Quantifying Inertia Needs for Future Electric Grids with High Penetration of Inverter-Based Resources

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***Abstract*—As the grid transitions towards renewable energy, the decline in synchronous generators necessitates a thorough understanding of system inertia requirements to maintain reliability and stability. This paper employs a production cost simulation framework to evaluate system inertia, focusing on an isolated power system. For the Spanish electric system, the analysis reveals that while conventional generation meets inertia requirements in 2025, significant shortfalls are expected by 2040 due to the decline in synchronous capacity and increased Inverter-Based Resource (IBR) penetration. The paper quantifies the additional inertia needs and explores the potential of virtual inertia from IBRs to mitigate these shortfalls. The findings highlight the importance of market incentives, technical standards, and regional cooperation to ensure reliable grid support in future decarbonized power systems.**

***Index Terms*—Inertia, inverter-based resources, production cost modeling.**

I. Introduction

The electric grid is experiencing unprecedented changes, from generation to load. The rapid growth of load and the proliferation of data centers have led to a significant increase in energy demand, necessitating the procurement of additional generation resources [1]. Concurrently, many countries have established ambitious clean energy and net-zero emission targets [2], which impose constraints on the types of generation that can be built. These factors collectively make it increasingly challenging for the grid to meet demand reliably. Furthermore, the grid is facing higher outage rates due to operating at capacity limits and the impacts of extreme weather events [3]. Renewable energy resources, while essential for meeting energy demands, exhibit a variable nature and different performance characteristics in response to grid disturbances compared to conventional synchronous generators. Key aspects such as inertia, short-circuit capabilities, and synchronization are critical for grid reliability and stability [4].

To address these challenges, significant efforts have been made to ensure the performance of Inverter-Based Resources (IBR) and Distributed Energy Resources (DER). The Institute of Electrical and Electronics Engineers (IEEE) has developed multiple standards providing guidelines for IBR performance in both steady-state and dynamic conditions [5] [6]. Additionally, the Federal Energy Regulatory Commission (FERC) has introduced rules for IBR and DER to govern their performance and ensure system reliability [7]. These guidelines and regulations pave the way for higher penetration of IBR in the energy mix, ultimately aiming for a 100% IBR electric grid.

Maintaining system reliability requires, among many things, a thorough understanding of inertia needs across synchronous areas. Previous studies have quantified these needs. For instance, [8] examined two scenarios for various European grids, exploring the implications for renewable energy curtailment and carbon emissions. The authors in [9] optimized virtual inertia for frequency stability during large generator contingencies, considering stochastic load and renewable variations, while [10] introduced an inertia adequacy constraint to system expansion planning studies. Others have employed dynamic simulation to calculate system inertia needs [11].

This work aims to quantify the inertia needs for any grid, considering different planning energy mix portfolios. This task is particularly challenging when the system operates as part of a larger synchronous area. Therefore, this paper provides insights and recommendations on the minimum inertia requirements for such systems. Additionally, it evaluates how different inertia technologies can contribute to meeting these requirements for reliable operations.

The remainder of this paper is organized as follows. Section II reviews system inertia calculations and contributions from different technologies. Section III introduces the methodology used in this paper to analyze system inertia and evaluating minimum requirements. In Section IV, a case study is presented to demonstrate the approach. Finally, Section V draws conclusion and findings.

II. Background/Objective

A. Evaluation of system inertia

System inertia is the energy stored in the rotating mechanical parts, typically found in synchronous machines and motors. Inertia for a given machine is quantified with the

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inertia constant (H), which is normalized with respect to the rated power of the unit (S), and measured in units of seconds:

$$H = \frac{kinetic\ energy\ [MWs]}{rated\ power\ [MVA]} \quad (1)$$

The system total inertia is the sum of generators' inertia divided by the system rated power:

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i}{S_{sys}} \quad (2)$$

B. System Inertia Requirements

Power system inertia is usually evaluated using dynamic studies, where the system is subjected to a large disturbance (typically loss of a large generator) and the frequency response of the system is monitored.

Following a power mismatch in the system, the Rate of Change of Frequency (RoCoF) is inversely proportional to the system inertia and governed by the swing equation:

$$RoCoF = \frac{\Delta P\ f_n}{2 H_{sys} S_{sys}} \quad (3)$$

where, ΔP is the power mismatch between generation and load, and f_n is the system nominal frequency. The minimum inertia requirements for a system are mostly based on the maximum RoCoF the system can experience.

C. IBR Inertia Contribution

While IBRs have the technology capability to provide inertial response (i.e., active power response that is proportional to the RoCoF), they lack the energy reserve to supply it. IBR don't have any mechanical rotating parts and, therefore, require energy reserve to provide an inertia-like (or virtual inertia) response.

Virtual inertia from IBRs has been demonstrated in earlier efforts. This has been leveraged by using Battery Energy Storage Systems (BESS) to dispatch reserved power. Technologies such as grid-forming control and virtual synchronous machines [12] are some examples. These technologies have made its way to actual systems and have been used to support system performance where inertia has already hit below minimum thresholds. In Australia [13], BESS equipped with grid forming control is currently being used.

Since the virtual inertia is not a hardware constant, it is a tunable control parameter limited only by available stored energy, inverter current capability, and the operating point headroom. Therefore, while large values are possible, it is typical to set it in the range of 2-4 s [14] to allow for a trade-off between having comparable values of synchronous machines, while keeping energy needs reasonable.

III. Methodology

A snapshot of the system is typically used to draw system inertia thresholds, usually a light-load condition where a minimum number of synchronous generators are online. Where inertia is of a concern, system operators consider inertia as part of their planning studies [15].

While a single snapshot to capture the worst inertia conditions has been sufficient, the changes that the electric grid going through will make this approach obsolete. Many system operators see their load profiles shift throughout the year [16]. And with the higher shares of IBRs, it is harder to anticipate which period of the system is going to experience lower inertia levels. Therefore, it is important to capture the inertia-level variations of the system throughout the year.

In this work, an alternate approach to evaluate system inertia is proposed. Production Cost Simulations [17] is used to study multiple scenarios of a system, from which inertia can be computed for each time step. The details of each step are explained in the following sections.

A. Computation of Inertia

The approach adopted in this study is to utilize a unit commitment and economic dispatch. Once the commitment for each time interval is determined, the inertia of the system is the sum of the inertia of all generators' that are online; the same method for estimating total system rotational inertia in real time operation in most power systems is used.

An inertia requirement is derived for the system for each time interval based on the largest generation outage or power infeed loss (ΔP_{max}) along with a maximum $RoCoF_{limit}$ that the system can reliably withstand. Rearranging the swing equation in (3):

$$H_{min} \geq \frac{\Delta P_{max}\ f_n}{2 \cdot RoCoF_{limit}} \quad (4)$$

Based on this computation, the following steps are used to calculate the inertia requirements for an isolated system:

1) Step 1: Inertia Calculation:

Hourly inertia is calculated from all conventional generators in the system. Inertia constants for each technology type are shown in Table I.

Table 1. Inertia constant by technology type

Type	Inertia (s)	Type	Inertia (s)
CCGT	5	Nuclear	5
Coal	7	OCGT	3
Hydro	3	ST	2
IC Engine	3	Solar/ Wind	0

2) Step 2: Threshold Definition

The required system inertia threshold is defined based on the Most Severe Single Contingency (MSSC). MSSC is used for ΔP_{max} in (4).

3) Step 3: Inertia Shortfall

Shortfall occurs when the inertia available from conventional generators, H_{sys}, is below the threshold, H_{min}.

$$H_{shortfall} = H_{min} - H_{sys}$$

Unmet Inertia is equal to the $H_{shortfall}$ when is larger than zero.

IV. Case Study

In this case study, the system inertia requirements for an isolated national power system are quantitatively assessed. Spain is selected as a representative example from the Continental Europe synchronous area, and a hypothetical islanded operation scenario is considered, wherein no inertial support is available from interconnected neighboring systems.

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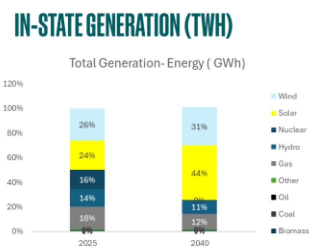
The analysis estimates the existing synchronous inertia contribution from conventional generation resources and evaluates the potential for synthetic or virtual inertia provision from IBR in future grid configurations. Additionally, the study investigates whether supplementary conventional generation capacity would be necessary to ensure adequate frequency stability and inertia margin under evolving operational conditions.

A. Case Set Up

For this study, a production cost modeling framework is employed using a detailed system model representing the Continental Europe power system. The base year for system characterization is set to 2025, reflecting the expected installed nameplate capacity across all generation technologies. The temporal evolution of the supply stack is analyzed through 2040 to capture the impact of increasing renewable generation and the corresponding reduction in conventional synchronous generation sources. A summary of the energy mix comparison between 2025 and 2040 is shown in Fig. 1.

NAMEPLATE (GW)

Type	'25 (GW)	'40 (GW)	D
Coal	2	0	(2)
Gas	30	30	-
Hydro	19	19	-
Nuclear	7	0	(7)
Solar	34	110	+91
Wind	32	28	+18
Storage	3	27	+25
Other (Oil)	1	1	-
Total	~131	~241	+110



(a) (b)

Figure 1. Comparison of Spain energy mix between 2025 and 2040. a) Nameplate capacity in GW, and b) dispatched generation over the year in TWh

B. Modelling framework and data sources

The Spanish transmission network and generation fleet data were derived from publicly available datasets and national planning reports [18]. Technology-specific parameters, including ramp rates, minimum generation levels, heat rates, and inertia constants, were incorporated based on GE Vernova's proprietary databases and literature benchmarks [19]. Renewable generation profiles were developed using historical solar and wind data adjusted for 2025 and 2040 capacity projections. All scenarios were simulated under consistent demand forecasts and reserve margin assumptions to ensure comparability of system inertia and operational outcomes.

C. Key Modeling Assumptions

1) Generation Mix and Operational Dynamics

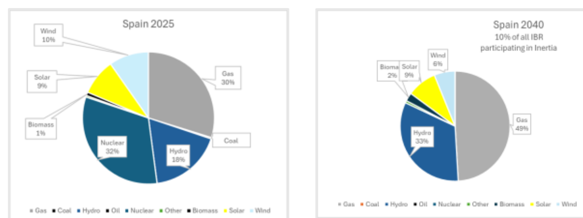
In 2025, natural gas-fired units contribute approximately 30% of the total system inertia, complemented by nuclear and hydro generation. Nuclear plant retirements and constraints on hydro expansion (due to geographical and water resource limitations) are expected to reduce the availability of conventional inertia in future years. Consequently, as IBR penetration increases and synchronous capacity retires, gas-based generation is projected to experience higher utilization to maintain system stability.

2) System Dispatch and Time Resolution

Production cost simulations were conducted for representative years 2025 and 2040 on an hourly basis. The hourly dispatch outcomes were aggregated where necessary to evaluate system-level inertia contributions and operational patterns.

3) Inertia Provision by IBRs

IBRs were assumed to contribute to system inertia only under the presence of a remuneration mechanism that compensates them for foregone energy revenue. IBRs were modeled to allocate only surplus or curtailed renewable energy for synthetic inertia provision, as no existing market incentive currently supports withholding active power from the energy market solely to provide inertia. The inertia contribution per generation type is shown in Fig. 2.



(a) (b)

Figure 2. Inertia contribution per generation type: a) 2025 and b) 2040

D. Simulation

The study analyzes Spain's system inertia requirements to ensure grid stability and quantifies potential shortfalls in the coming years. The analysis focuses solely on conventional generators; no virtual inertia from IBRs was considered. The analyzed system is demonstrated in Fig. 3. MSSC for Spain's standalone system is based on the largest infeed, contrary to the 3,000 MW used for continental Europe.

Figure 3. Spain electric grid without interconnection to neighboring systems

System parameters:

- MSSC (Standalone Spain) = 1,400 MW
- System frequency, $f_n = 50\ Hz$

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- ROCOF limit, $RoCoF_{limit} = 0.5\frac{Hz}{s}$ [20]
- Threshold calculation:

$$Threshold = \frac{\Delta P_{max}\, f_n}{2 \cdot RoCoF_{limit}} = \frac{1400 \cdot 50}{2 \cdot 0.5} = 70{,}000\ MW \cdot s$$

The inertia shortfall for 2025 and 2040 are shown in figures 4 and 5, respectively. In 2025, Spain's conventional generation generally meets inertia requirements, but shortfalls occur during spring months (February–June), due to planned outages and partial dispatch of conventional units.

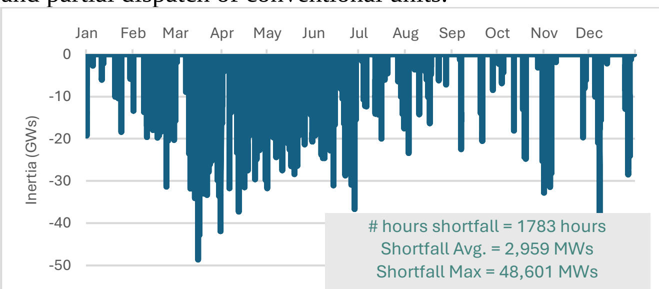

Figure 4. Spain's inertia shortfall in 2025

By 2040, internal conventional generation is insufficient to meet the threshold for almost the entire year. This indicates increasing reliance on alternative sources of inertia or system measures to maintain stability.

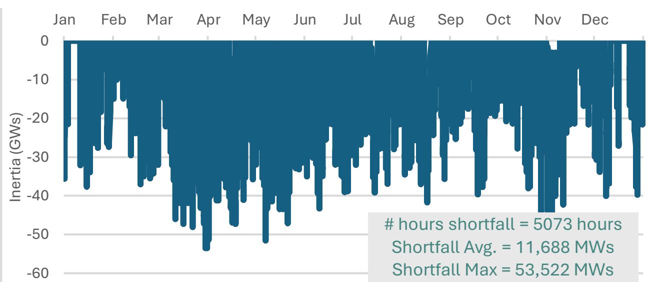

Figure 5. Spain's inertia shortfall in 2040

The analysis highlights the need for additional inertia solutions, such as Synchronous Condensers, Grid-forming inverters from renewable generation or energy storage with synthetic inertia capabilities. Without these measures, Spain may experience frequency stability risks in periods of high IBR penetration.

E. Virtual Inertia – Generation Curtailment

In this part of the study, the curtailment trends of inverter-based resources (IBRs) and their potential to provide virtual inertia are analyzed. The results for 2025, shown in Fig. 6, indicate minimal curtailment, with less than 20% during the summer months and almost no curtailment for the remainder of the year. IBRs are capable of supporting a very high percentage of the system load, often exceeding 80% on many days and reaching as high as 98% in some instances.

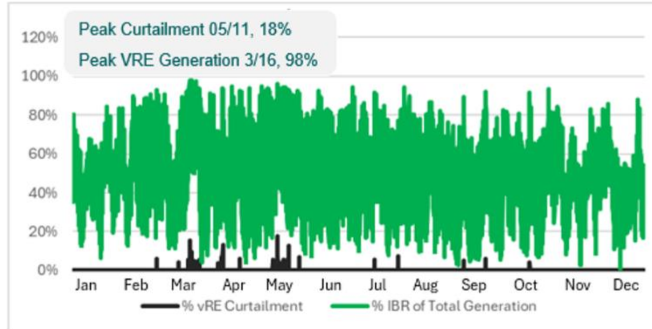

Figure 6. Renewable energy penetration percentage and curtailment percentage in 2025

Looking ahead to 2040, with higher penetration of IBRs in Spain, curtailment increases significantly, shown in Fig. 7. The share of load served by IBR generation rises accordingly, demonstrating the growing capability of these resources to provide inertia support. This scenario highlights the potential for virtual inertia from IBRs to contribute meaningfully to system stability as conventional generation alone becomes insufficient.

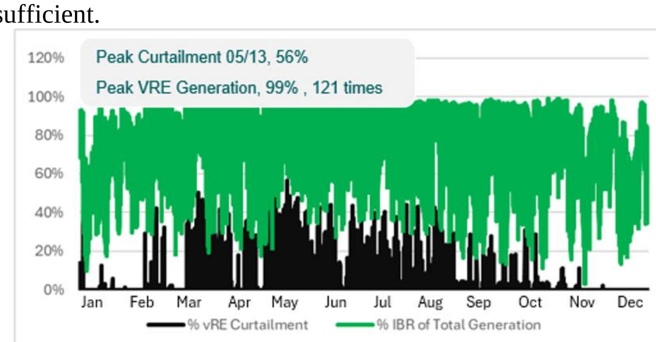

Figure 7. Renewable energy penetration percentage and curtailment percentage in 2040

F. Results and Discussion

Based on the analysis presented above, the additional inertia requirements beyond the contribution from installed and dispatched conventional generation were quantified for 2025 and 2040, summarized in Fig. 8.

For 2025, Spain's system requires, on average, approximately 4.2% of the total system inertia threshold of 70,000 MW·s, corresponding to roughly 1.7 GW of additional conventional inertia. This shortfall is currently met through interconnections with neighboring France, which possesses a nuclear-generation-dominated system capable of providing the necessary support.

Figure 8. Spain inertia needs in 2025 and 2040

In the near term (2025), IBRs are unlikely to contribute significantly to system inertia. However, projections for 2040 indicate that high penetration of IBRs could enable these resources to provide up to 45% of the total inertia requirement. These results underscore the growing importance of IBRs and virtual inertia in supporting frequency stability, particularly under scenarios of reduced conventional generation availability and increased renewable integration.

V. CONCLUSIONS

This study outlined a framework to calculate system inertia adequacy under increasing renewable penetration scenarios. We demonstrated the methodology using Spain for the years 2025 and 2040. The analysis quantified inertia contribution from conventional generators and assessed shortfalls relative to the system stability threshold derived from the most severe single contingency. Results indicate that, while conventional generation is generally sufficient to meet inertia requirements in 2025-with occasional deficit during low demand, high renewable periods, significant shortfalls are expected in 2040 as conventional capacity declines and IBRs dominate system generation.

The findings demonstrate that, by 2040, IBRs possess the technical potential to supply up to 45% of the total system inertia requirements through virtual inertia mechanisms. However, realizing this potential will require appropriate market incentives, technical standards, and control coordination to ensure reliable grid support. Additionally, Spain's reliance on interconnection with neighboring system, such as France, highlights the importance of regional cooperation and cross-border inertia sharing. Overall, the study underscores the necessity of proactive system planning to integrate synthetic and virtual inertia solutions, it outlines the approach system planners should conduct the calculation with an interconnection system and be self-reliant ensuring frequency stability and maintaining operational security in a decarbonized power system.

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