



The Average Day Illusion: Why Full Chronology is Essential for Renewable Power System Planning

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The Average Day Illusion: Why Full Chronology is Essential for Modern Power System Planning

Executive summary

As power systems transition toward high shares of variable renewable energy (VRE), the tools and methodologies used to plan them must evolve. Historically, simplifications like load blocks and typical days were unavoidable due to limited computational capacity and the stable nature of fossil-dominated systems. However, these approaches are no longer acceptable. They distort key system dynamics, underestimate the value of flexibility, and can lead to costly mis-investments.

This whitepaper demonstrates, through both conceptual arguments and quantitative exercises, that:

- Load blocks and typical days are unable to represent the time-linked behavior of storage and renewables.
- Errors introduced by these methods grow with renewable penetration and can reach 40%.
- Full chronological modeling is now computationally feasible and necessary, especially when planning investments in the hundreds of millions or billions.
- Even with simplifications, traditional models remain slow—taking several hours or days to run—raising serious questions about their practicality.

We argue that full chronology must become the new standard in power system planning. This is no longer a technical luxury — it is a foundational requirement.

Introduction: The Legacy of Load Blocks and Typical Days

Power system planning tools originated in a context where fossil fuels dominated the energy mix and computational power was scarce. In this setting, simplifications like load duration curves, load blocks, and representative typical days, were sufficiently accurate. The systems being modeled were largely stable, with predictable demand profiles and dispatchable generation. Modeling every hour of a year, let alone multiple years, was simply not an option.

These simplifications were baked into the architecture of many tools used today in regulatory, utility, and donor-sponsored planning processes. But while the power systems of the world have transformed, many of the planning tools have not.

With the rise of VRE—solar, wind, and hybrid systems—temporal variability and uncertainty have become of paramount importance. Storage technologies, especially batteries, require chronological modeling. Yet many tools model the future using methods built for the past.

This creates a dangerous mismatch between the complexity of the system and the fidelity of the model—a mismatch that, as we will show, leads to systematic errors in investment and policy recommendations.

The Chronological Crisis in a Renewable Era

Variable renewable resources such as solar PV and wind fluctuate over timescales ranging from hours to seasons. Their generation patterns are tightly interdependent to storage and import/export for balancing. Capturing this interaction properly requires a chronological representation of demand, generation, and system constraints.

For example:

- Solar PV has sharp intraday cycles and often saturates the system in mid-afternoon hours.
- Batteries rely on sequential storage and discharge cycles that must be modeled hour-to-hour.
- Wind exhibits correlated variability over regions and days, making system-level balancing nontrivial.

Ignoring these aspects results in distorted conclusions. Storage may appear less valuable than it is. Flexible generation may be undervalued. Grid bottlenecks may go undetected. In short: systems designed under non-chronological assumptions are likely to fail in practice.

Why Load Blocks Fail in the Presence of Short-Term Storage

Load blocks—groupings of hours with similar demand levels—eliminate temporal chronology entirely. While useful for simple dispatch modeling, they fundamentally break the logic required to simulate storage. Batteries operate by storing energy in one hour and discharging it in another. Without sequential information, the charging and discharging process of battery storage, or any other storage equipment, cannot be properly represented.

This has strong implications for modeling solar PV, which is often coupled with batteries. Solar generation ramps up and down rapidly during the day, producing excess midday

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energy and evening shortages that change in intensity every day. A model using load blocks cannot capture this daily charging and discharging sequence that changes daily, especially:

- The saturation of solar generation during mid-day hours
- The need for evening discharge from batteries
- The interaction between solar variability and system ramping

As a result, the true value and operational requirements of solar and battery configurations are obscured. In regions where solar PV is the cheapest resource, as is now the case in much of the world, this distortion leads to flawed investment signals and an underestimation of system flexibility needs.

Typical Days: Better, but Still Fatally Flawed

To address the shortcomings of load blocks, some models introduce “typical days” — representative daily profiles chosen through clustering or statistical sampling. This approach reintroduces chronology within a day, which helps modeling storage and renewables over full day cycles. However, it still fails to represent:

- Extreme days (e.g., days of wind drought and/or of high demand)
- Sequences of cloudy or windless days
- Grid congestion between areas that have different generation or demand patterns

System peaks and critical stress periods may not be captured at all. Interactions between days are entirely excluded, leading to incorrect assumptions about storage utilization and dispatch costs. In short, typical days improve upon load blocks but still fall short—particularly as renewable shares rise above ~40%.

High Stakes, Hidden Errors: Planning with Blindfolds

The risks of using oversimplified models are not only theoretical. Power system planning studies guide multi-decade infrastructure investments. Transmission corridors, generation capacity additions, and grid codes are defined based on the results of these studies.

At high renewable shares, simplifications can lead to:

- Underinvestment in storage
- Underestimation of transmission needs
- Misrepresentation of reserve and ramping requirements

As you will see in the simulation cases presented below, these errors can in some cases exceed 40% in installed capacity, renewable curtailment, or grid expansion projections. Worse, these errors are not quantifiable, as existing tools are unable to do the calculations

using full chronology. The user cannot know how far off the result is, because the simplification hides the counterfactual.

When decisions involve hundreds of millions or billions of dollars, and long-lasting regulatory commitments, this level of uncertainty is not acceptable.

The Paradox of Complexity: Simplified Models, High Costs and Long Run-Times

One of the primary justifications for using simplifications such as load blocks and typical days is that full-chronology models are presumed to be too slow. However, this assumption no longer holds. Even with heavy simplifications, most legacy tools still take several hours to solve a single scenario. In some long-term planning contexts—especially with multiple regions or scenarios—runtimes can extend to days. This performance bottleneck persists despite massive advances in computing technology.

This leads to a paradox: why are we accepting these strong simplifications, slow performance and high costs?

Modern tools using high-performance computing and parallelized algorithms can solve full-chronology, multi-decade problems in under 30 minutes, even for large systems. Thus, the long runtimes of legacy models are not due to problem size but to outdated software architecture.

The Cost Barrier for Emerging Markets

Beyond runtime, cost remains a major barrier—especially in emerging economies. Many commercially available planning tools carry license fees that exceed the annual cost of employing 1 to 10 full-time utility engineers. This forces utilities and government agencies in lower-income countries to make stark trade-offs between developing internal capacity and outsourcing analysis. If planning tools are inaccessible or unaffordable, countries are left either using inadequate models and/or relying on black box results they cannot validate.

Modern, open, or affordable high-performance alternatives exist and should be prioritized by donors, regulators, and system operators seeking to enable robust long-term planning at scale.

The Fallacy of Hourly Post-Processing: Why a Flawed Baseline Leads to Misleading Results

It is often argued that even if capacity expansion modeling uses simplifications like load blocks or typical days, the results are “corrected” by simulating system operation in a second, post-processing step using full chronology with hourly resolution. While this sounds reasonable in theory, it fails in practice for one fundamental reason:

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If your baseline infrastructure plan is wrong, your high-resolution simulation merely quantifies the consequences of a bad plan. When the original model underestimates storage, transmission, or renewables, even a perfect operational simulation cannot undo the initial bias. It simply shows how the flawed system would behave in detail. This creates a dangerous feedback loop where planning tools report profitability metrics or curtailment levels that appear reasonable—because they are based on a flawed infrastructure expansion plan.

The distortion becomes particularly severe in investment assessments. For example:

- Underbuilt transmission leads to high local curtailment, reducing the simulated return on solar and wind projects.
- Undersized storage fails to balance solar midday surpluses, increasing fossil fuel use in the evenings.

Brought to an extreme, this is like evaluating the profitability of a business under the assumption that not sufficient competitors will enter the market. The core assumptions are detached from reality, and the outputs, however detailed, are unreliable.

To ensure meaningful simulation and investment analysis, the infrastructure baseline itself must be built from accurate, full-chronology models. Anything else embeds distortion from the start.

Grid Expansion Needs Optimization—Not Just a Rules Based Approach

Grid planning is one of the most complex aspects of power system development, particularly in the face of growing variability and uncertainty. Planners are expected to:

- Simulate N-1 contingency events to ensure system security under the failure of any single element.
- Consider multiple future pathways, including high and low demand or renewable growth scenarios.
- Balance cost, flexibility, and resilience in developing the grid of the future.

Traditionally, many of these studies rely on planning expert's ability or rule-based approaches. Planners identify security violations and iteratively propose reinforcements—line by line, substation by substation. While this method can work, it often leads to overbuilding or piecemeal solutions.

In contrast, optimization-based planning allows for a more efficient and cost-effective process. Rather than resolving each violation independently, optimization identifies the least-cost portfolio of reinforcements and flexibility measures that collectively satisfy all constraints, including N-1, voltage limits, and long-term growth.

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To illustrate, suppose two nearby contingencies cause overloads on two separate lines. A rule-based method might propose upgrading both lines individually. But an optimization model might find that deploying a single flexibility solution—such as a battery, topology control, or reactive support—can relieve both constraints at once, at lower cost.

Optimization captures non-obvious synergies that rule-based approaches often miss. It also allows the planner to explore trade-offs between physical expansion and operational flexibility—precisely what is needed in modern systems where storage, demand response, and control technologies are part of the toolbox.

By combining full-chronology modeling with grid optimization, planners can make smarter, more cost-effective investment decisions that enhance both reliability and affordability.

Quantifying the Distortion: Three Exercises

To concretely illustrate the problem, we conducted three modeling exercises:

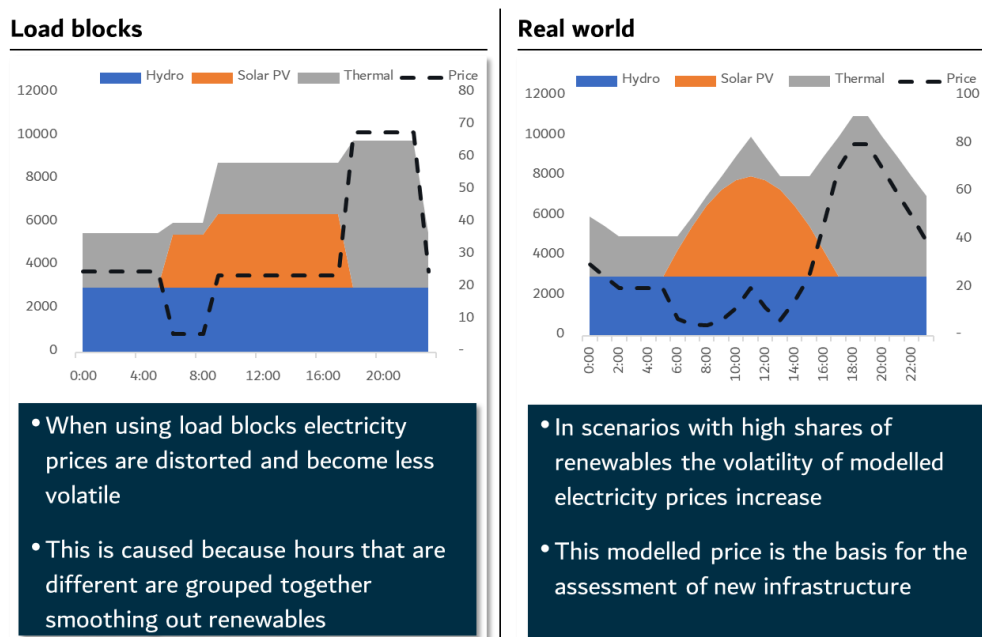
Small system

A simplified model was created within a spreadsheet to introduce with a very easy to understand power system consisting of:

- A hydropower plant with stable generation
- Thermal generation with output dependent variable cost
- Solar PV with different penetration levels

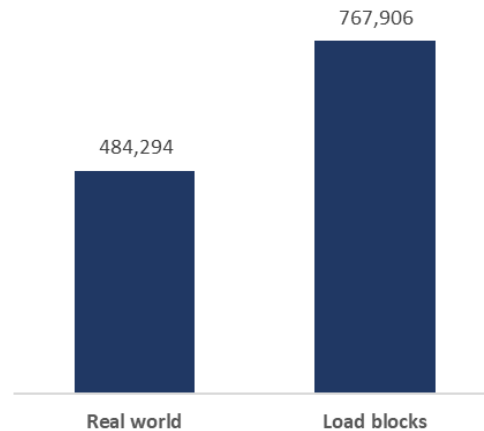
The following chart illustrates the impact of the temporal grouping, which introduce an averaging effect (or smoothing) to the demand and renewable power generation.

Exhibit 1: Load demand coverage in a simple power system with load blocks vs real world



The results show that when using load blocks or typical days, the captured price of solar PV can be overestimated by 59% for 21% solar PV share and by 149% at just 25% penetration.

Exhibit 2: Real world revenues, and with load blocks for solar PV capacity of 5,000 MW

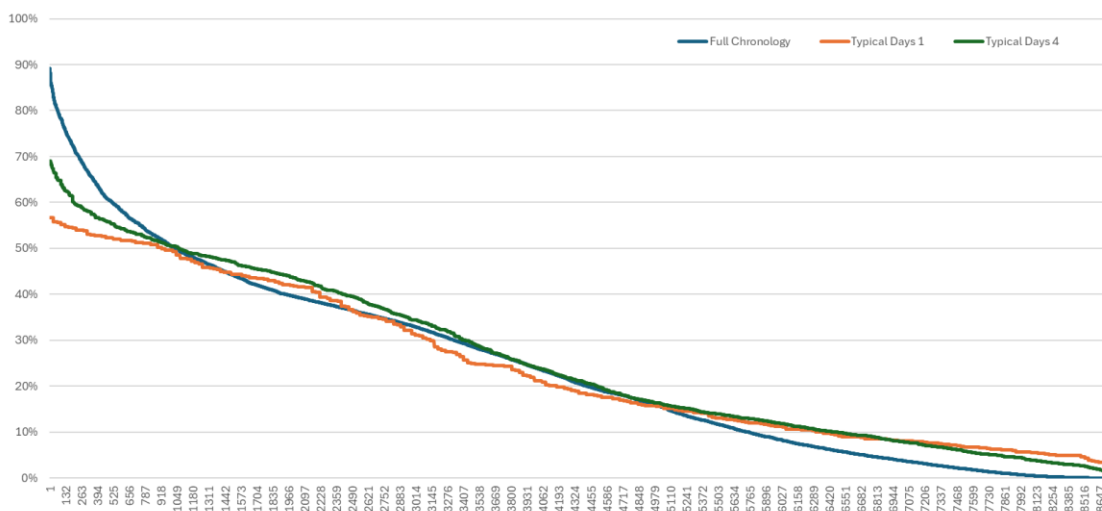


This example highlights how the use of load blocks even small systems produce distorted results through aggregation. The spreadsheet-based model is available on request at info@pharoes.com.

Renewable production profile analysis

A second spreadsheet-based model was developed using full hourly data for demand, wind generation, and solar PV over the course of a year. Its purpose is to illustrate, in a transparent and easily reviewable way, the impact of the "typical days" on power generation and transmission modeling. The following chart presents the resulting renewable generation profiles, assuming an installed capacity of 40 GW for wind and 26.7 GW for solar PV.

Exhibit 3: Load demand coverage in a simple power system with load blocks vs real world



The chart shows the renewable generation load duration curves derived from three approaches:

- **Full Chronology (FC):** using all 8,760 hourly values,
- **Typical Days 1 (TD1):** using 1 representative day per month,
- **Typical Days 4 (TD4):** using 4 representative days per month.

As expected, the typical day approaches smooth out the generation profile, particularly at the extremes. This results in a reduced contribution at peak demand, by 27% for TD1 and 19% for TD4 compared to the full chronology.

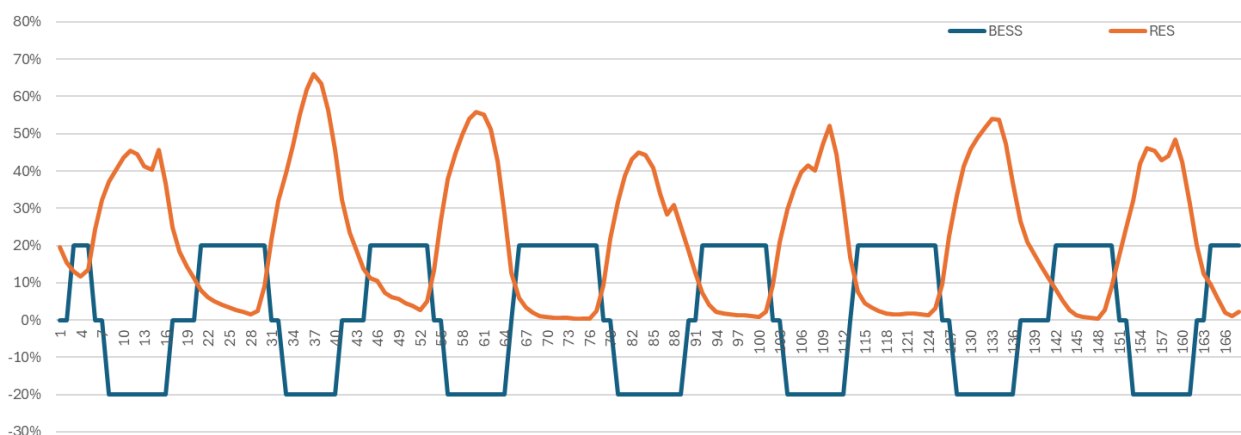
However, when assessing the implications for transmission needs, the critical metric is not the contribution to peak generation, but rather its inverse: how many megawatt-hours can be transmitted per MW of peak generation measured in full-load hours. Put in other words, if transmission is built with capacity equal to the peak renewable generation, how much will it be used throughout the year. In this respect, the following results can be seen:

- **Full Chronology (FC):** 2,371 full-load hours,
- **Typical Days 1 (TD1):** 3,456 full-load hours (+46%),
- **Typical Days 4 (TD4):** 3,014 full-load hours (+27%).

These inflated estimates of transmission utilization can mislead planning tools, resulting in an over-optimistic grid performance and an underestimation of transmission needs.

Transmission utilization metrics can also be significantly affected by short-term storage, which is increasingly deployed to help balance variable renewable generation. In this simplified, spreadsheet-based example, storage is operated with a basic heuristic: it charges when renewable generation is at its highest and discharges when generation is lowest, as illustrated in the chart below.

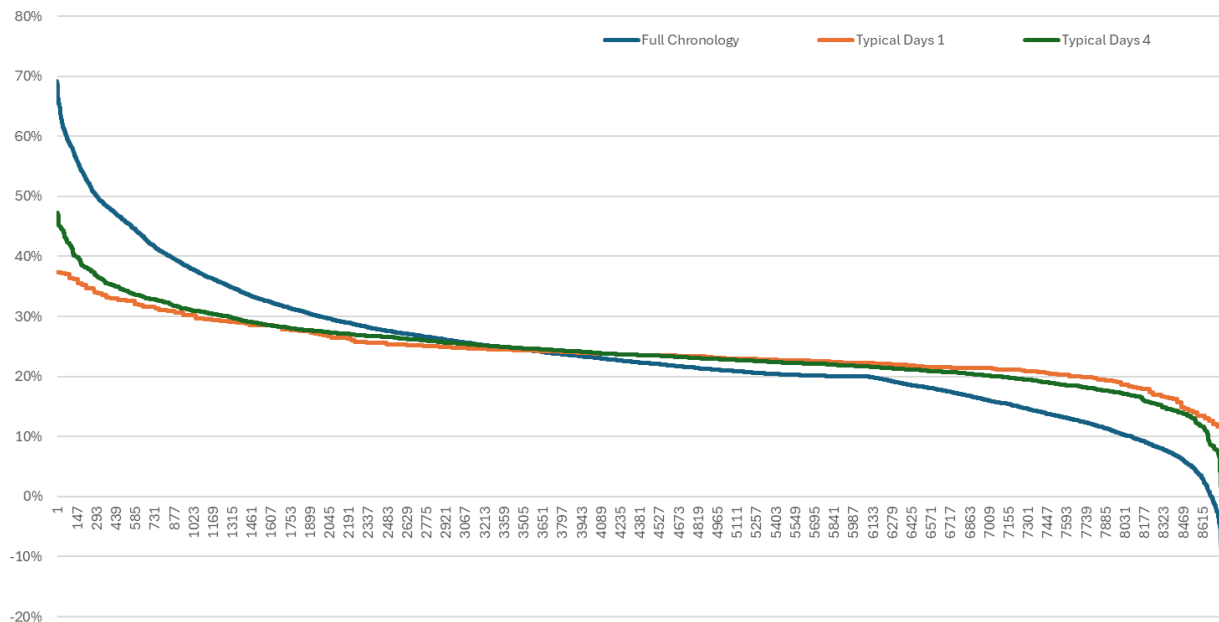
Exhibit 4: Load demand coverage in a simple power system with load blocks vs real world



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Once storage is introduced, we can recalculate the load duration curves for the three approaches discussed earlier.

Exhibit 5: Load demand coverage in a simple power system with load blocks vs real world



In this case, the typical day approximations further exaggerate the smoothing effect. This becomes especially apparent in the **energy per unit of peak generation** metric (i.e., full-load hours), which increases as follows:

- **Full Chronology (FC):** 3,186 full-load hours
- **Typical Days 1 (TD1):** 5,374 full-load hours **(+69%)**
- **Typical Days 4 (TD4):** 4,406 full-load hours **(+38%)**

These results show that the use of typical days can introduce **systematic and substantial distortions** in transmission and storage expansion planning. Specifically:

- **For transmission,** full-load hours can be overestimated by up to 69% using TD1 and 38% using TD4.
- **For storage,** the error in estimated utilization can reach up to 27% for TD1 and 19% for TD4.

These deviations are structural and not merely statistical noise. They highlight the risks of relying on oversimplified time representations in least-cost planning models, especially as systems incorporate more renewables and storage.

For those interested, the spreadsheet-based model used in this analysis is available upon request at info@pharoes.com.

Full Chronology Validation with CERES

To validate the findings from the spreadsheet model, we replicated the analysis using our in-house model, CERES, which simulates all 8,760 hours of the year, thereby eliminating the need for Typical Days or Load Blocks. This is the same model we have applied extensively in price forecasting and transmission planning projects in India.

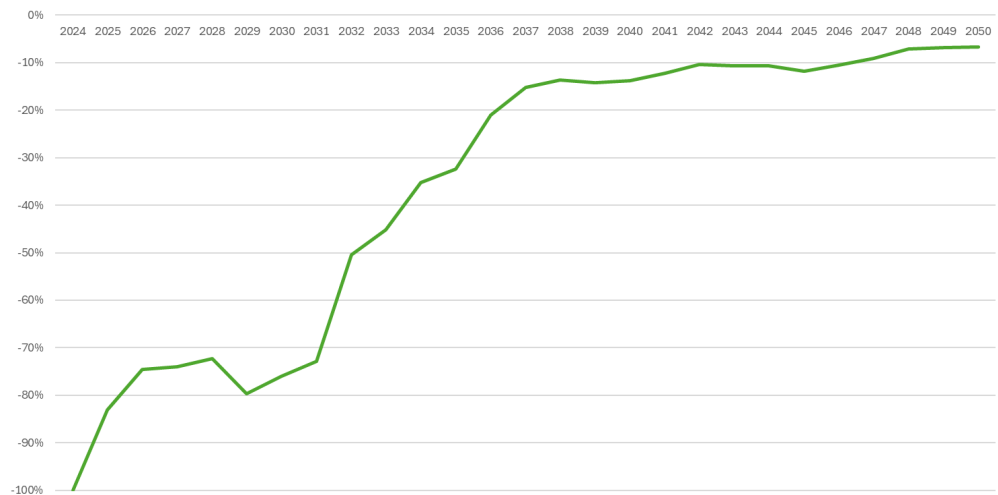
The dataset includes over 1,300 power generators—spanning renewables, thermal, nuclear, and hydropower, distributed across India’s five market zones (North, South, East, West, and Northeast). It also incorporates electricity interconnectors between regions and battery storage in each zone.

The relative results for the TD4 approximation compared to the Full Chronology (FC) case are shown below for both regional network interchange capacities (Exhibit 6) and battery storage deployment (Exhibit 7).

Exhibit 6: Relative exchange capacity of the regions for mean and percentile 20% of TD4 vs FC



Exhibit 7: Relative storage capacity of TD4 vs FC



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The median interchange capacity across the five zones under TD4 increases progressively relative to FC, reaching a ~25% overestimation by 2050. In the most extreme case, corresponding to the zone with the highest deviation, interchange capacity is overestimated by more than 25% by 2035, and by over 33% in 2048 and 2049.

For battery storage, the deviation is even more pronounced: it reaches 75% until 2031, then gradually declines to stabilize around 10% after 2038.

These results confirm that the deviations identified in the spreadsheet model are not just theoretical but can also occur in realistic, full-system simulations. While the magnitudes are slightly more conservative in CERES, the overall pattern of distortion remains consistent.

This reinforces two key conclusions:

- The spreadsheet-based insights scale to real-world systems.
- Full-chronology modeling is not only more accurate, but thanks to our acceleration technologies is also faster to run than most commercial tools.

Impacts on profitability assessments of a flawed reference plan

Network projects for financial approval require a Cost-Benefit Analysis (CBA) in many part of the world, typically following standardized methodologies such as those outlined in the EU's TYNDP framework. A critical component of this CBA is comparing system costs with and without the project. However, the accuracy of the analysis depends heavily on the underlying reference system development plan.

If this reference plan is developed using simplified temporal representations, such as Typical Days or Load Blocks, it tends to underestimate required capacity for generation, storage, and transmission. Raising a key question: To what extent does this distort profitability assessments as those conducted under CBA?

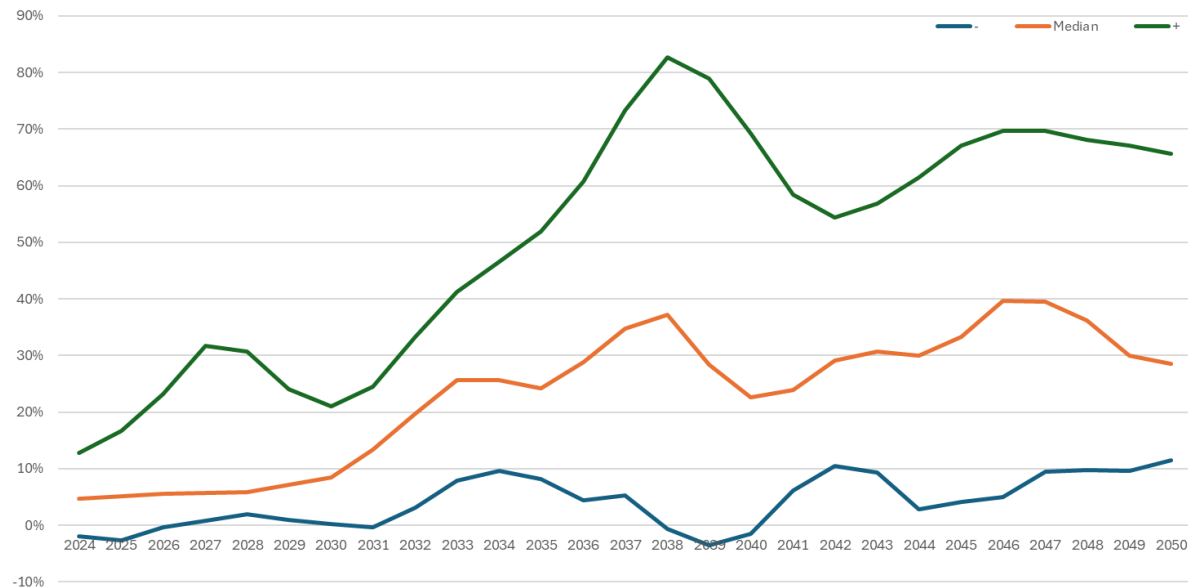
To explore this, we conducted two simulations using our **Full Chronology** approach with our tool CERES:

1. In the first, generation, storage, and transmission capacities were optimized freely, converging to the least-cost configuration.
2. In the second, capacity values were fixed to match those obtained under the TD4 (Typical Days – 4 per month) approach.

We then compared the operating profits of **transmission interconnectors** across regions and calculated the ratio of congestion rents, the key driver for CBA, of the two

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simulations: one is Full Chronology and the other is Full Chronology but assuming the renewable generation, storage and network expansion resulting from the TD4 approach. As expected though in the first years the difference of both approaches is not very large as the share of renewables is lower, as the shares of renewable energy grows it increases substantially reaching average deviation values of around 30% in year 2033 and exceeding 50% in some cases after 2035.

Exhibit 8: Relative transmission network congestion rents resulting from the resulting capacity in FC and in TD4



For **battery storage**, the operating income ratio (i.e., profits from market arbitrage) between the two scenarios ranges from **2x to 3x**. This means that CBAs where the expansion plan is based on TD4 **can overestimate profitability assessment by a factor from 2 to 3, even when conducting hourly simulations**. The distortion is not corrected by the hourly simulation because **the capacity itself is underestimated**.

For **transmission infrastructure**, the deviation in operating profits starts at around **18% in the first decade**, and grows steadily to **approximately 75% by 2050**.

It is also important to note that the impact is not uniform: while some transmission corridors exhibit higher deviations, others show smaller effects.

For those interested, the inputs and outputs of the model used are available upon request at info@pharoes.com.

Policy and Regulatory Implications

The transition to full-chronology planning is not just a technical upgrade, it is a regulatory imperative. As governments, regulators, and donors increasingly rely on planning studies to shape investment priorities and policy frameworks, the credibility of these studies must be safeguarded.

Key policy implications include:

- **Mandating transparency in time resolution:** Regulatory bodies should require all planning studies to clearly report the temporal resolution used and whether any simplifications such as typical days or load blocks were applied. Planners must disclose how variability, storage behavior, and peak stress periods were represented or not.
- **Establishing minimum standards for high-VRE scenarios:** In systems where renewable energy penetration exceeds a specific level, regulators should require that full chronological modeling be used, or that the error introduced by simplifications be quantified and reported. This includes impacts on storage sizing, transmission needs, and curtailment.
- **Donor support for open and accessible tools:** Development finance institutions and multilateral donors should prioritize the use of transparent, open, and affordable planning tools especially in emerging economies. Relying on expensive black-box models exacerbates asymmetries of knowledge and undermines local ownership of planning results.

The regulatory and policy community must therefore evolve in parallel with technology. Accurate planning is not a luxury; it's a foundational input to national energy strategy.

Conclusions and Recommendations

The energy transition requires new tools, not just new targets.

Legacy simplifications, load blocks and typical days, were designed for an era of fossil generation and limited computing capacity. They are no longer appropriate for systems dominated by solar, wind, and short-term storage. These methods obscure key dynamics, distort investment signals, and risk underperformance of critical infrastructure.

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The transition to full-chronology models is both necessary and practical. Tools that leverage modern optimization techniques and parallel computing can now solve these problems in minutes, not days. The added resolution provides confidence, transparency, and resilience in planning.

We recommend:

- Planners and regulators demand disclosure of temporal resolution used in studies.
- Donors and financing institutions require full-chronology models for high-impact investment plans.

The cost of inaccurate planning is too high and unnecessary. If we are serious about building reliable, low-carbon power systems, we must stop introducing these outdated simplifications.

This whitepaper has shown that simplifications like load blocks and typical days introduce **structural errors** that misrepresent the value of renewable energy, storage, and grid infrastructure. These errors are not minor, they scale with renewable penetration and increasingly shape billion-dollar decisions.

Power system planning is too important to be done with outdated tools. By reclaiming chronology, we reclaim accuracy, transparency, and trust. It is time to build not just better models, but better decisions.



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