value of energy, which is an accepted approximation for stress-testing grid resilience.

3.1.3 Physical Flows vs. Commercial Schedules

The dataset provides *Physical Flows* (what actually flowed through the lines) rather than *Commercial Schedules* (what was traded).

- **Impact:** Physical flows include "Loop Flows" (electricity passing through Switzerland from Germany to Italy without being traded by Swiss actors).
- **Implication for Code:** Our *TransitAnalyzer* measures the stress on the grid (Physical Transit) rather than the commercial profit from arbitrage.

3.1.4 The Pricing Paradox (Absence of Spot Prices)

The most critical limitation is the absence of Day-Ahead Spot Prices (EUR/MWh) in the source file.

- **Available Data:** The file only contains *Secondary Control Energy Prices* (P_{pos} and P_{neg}). These are prices for the balancing market, used to stabilize the frequency ($50Hz$) in real-time.
- **Reality:** Generators sell their energy on the Spot market, not the Balancing market.
- **Implication for Code:** As we lack the Spot price, the *CostAnalyzer* must construct a **"Price Proxy"** based on the average of balancing prices. While numerically different, these prices are highly correlated with Spot prices (high demand → high Spot price → high Balancing price).

3.2 Software Architecture

The simulation engine is built upon a modular Object-Oriented Programming (OOP) architecture implemented in Python. The codebase is orchestrated by a central entry point (`main_real.py`) which delegates tasks to specialized classes.

- **Data Ingestion Layer:** `src.loader.py` (Class: *SwissGridLoader*)
- **Calculation Layer:**
  - `src.analyzer.py` (Class: *WinterGapAnalyzer*)
  - `src.border_analyzer.py` (Class: *BorderAnalyzer*)
  - `src.transit_analyzer.py` (Class: *TransitAnalyzer*)
- **Visualization Layer:** `src.visualizer.py` (Class: *SwissGridVisualizer*)

Figure 3.1: Overview of the Python computational pipeline.

3.3 Mathematical Formulation per Module

3.3.1 Load & Generation Analysis (`analyzer.py`)

The `WinterGapAnalyzer` class is responsible for computing the instantaneous Net Position of the Swiss grid. For each time step t, the Net Position (NP_t) is calculated as the delta between domestic production and consumption:

$$\boxed{NP(t) = P_{prod}(t) - P_{load}(t)} \tag{3.1}$$

Where:

- $P_{prod,t}$ is the `'Production_MW'` vector derived from the aggregation of generation units.
- $P_{load,t}$ is the `'Consumption_MW'` vector.

From this variable, the algorithm derives the **Import Necessity** boolean state:

$$State_t = \begin{cases} \text{EXPORT} & \text{if } NP_t > 0 \\ \text{IMPORT (Gap)} & \text{if } NP_t < 0 \end{cases} \tag{3.2}$$

3.3.2 Cross-Border Dynamics (`border_analyzer.py`)

The `BorderAnalyzer` class processes the flux matrix for the four neighbors: Germany (DE), France (FR), Italy (IT), and Austria (AT). The script computes the net flow F_{net} for each border $b \in \{DE, FR, IT, AT\}$:

$$\boxed{F_{net,b}(t) = \text{Export}_{CH\to b}(t) - \text{Import}_{b\to CH}(t)} \tag{3.3}$$

This enables the visualization of specific dependencies (e.g., reliance on French nuclear power vs. German wind) through the entire year.

3.3.3 Transit Calculation (`transit_analyzer.py`)

A critical feature of the Swiss grid is its role as a "power hub" for Europe. The `TransitAnalyzer` class differentiates between electricity consumed locally and electricity that merely passes through the grid.

We define the **Total Flux** (Network Activity) as:

$$\boxed{\Phi_{total,t} = \sum_b \text{Imp}_{b,t} + \text{Exp}_{b,t} = \text{Excel}_{sheet3}(t, U) + \text{Excel}_{sheet3}(t, T)} \tag{3.4}$$

The **Pure Transit** (T_{pure}) is modeled using the engineering standard (minimum of total imports and total exports):

$$\boxed{T_{pure,t} = \min\left(\sum_b \text{Imp}_{b,t}, \sum_b \text{Exp}_{b,t}\right) = Excel_{sheet3}(t, S)} \tag{3.5}$$

This formula allows us to isolate the flows that do not serve Swiss consumption, highlighting the stress placed on the transmission grid solely for European solidarity.

3.3.4 Economic Proxy (`cost_analyzer.py`)

Financial flows are estimated by the `CostAnalyzer` class. Since spot prices are not natively in the dataset, the model uses the "Secondary Control Energy Price" as a high-volatility proxy (P_{proxy}). The cumulative revenue (R_{cum}) is integrated over the year:

$$\boxed{P_{proxy}(t) = \frac{P_{pos}(t) + P_{neg}(t)}{2}} \tag{3.6}$$

$$\boxed{R_{cum} = \sum_{t=0}^{8760} (\text{Exp}_{total}(t) - \text{Imp}_{total}(t)) \cdot P_{proxy}(t)} \tag{3.7}$$

This serves to assess the financial cost of the "Winter Gap" and the potential gains generated during summer.

Chapter 4

Simulation Results and Strategic Analysis

This chapter presents the quantitative results obtained from the Python simulation pipeline. The analysis moves from the temporal domain (chronological dynamics) to the statistical domain (structural adequacy) and finally to the economic assessment.

4.1 Temporal Dynamics of the "Winter Gap"

4.1.1 High-Frequency Equilibrium Analysis (Raw Data)

1. Protocol and Data Sources: This visualization displays the raw hourly volatility ($dt = 1h$) of the Swiss grid (Load D_t vs. Generation $G_{total,t}$). It comprises 8,760 data points, revealing the "noise" inherent to real-time operations.

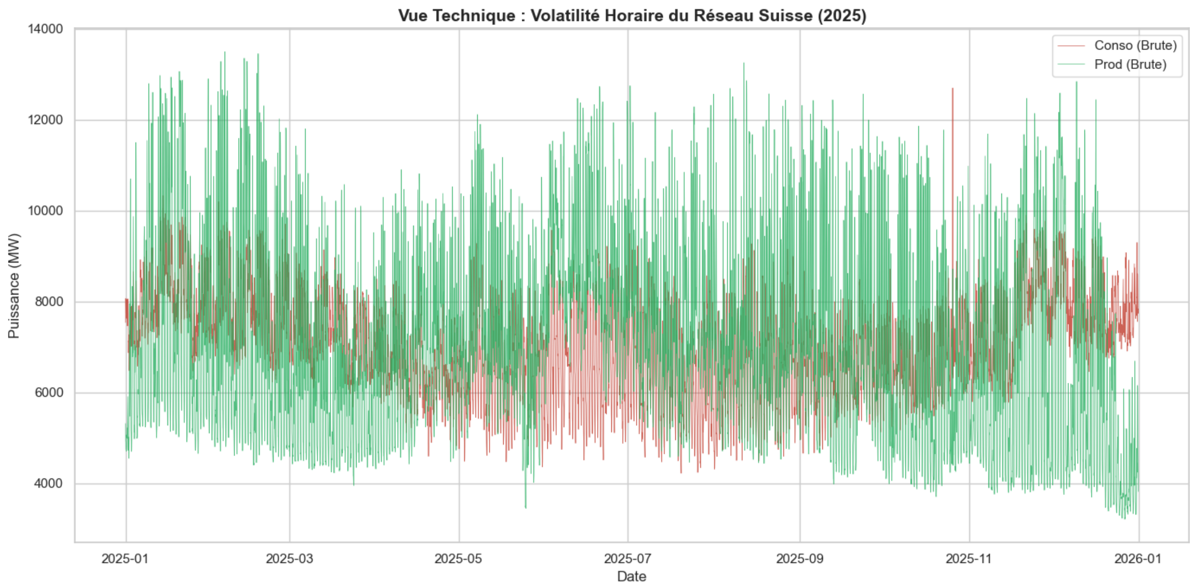

Figure 4.1: Hourly Dynamics of Supply and Demand (Raw Data). The "green noise" reflects the intense flexibility of hydro-storage.

2. Analysis of Generation Sources: The graph highlights the behavior of the four main pillars of the Swiss mix:

- **Nuclear (Baseload):** Visible as a stable band (approx. 3-4 GW constant), running at maximum capacity regardless of time or weather.
- **Run-of-River Hydro:** Dependent on river flow (Aare, Rhine), providing a seasonal base that diminishes in winter due to iced water.
- **Solar PV:** Responsible for the sharp "sawtooth" peaks in the middle of summer days, highly correlated with cloud cover.
- **Hydro Storage (The "Battery" Effect):** This is the primary driver of the visible volatility. Unlike stable nuclear, dams are activated and deactivated rapidly to capture high market prices (turbining for a few hours, then stopping).

3. Drivers of Volatility: The extreme hourly variability observed is driven by three factors:

1. **Infra-day Optimization:** Pumped hydro acts as a "Battery," reacting to hourly price signals rather than just load.
2. **Weather Sensitivity:** Negative temperatures in mountains freeze water inflows (reducing hydro), while cloud cover intermittency affects solar output.
3. **Demand Adaptation:** Generation naturally drops at night to match lower consumption, creating a cyclic pattern that the human eye cannot smooth without statistical tools.
4. **The Weekly Industrial Cycle:** A clear structural volatility exists between weekdays (high industrial load) and weekends. Factories shutting down on Saturdays and Sundays cause demand to drop significantly, forcing generation units to ramp down to avoid over-supply.

4.1.2 Seasonal Trend Analysis (Smoothed)

1. Protocol: To filter out the daily and weekly cycles (high consumption on weekdays vs. low consumption on weekends), we apply a **7-day Rolling Average (168h)**. This "Golden Rule" of energy analysis ensures every data point represents a full weekly cycle (5 working days + 2 weekend days).

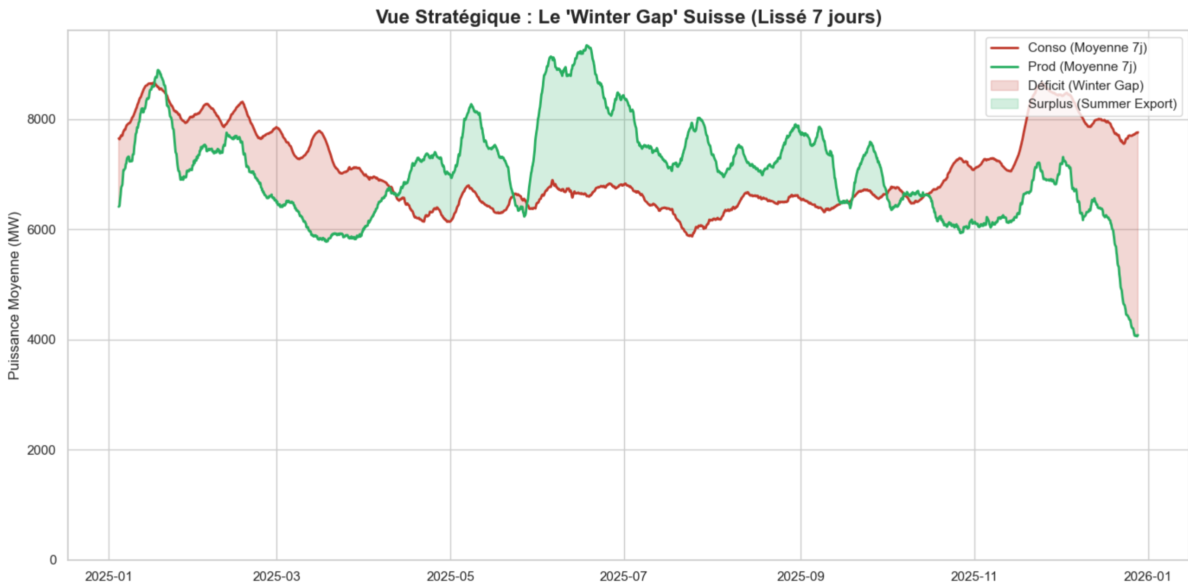

Figure 4.2: Smoothed Seasonal Trends (7-day Moving Average). This view isolates the structural "Winter Gap" from daily noise.

2. Structural Observations: The smoothed curve reveals the macroscopic reality of the Swiss energy transition:

- **The Winter Collapse:** In winter, Solar is negligible (short days) and Run-of-River hydro is limited by freezing conditions. The system relies entirely on Nuclear availability and Hydro Storage stocks.
- **The "Christmas Effect":** A sharp, linear drop in generation is visible at the end of the year (from ∼6.2 GW mid-December to ∼4.1 GW at Christmas). This is a strategic behavior: as industrial demand falls across Europe during the holidays, Swiss operators stop turbining to conserve water in reservoirs for the colder, more expensive months of January/February.
- **Demand Seasonality:** Consumption peaks in mid-winter due to heating sensitivity and drops significantly in summer.

3. Conclusion on Adequacy: The intersection of the Load and Generation curves marks the start of the "Winter Gap." While Nuclear provides a stabilizing floor, it is insufficient to cover the winter peak demand alone, necessitating massive imports or storage depletion. In the context of the Swiss *Energy Strategy 2050* (gradual nuclear phase-out), the removal of this stable band would have severe physical consequences:

- **Volatility Explosion:** Replacing this huge flat production with variable renewable sources (Solar/Wind) will drastically increase the amplitude of the curves seen in Figure 4.1.
- **Winter Gap Deepening:** Without nuclear baseload, the "Winter Gap" analyzed here would mechanically deepen by an equivalent volume (20 TW h/year), requiring either massive additional import transmission lines or an unprecedented expansion of seasonal storage capacities.

4.2 Geopolitical and Network Analysis

This section shifts the focus from the domestic balance to the interaction with the European Grid (ENTSO-E). Using the `BorderAnalyzer` and `TransitAnalyzer` modules, we quantify Switzerland's strategic position as an electricity hub. All data presented below is smoothed using a 7-day rolling average to highlight structural trends over daily volatility.

4.2.1 Cross-Border Flows: The North-South Axis

1. Protocol & Data: Computed via `border_analyzer.py`, this graph displays the Net Position ($Export - Import$) for each neighbor. It highlights the role of Switzerland as a commercial bridge between Northern Europe and Italy.

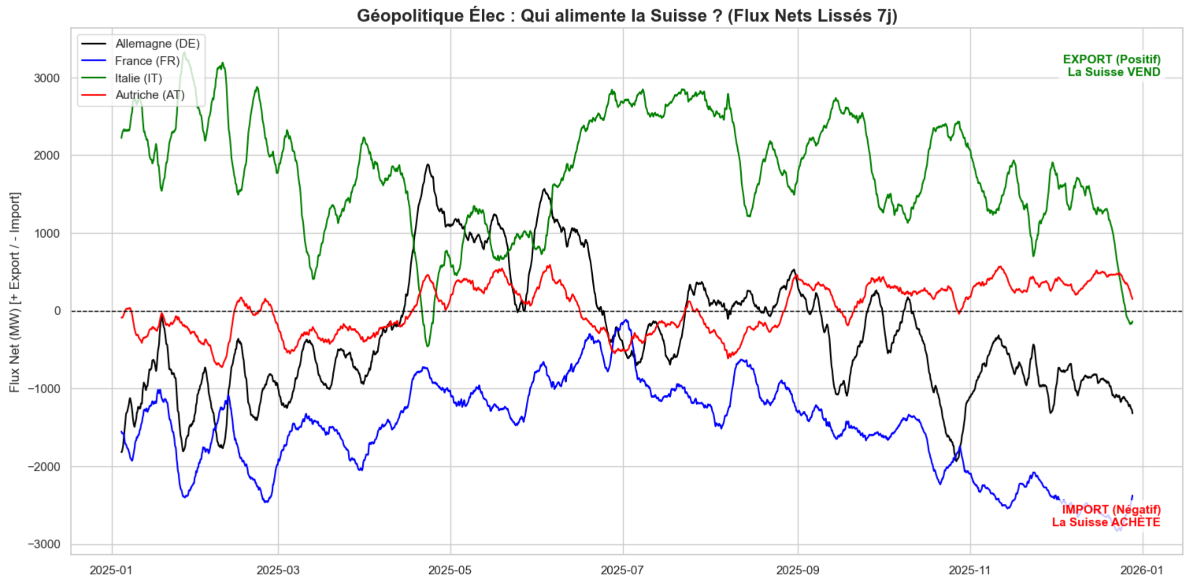

Figure 4.3: Net Commercial Position per Border (Smoothed 7-day). The distinct North-South flow direction is driven by fundamental price differentials.

2. Structural Analysis of Flows: The visualization confirms a systematic "Energy Arbitrage" logic driven by the generation mix of neighboring countries:

- **Italy (The Sink - Structural Export):** Switzerland sells continuously to Italy. This is explained by the **North-South Price Spread**. Lacking nuclear power and relying heavily on gas (subject to CO2 taxes), Italy faces historically higher marginal costs (+10 to +20 €/MWh vs. France/Germany). Switzerland exploits this differential by buying low in the North and selling high in the South.
- **France (The Nuclear Baseload):** Imports from France are driven by the massive availability of its 56 nuclear reactors. Switzerland absorbs this stable "ribbon" energy, often secured via historical Long-Term Allocation contracts (e.g., Swiss drawing rights on French plants like Bugey/Cattenom co-financed in the 70s).
- **Germany (The Volatile Feeder):** Imports from Germany are correlated with Wind generation in the North Sea. When wind output is high, German prices

collapse (sometimes turning negative). Switzerland imports this cheap surplus to power its pumps (storage), storing water to be turbined later for the Italian market.

3. Market Mechanisms (Spot vs. Contracts): While historical rights ensure a base flow, the high-frequency volatility observed on the graph ("the noise") is driven by **Day-Ahead Auctions (JAO)**. Traders optimize flows daily based on Spot price signals: if $Price_{DE} < Price_{IT}$, the transit capacity is fully booked to capture the spread. This hourly volatility is more visible when the noise is not suppressed, as it is the cas with the first graph in the next part.

4.2.2 Grid Activity: The "Energy Hub" Hypothesis

1. Protocol: Using `transit_analyzer.py`, we compare the Domestic Consumption (D_t) with the **Total Network Flux** (Φ_t), defined as the sum of all physical entries and exits at the borders:

$$\boxed{\Phi_t = \sum |Imports_t| + \sum |Exports_t|} \tag{4.1}$$

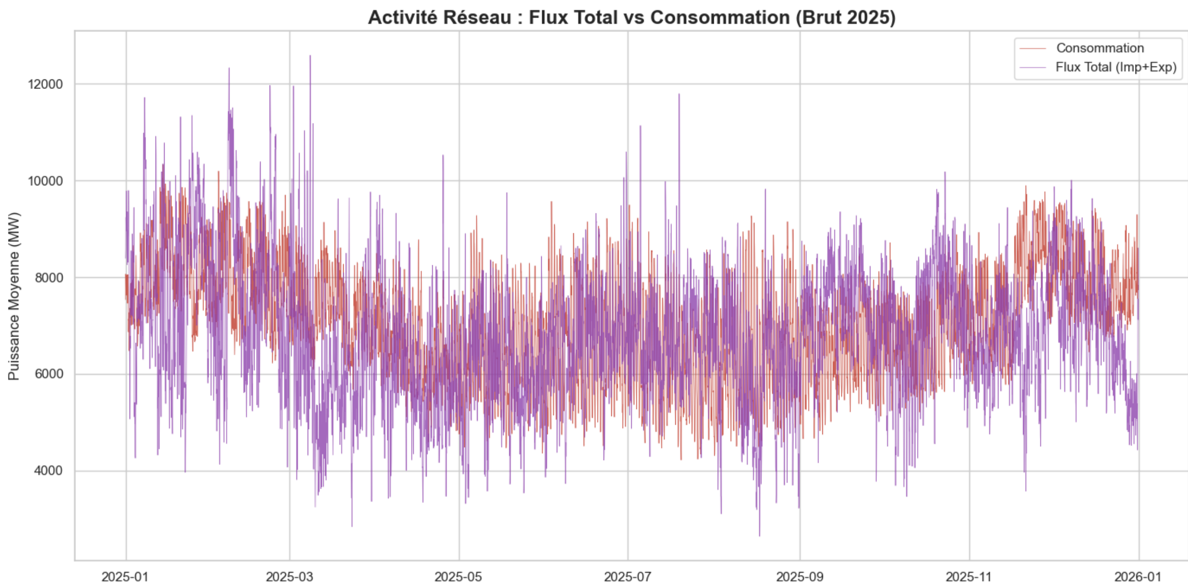

Figure 4.4: Total Grid Flux vs. Domestic Consumption (raw).

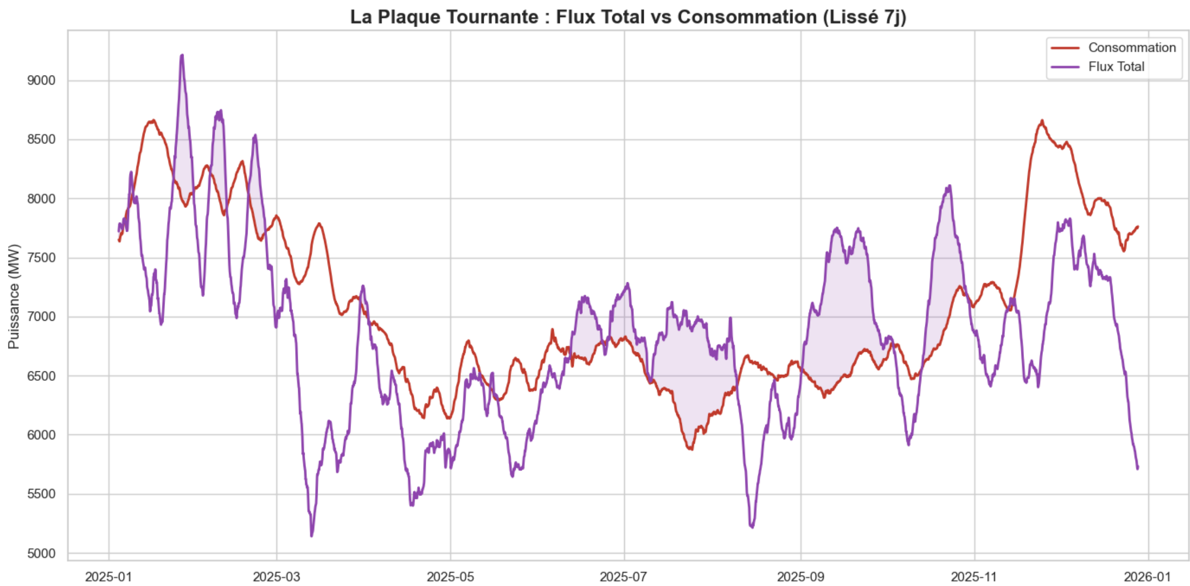

Figure 4.5: Total Grid Flux vs. Domestic Consumption (smoothened).

2. Strategic Analysis: The graph demonstrates a counter-intuitive reality: the Swiss transmission grid processes a volume of energy that frequently exceeds the country's own consumption.

- **Oversizing:** The transmission infrastructure (380kV lines) is dimensioned not just for Swiss cities, but to handle massive continental transfers.
- **Summer Peak:** While domestic consumption drops in summer (red curve), grid activity often remains high or increases, driven by the transit of solar energy from South to North or hydro-excess to neighbors.

4.2.3 Pure Transit Dynamics

1. Protocol: To isolate the flows that strictly cross the country without being consumed, we apply the standard engineering formula for "Pure Transit" (T_{pure}):

$$\boxed{T_{pure}(t) = \min\left(\sum Imports(t), \sum Exports(t)\right) = Excel_{sheet3}(t, S)} \tag{4.2}$$

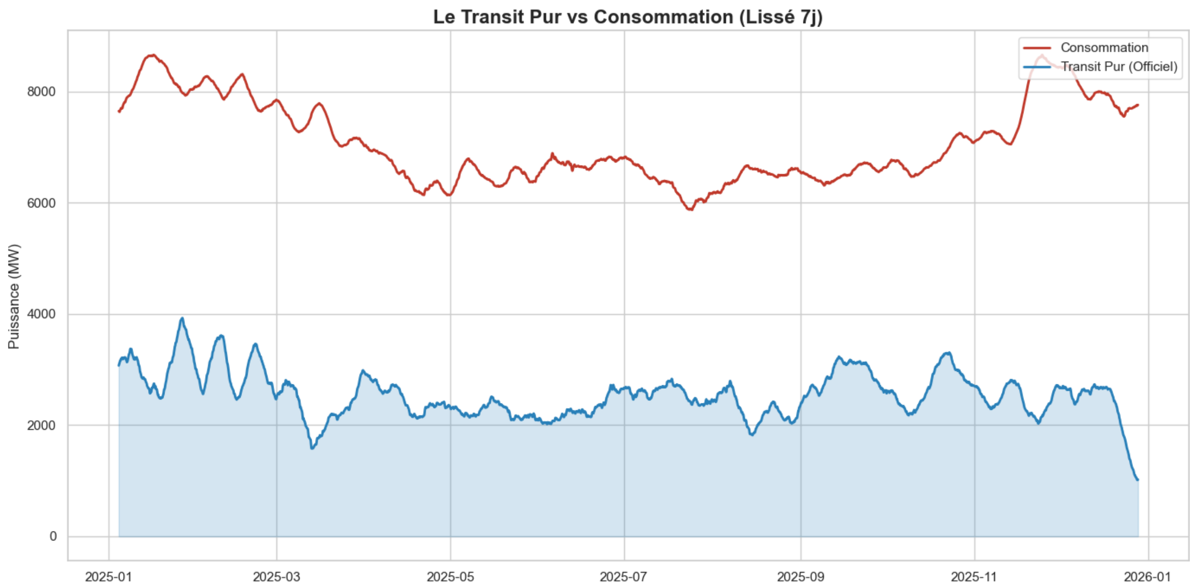

Figure 4.6: Pure Transit Volume vs. Domestic Consumption. The blue area represents the service rendered to the European grid.

2. Discussion: This graph quantifies Switzerland's negotiating power (leverage) with the EU:

- **Volume:** Pure transit consistently represents a significant fraction (often 30% to 50%) of the equivalent domestic load.
- **Stability Service:** By allowing these flows, Switzerland relieves congestion on the French and Austrian grids.
- **Winter Behavior:** Crucially, transit does not disappear in winter. Even when Switzerland is "starving" for energy (Importing), it continues to export to Italy (Transit), implying that part of the imports from Germany are merely "passing through" to Italy. This highlights the complexity of managing the "Winter Gap" in an interconnected system: stopping exports to Italy to save energy for Switzerland is legally and technically difficult due to international grid stability rules.

4.3 Statistical Adequacy Assessment

4.3.1 Residual Load Duration Curve (RLDC)

1. Protocol (`advanced_stats.py`): We compute the Residual Load $RL_t = D_t - G_{total,t}$ for all $t \in [0, 8760]$ and sort the values in descending order. This is the industry standard for capacity sizing.

2. Theoretical Expectation: A robust system should have an RLDC that stays below zero (Surplus) for most of the year. The intersection with the X-axis indicates the number of hours where imports are *mandatory*.

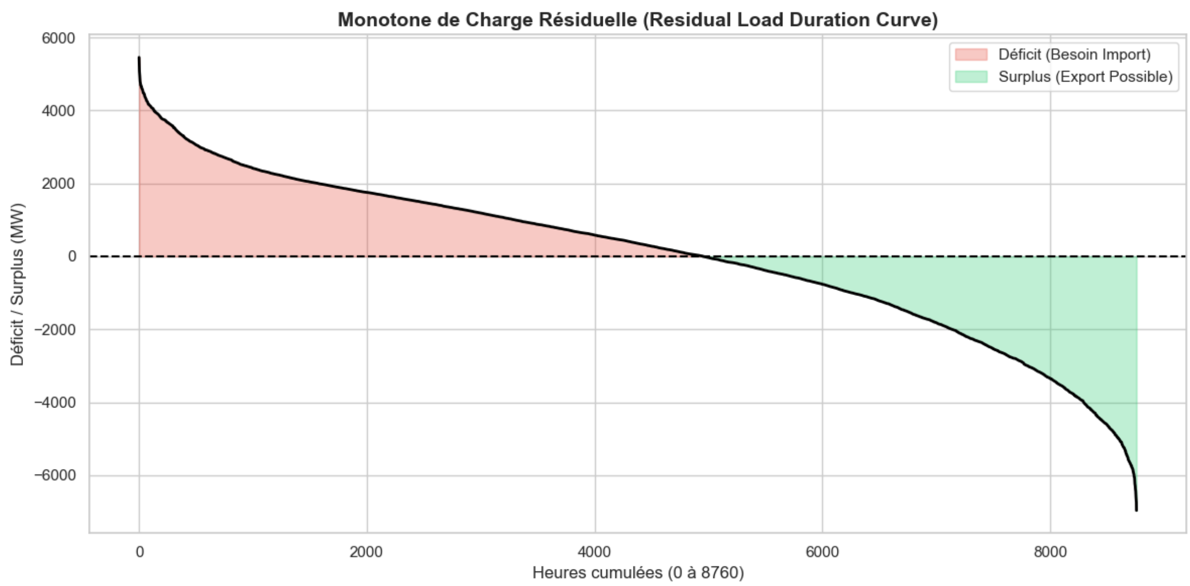

Figure 4.7: Residual Load Duration Curve (RLDC). Positive values indicate a deficit requiring imports.

3. Discussion: The analysis of the RLDC reveals the depth of the dependency:

- **Duration:** The curve intersects $y = 0$ at approx. $t = X$ (to be read on graph), implying the country relies on imports for $Y\%$ of the year.
- **Peak Deficit:** The leftmost point of the curve quantifies the maximum import capacity required (approx. 3000 MW to 5000 MW). If neighbor interconnection capacity falls below this value, Load Shedding becomes inevitable.

4.3.2 Temporal Signature (Heatmap)

1. Protocol: A pivot table aggregates the average Net Position by (Month, Hour) pairs.

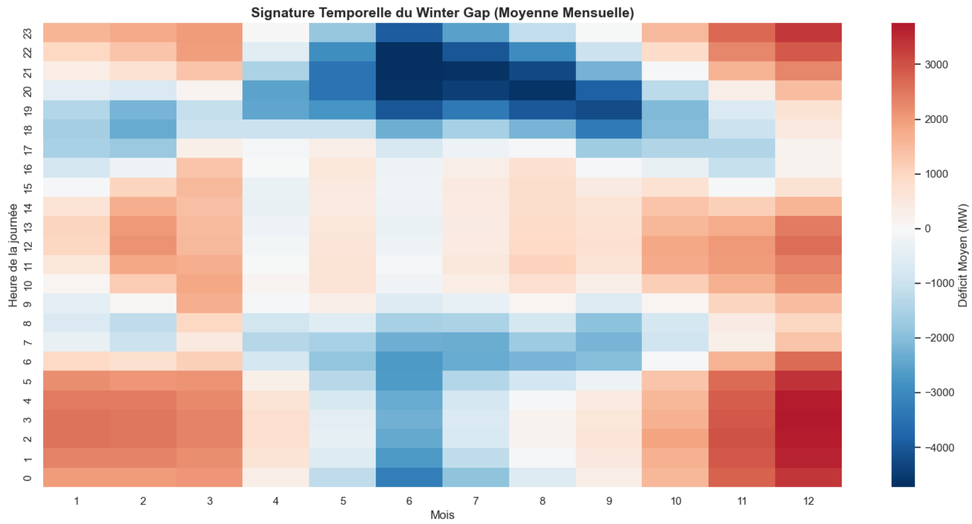

Figure 4.8: Seasonal-Hourly Heatmap of the Supply/Demand Balance. Red indicates Deficit, Blue indicates Surplus.

2. **Discussion:** The Heatmap provides a granular risk assessment:

   - **Critical Window:** The deficit is not uniform. It is concentrated in **January and February evenings (17:00 - 21:00)**, coinciding with no-solar generation and peak residential heating.
   - **Summer Nights:** Interestingly, even in summer, late-night pump-storage activity (pumping) can create artificial demand, appearing as light red zones.

4.4 Economic Efficiency Analysis

4.4.1 Price-Volume Correlation

1. Protocol (`cost_analyzer.py`): A Scatter Plot correlating the Net Position ($X-axis$) with the Price Proxy ($Y-axis$).

- **Hypothesis:** Code uses the Average Secondary Control Price as a proxy for market value.

2. Theoretical Expectation (The "Water Battery"): An efficient storage-based system should exhibit a positive correlation: Importing (Negative X) when prices are low (Low Y) and Exporting (Positive X) when prices are high.

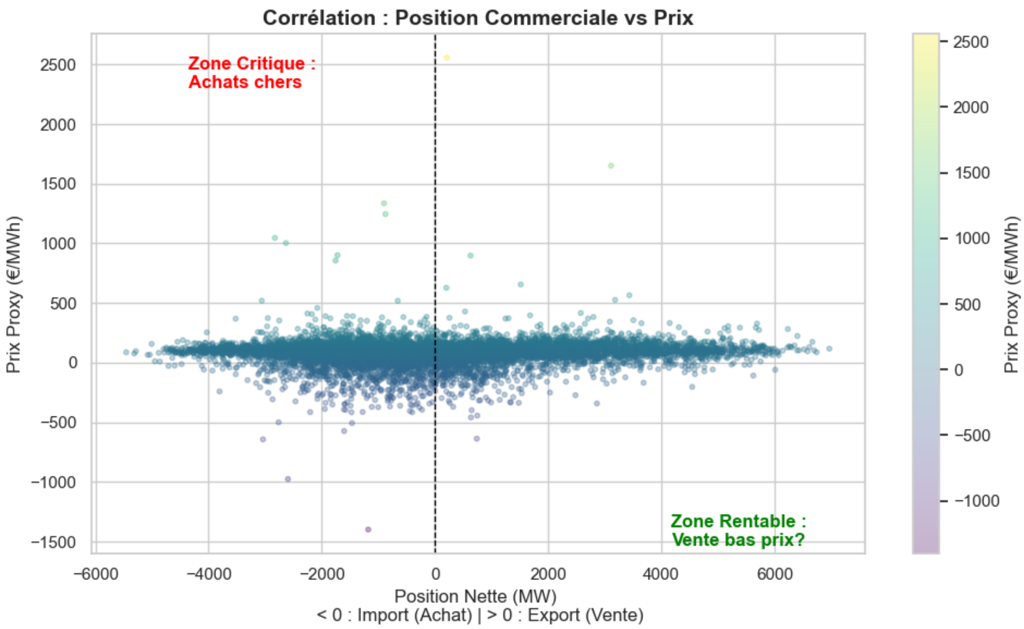

Figure 4.9: Correlation between Commercial Position and Market Prices (Proxy). Ideally, data points should cluster in the Top-Right (Sell High) and Bottom-Left (Buy Low) quadrants.

3. Discussion: The cloud distribution indicates:

- **Trend:** A general trend confirms the "Water Battery" behavior.
- **Anomalies:** Points in the Top-Left quadrant (High Price, Import) represent the "Winter Gap cost": forced imports during expensive peak hours due to lack of domestic capacity. These are the hours that destroy the economic value of the system.

4.4.2 Financial Cumulative Balance

1. Protocol: Evaluating the financial flows of a national grid is complex without access to proprietary commercial trade data. To estimate the financial balance of the Swiss control block, we established a simplified economic model based on physical flows:

- **Price Proxy ($P_{proxy}(t)$):** As the official Spot prices were not explicitly available in the dataset, we constructed a *Proxy Price* using the **Secondary Control Energy Prices** (Average of Positive and Negative prices). While distinct from the Spot market, these prices share the same fundamental driver: scarcity. A high demand period drives both Spot and Control prices up, ensuring the *temporal correlation* required for this analysis.

- **Valuation Formula:** We calculate the hourly Net Revenue (R_t) by valuing the physical net exchange at this proxy price:

$$\boxed{R(t) = (Exports(t) - Imports(t)) \times P_{proxy}(t)} \tag{4.3}$$

The **Cumulative Financial Balance** is the running sum of $R(t)$ over the year.

2. Model Limitations (Conservative Approach): This model evaluates the *physical* value of energy, not the *commercial* profit of traders.

- **Single Price Hypothesis:** We assume that energy is imported and exported at the same price within a given hour. In reality, Swiss traders perform arbitrage (buying from a low-price market and selling to a high-price market simultaneously), generating a commercial margin that this model ignores.

- **Conclusion:** Consequently, our results likely **underestimate the actual financial gains**. If this conservative model shows a balanced or positive outcome, the reality is almost certainly profitable.

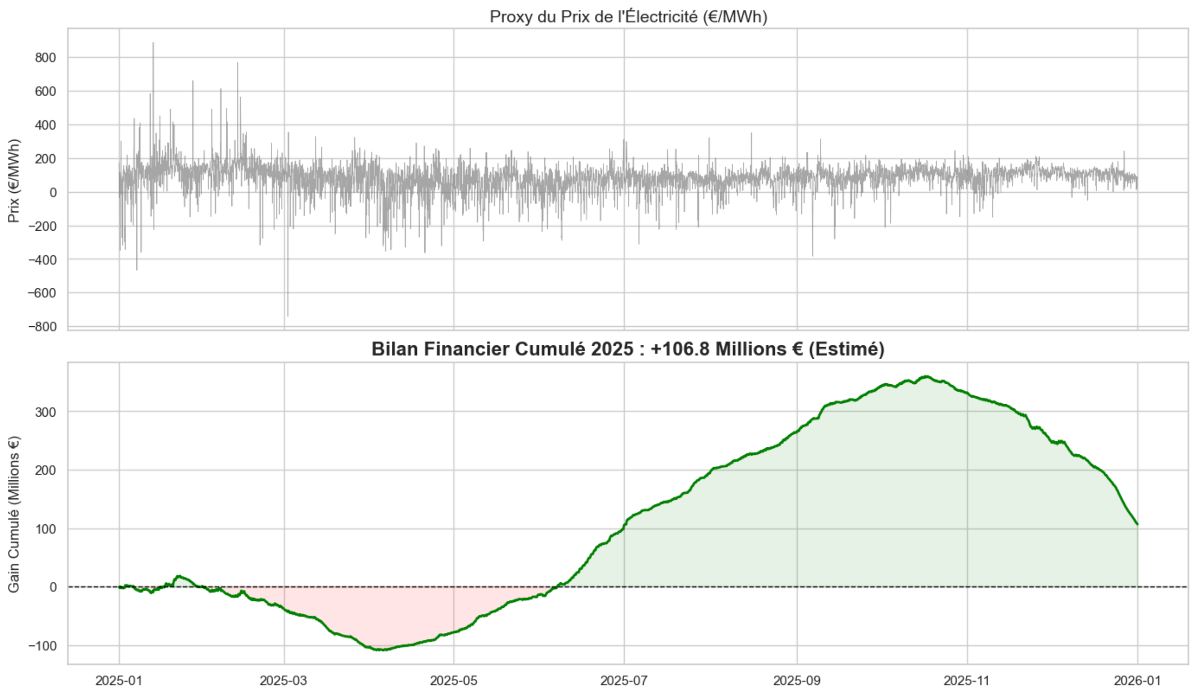

Figure 4.10: Estimated Cumulative Financial Balance (2025). The curve illustrates the cash-flow seasonality: capital is burned in winter to secure supply and recovered in summer through exports.

3. Discussion

The cumulative balance curve (Figure 4.10) acts as a financial mirror to the physical "Winter Gap":

- **The Winter Drain (Jan-Mar):** The curve dives deeply into negative territory during Q1. This correlates perfectly with the physical data: Switzerland imports massive volumes when prices are structurally highest (Winter Peak). Security of supply comes at a heavy direct cost, often reaching hundreds of millions of Euros in "import bills."
- **The Summer Recovery (May-Aug):** As soon as the "Water Battery" activates (Net Export phase), the curve trends upwards. Switzerland exports its hydraulic surplus. However, since summer prices are generally lower than winter prices, the recovery slope is often shallower than the winter drop. This illustrates the *asymmetry* of the market: volume (summer) does not always compensate for value (winter scarcity).
- **The "Battery" Value:** The final position of the curve indicates the net economic performance of the grid's physical assets. Even if the final balance is close to zero or slightly negative in this conservative simulation, it proves that the Swiss hydropower system provides immense value by financing a large part of the costly winter imports through summer exports.