# COSIMULATION: OPTIMIZING INDUSTRIAL POWER AND PROCESS SYSTEMS



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***Abstract*** – The integration of electrical and process simulation environments is critical for accurate design and operation in industrial electrification. This paper focuses on co-simulation, the synchronized execution of simulations across different domains, particularly for energy-intensive industries like green hydrogen and ammonia production. These facilities demand high coordination between grid infrastructure, electrochemical systems, thermal units, and digital controls. Using commercial electrical and process simulators, the paper demonstrates real-time data exchange, solver coordination, and unit operation mapping to simulate complex transient behaviours. A case study of a renewable-powered hydrogen and ammonia plant showcases how load shifts, electrolyser control, and battery energy storage optimization are harmonized across platforms. Key benefits include reduced capital expenditure (CAPEX) and operational expenditure (OPEX), improved power system stability, faster commissioning, and enhanced operator training. Challenges such as synchronization mismatches, licensing, and lack of universal data exchange standards are also discussed. Ultimately, this study positions co-simulation as a cornerstone for modern industrial design and operation, especially given the convergence of electrification, decarbonization, and digital transformation. The paper proposes strategies for wider adoption, including standards harmonization, AI integration, and model lifecycle continuity.

*Index Terms* – Co-simulation, Industrial Electrification, Green Hydrogen Production, Digital Twin, Energy Management System, Process Simulation, Electrical Simulation, Decarbonisation

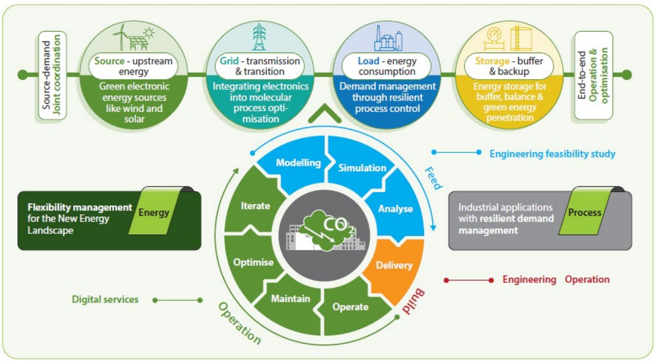


Fig. 1 Green hydrogen Integrated power and process design phases

## I. INTRODUCTION

Industrial systems are undergoing a fundamental transformation driven by the global push for electrification and decarbonization. Industries once heavily reliant on fossil fuels are shifting to electrified processes powered by renewable energy. This transition introduces significant challenges, including managing variability, maintaining stability, designing flexible control systems, and integrating high-fidelity models across engineering domains. The increasing interdependence of electrical and process systems, especially with new energy technologies like electrolysers and batteries, renders traditional, siloed simulation approaches insufficient. These methods, which typically model electrical and process aspects independently, lead to suboptimal control strategies, oversized equipment, and unexpected interactions in complex, integrated systems like green hydrogen plants or industrial microgrids.

In the context of process electrification, where fossil-fuel-based operations are being replaced by electric-driven systems, co-simulation provides the critical link between electrical infrastructure and thermal-chemical processes. Co-simulation couples two or more distinct simulation engines–typically an electrical simulator and a process/thermal simulator–to run synchronously, exchanging data in real-time. Unlike co-modelling, which attempts to unify models within a single software platform, co-simulation leverages each domain's best-in-class tools, synchronizing them during runtime through data exchange, bidirectional feedback, and precise time synchronization. This approach is increasingly relevant due to trends like Green Hydrogen and Power-to-X, Microgrids, Industrial Heat Electrification, and Digital Twins, all of which require a holistic, transient, and predictive view of system behaviour during various operational phases.

Without co-simulation, industries face substantial risks, including incorrect equipment sizing, control loop instability, unanticipated transients, and critical failures during commissioning. These issues can lead to project delays, increased operational expenses, and safety concerns. The limitations of static or separate design models become critically apparent when dealing with the dynamic interactions between electrical grids and highly variable process loads.

This paper aims to provide a technical roadmap for implementing co-simulation in an industrial context. We will offer a detailed technical breakdown of how co-simulation works, including synchronization, data mapping, and supported elements. An anonymized case study will demonstrate successful implementation in a green hydrogen-ammonia value chain, alongside a quantitative and qualitative analysis of the benefits achieved. Furthermore, we will candidly assess technical limitations and integration barriers, concluding with recommendations for future development and standardization, thereby bridging the gap between theory and practice for engineers and project developers.

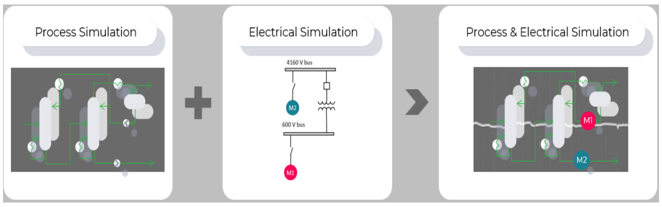

Fig. 2 Power and Process Simulation

## II. TECHNICAL BACKGROUND

### A. *Overview of Co-Simulation Architecture*

At its core, co-simulation architecture involves linking two or more discrete simulation platforms each responsible for a specific technical domain into a coordinated, time-synchronized modelling environment. Unlike monolithic simulation platforms that attempt to simulate all system components within a single framework, co-simulation allows each simulator to focus on what it does best. For example:

- An electrical simulator manages the transient and dynamic behaviour of the power grid, motors, generators, power converters, and battery storage.
- A process simulator models the thermodynamic and mechanical systems such as electrolysers, heat exchangers, ammonia synthesis units, and reactors.

The simulators exchange data at defined synchronization points, passing values such as voltage, current, torque, flow rate, pressure, temperature, and controller set points. A co-simulation "engine" or "orchestrator" ensures both simulators remain in lockstep with respect to simulation time. Co-simulation is not an Application Programming Interface (API), it is a methodology that requires coordinated control over time steps, solver execution, error management, and boundary data exchange.

### B. *Components of a Co-Simulation Platform*

Every successful co-simulation deployment involves the following architectural components:

TABLE 1
ARCHITECTURAL COMPONENTS

| **Component** | **Function** |
|---|---|
| Simulators | Independent engines responsible for physics-based modelling in their respective domains (e.g., electrical, thermal, chemical). |
| Mapping Interface | A configuration layer that defines which model components (e.g., motors, valves, electrolysers) are shared between simulators. |
| Data Exchange Protocol | The medium and structure of communication (e.g., file-based CSV, TCP/IP, OPC UA, FMI). |
| Time Synchronizer | A master clock or scheduling mechanism that ensures each simulator executes its time step in a coordinated fashion. |
| Controller/Adapter | Logic that enables simulation coupling rules (e.g., C#, Python, or compiled middleware). |
| Error Handling Layer | Mechanisms to detect divergence in solver outputs or unstable coupling dynamics. |

### C. *Time Synchronization Methods*

Time synchronization is a cornerstone of co-simulation. Without consistent time advancement between domains, the entire simulation becomes unreliable. Common methods include:

- Fixed-Step Synchronization: Both simulators operate at a common time step (e.g., 1 second). Simple and robust but can limit fidelity.
- Least Common Multiple (LCM) Timing: Each simulator maintains its preferred time step (e.g., 250 ms for electrical, 1 s for process), with synchronization at LCM intervals (e.g., 5 s).
- Variable Time-Step with Rollback: Allows dynamic time advancement with the option to roll back simulations if solver convergence fails–common in high-fidelity models.
- Master-Slave Coordination: One simulator acts as master and controls the simulation clock; the other only advances when requested–this can introduce lag or causality issues if not carefully designed.

In industrial contexts, LCM-based fixed synchronization is preferred due to deterministic behaviour and repeatable test scenarios.

### D. *Solver and Fidelity Matching*

Simulators employ different solvers: numerical integrators in process simulators (e.g., backward Euler, Gear's method) and differential algebraic solvers in power system simulators. Ensuring consistent fidelity across the coupled models is essential. Some best practices include:

- Level of Abstraction Matching: High-detail chemical reaction models must be harmonized with equivalent-resolution power loads.
- Unit Consistency: Conversions between SI and per-unit (p.u.) systems must be well managed.
- Stiffness and Convergence: Rapid transitions (e.g., motor start, valve slam shut) can destabilize simulations unless properly damped or filtered.

For instance, a dynamic electrolyser model that adjusts based on real-time current supply must be designed to accept rapid voltage variations without numerical instability.

### E. *Data Mapping and Exchange*

Co-simulation relies on accurate and consistent data exchange across domains. This involves:

1) *Supported Unit Operations:* The following are typical unit operations shared across electrical and process simulators:

TABLE 2
TYPICAL UNIT OPERATIONS

| Electrical Simulator Element | Process Simulator Equivalent |
|---|---|
| Synchronous Generator | Steam/Gas Turbine Model |
| Induction Motor | Compressor/Turbopump |
| DC Load (Electrolyser) | Electrochemical Stack |
| Series Impedance (Cable) | Power Distribution |
| Battery/Inverter | Energy Management Module |

Each of these has parameters that must be exposed for mapping:

- Voltage → Operating Pressure
- Torque → Flow Rate
- Current → Hydrogen Production Rate
- Frequency → Valve Actuation Timing

2) *Supported Data Types:* Data exchanged is typically structured as:

- Float / Double: For continuous variables like voltage, current, speed.
- Integer: For discrete states (on/off, fault flag).
- Boolean: For event triggers and logic gates.

Advanced co-simulation platforms support scaling, offsets, and unit conversion during data exchange via mapping tables.

### *F. File-Based vs. Real-Time Integration*

There are two primary models of integration:

- File-Based (Offline)
  - Data is exchanged via intermediate files (e.g., .csv,) processed at each simulation time step.
  - Benefits: Simple, transparent, easy to debug.
  - Drawbacks: Slow, prone to I/O errors, limited to offline simulations.
- Real-Time Communication
  - Data is transferred via Open Platform Communications Unified Architecture (OPC UA), or Functional Mock-up Interfaces (FMUs).
  - Benefits: Enables real-time, closed-loop simulation and hardware-in-the-loop (HIL) testing.
  - Drawbacks: Complex to implement, requires robust error management.

For critical simulations (e.g., digital twins, operator training systems), real-time integration is preferred. Offline methods are useful for feasibility studies and early-stage design.

### *G. Example: Time-Domain Load Flow (TDLF) Co-Simulation*

In a TDLF-enabled co-simulation, an electrical simulator executes a time series of load flow calculations, incorporating renewable energy profiles (e.g., wind, solar) and process load demands.

- The process simulator models electrolysers and compressors whose power demand changes based on control logic.
- At each time step, power demand from the process simulator is sent to the electrical simulator.
- The electrical simulator returns voltage/current feedback.
- This loop continues for the defined time horizon (e.g., 600 seconds), enabling accurate analysis of dynamic interactions.

A typical outcome includes verifying whether a battery energy storage system (BESS) is appropriately sized to cover electrolyser ramp-up during low solar availability.

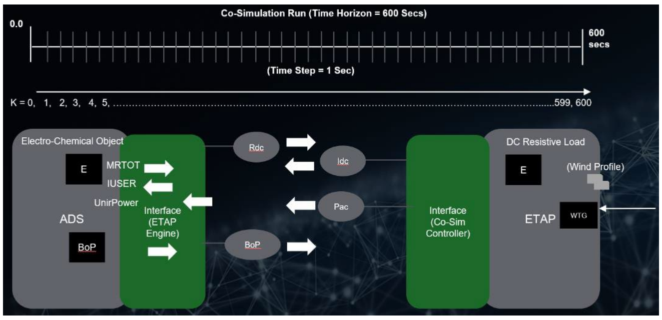

Fig. 3 Example TDLF use case

### *H. Transient Stability (TS) Co-Simulation*

This involves simulating system disturbances like generator trips, short circuits, or sudden load rejection, and observing how the combined electrical-process system responds.

- Transient events are introduced in the electrical domain.
- Resulting frequency drops or voltage sags are propagated to the process simulator.
- The process model then responds by tripping equipment, throttling valves, or adjusting load.

Transient stability co-simulation is particularly important for systems with low inertia, such as renewable-heavy microgrids.

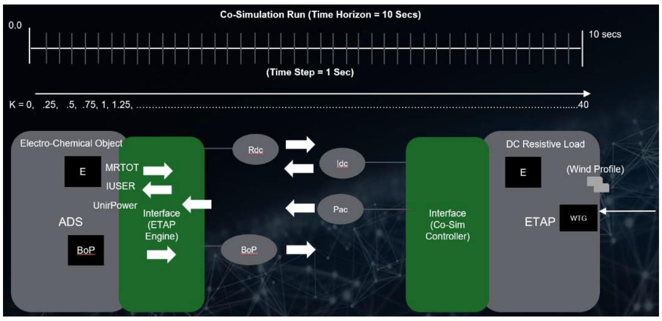

Fig. 4 Example TS Use Case

### *I. Modular Configuration*

To scale co-simulation across projects, it's common to adopt template-based mapping files, where each unit operation (e.g., electrolyser, motor) has its own configuration script.

Typical files include:

- Electrolyser.csv – Defines inputs like voltage/current and outputs like $H_2$ flow rate.
- InductionMotor.csv – Maps torque, speed, and load curves.
- PowerSource.csv – Used to link renewable input profiles with available power.

These files are compiled into an interface configuration (.xml or json) read by both simulators during runtime.

### J. *Integration into Digital Twin Platforms*

Modern industrial digital twins go beyond visualization; they simulate full system behaviour in real-time. Co-simulation feeds into digital twins by:

- Providing synchronized, validated dynamic models
- Supporting predictive analytics using real-time and simulated data
- Improving operator training through realistic response scenarios
- Enhancing asset lifecycle by continuously updating simulation models with live data

When combined with AI models and historical datasets, co-simulation-enhanced digital twins become powerful decision support tools.

## III. CO-SIMULATION METHODOLOGY

### A. *Introduction to Methodology*

Co-simulation is not plug-and-play; it requires structured planning, rigorous interface configuration, and precise mapping between domain-specific simulators. The methodology outlined here presents a generalizable, step-by-step approach to deploying co-simulation across electrical and process simulation tools. Though proprietary simulators are anonymized in this paper (referred to as "electrical simulator" and "process simulator"), the techniques described are transferable across vendors and platforms.

The four phases of implementation are:

1. Pre-integration modelling
2. Interface configuration
3. Synchronization and control logic setup
4. Scenario execution and analysis

### B. *Pre-Integration Modelling*

Before co-simulation can begin, each simulator must have a baseline model that represents the system independently.

1) *Electrical Simulator Model:* A typical electrical model includes:

- Bus systems and switchgear
- Power sources (e.g., wind, solar, grid import, generators)
- Transformers and protective relays
- Loads (constant, motor, variable, resistive)
- Storage (battery energy storage systems)
- Motor drives and VFDs
- Control elements like power plant controllers (PPC)

The goal is to develop a model capable of steady-state (load flow), dynamic (TDLF), and transient (TS) simulations.

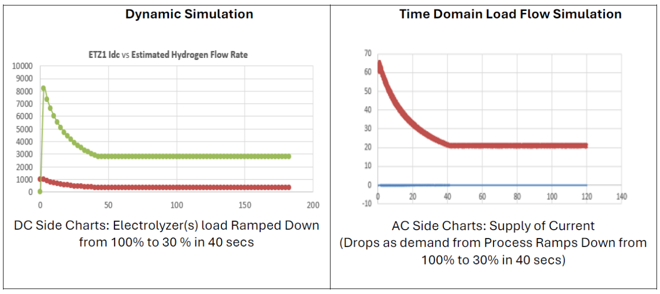


Fig. 5 Current Charts and AC Current Illustration

2) *Process Simulator Model:* A process model typically includes:

- Electrolysers, compressors, or reactors
- Thermal systems: heat exchangers, steam headers
- Storage vessels: hydrogen, ammonia, methanol
- Valves, flow control devices, and pumps
- PID or advanced control logic
- Pressure, temperature, flowrate sensors
- Dynamic material balances and heat integration

The objective here is to build a dynamic-first-principles model that reacts to control inputs and physical interactions with high temporal resolution.

### C. *Interface Configuration*

Once both baseline models are validated, the interface layer is created. This consists of mapping files and integration rules defining what data is exchanged and how.

1) *Mapping File Creation*

The first step involves creating mapping files that pair elements in the electrical and process simulators. These are usually structured as:

- Object Mapping File (.csv) – Lists instance names of paired units (e.g., Motor_1 in electrical sim ↔ Comp_A in process sim).
- Parameter Mapping Files (.csv) – Defines variables to exchange: e.g., Current, Voltage, Speed, Torque, Pressure, Temperature.
- CoSimSettings.txt – Contains flags for timestep duration, unit conversions, interpolation, and error handling.
- Master .xml or. json File – Consolidates all mappings into a machine-readable configuration for both simulators.

Each mapping entry includes:

TABLE 3
MAPPING ENTRY

| Field | Example |
|---|---|
| **Object Name** | Electrolyser_1 |
| **Source Sim Param** | Idc (DC current) |
| **Target Sim Param** | H2_FlowRate |
| **Direction** | Bidirectional |
| **Unit Conversion** | A → Nm³/h |
| **Scaling** | *0.95 + 10 |
| **Sync Step** | 1 sec |

### D. *Synchronization Strategies*

#### 2) *Master-Slave Simulation Control*

One simulator is designated the master (usually the electrical simulator due to faster time scales) and controls time advancement. The slave (process simulator) is paused until data from the master is received. This ensures stability but may delay faster physics (e.g., chemical reactions).

#### *3) Least Common Multiple (LCM) Time Step*

Each simulator runs on its preferred timestep (e.g., 0.25s for electrical, 1s for process). Synchronization occurs at the least common multiple (e.g., every 5s). This is common in batch simulations and well-suited to off-grid hydrogen or ammonia systems.

#### 4) *Real-Time Mode with Co-sim Engine*

For applications like operator training or digital twins, real-time simulation requires both simulators to run in parallel using socket-based communication or shared memory. Latency and error handling become critical. Simulation time must never exceed real time.

### E. *Types of Data Exchanged*

Depending on the scenario, data types exchanged between simulators can include:

TABLE 4
TYPES OF DATA EXCHANGED

| Data Type | Example |
|---|---|
| **Analog** | Voltage (kV), Current (A), Speed (RPM) |
| **Discrete** | Fault condition, Start command |
| **Control** | PID Set Point, Load Demand, Safety Interlocks |
| **Process** | $H_2$ Flowrate, Tank Pressure, Valve Position |
| **Status** | ON/OFF, Alarm Code, Trip signal |

All values must be synchronized and, if needed, interpolated to align with mismatched simulation time steps.

### F. *Execution Flow*

A typical co-simulation time step involves:

- T = 0.00 s: Electrical simulator initializes voltage, current, frequency.
- T = 0.00 s: Data sent to process simulator.
- T = 0.25 s: Process simulator computes new process state, outputs load request.
- T = 0.25 s: Load demand returned to electrical simulator.
- T = 0.50 s: Both simulators advance time, loop continues.

If configured correctly, this sequence simulates a fully transient response across both domains.

### G. *Event Handling in Co-Simulation*

Real industrial systems face unplanned events. Co-simulation enables simulating these in a coordinated fashion:

- Voltage Sag → Electrolyser trips, hydrogen flow halts.
- Overpressure → Compressor motor load spikes.
- Frequency Dip → Load shedding initiated in electrical model, reducing process output.
- Solar Curtailment → Power delivery profile changes mid-simulation, electrolyser setpoint must adjust.

Simulation of these events requires both simulators to respond in milliseconds-to-seconds with accurate cause-effect propagation.

### H. *Example Use Case: Hydrogen-Ammonia Production System*

In this use case:

- Wind turbine power is modelled in the electrical simulator, providing a variable power profile.
- Four electrolysers modelled in the process simulator receive current setpoints from the electrical model.
- The process simulator calculates hydrogen production, tank pressure, and downstream flow to ammonia synthesis.
- Ramp-down and ramp-up events (100% → 30%) are modelled, and battery energy storage system (BESS) size is optimized to smooth out fluctuations.
- Controller logic is deployed to allow setpoint change if frequency dips below 49.8 Hz for >2s.

Resulting benefits:

- Accurate sizing of BESS and inverters
- Prevention of overpressure in electrolyser stacks
- Validation of operator control logic before commissioning

### I. Model Fidelity and Interoperability

Each unit in co-simulation must be configured for:

- Fidelity Level: Low-fidelity blocks for pre-FEED, high-fidelity for detailed design.
- Reset Behaviour: Ability to rollback or reset to last valid timestep during divergence.
- Solver Matching: Ensure compatible solver families (implicit/explicit) are used.
- Platform Interoperability: Support for APIs, open standards (FMI, OPC UA, Modbus TCP).

A modular design allows the same co-simulation configuration to scale across multiple projects or phases (FEED, EPC, O&M).

### J. Verification and Validation

A rigorous V&V process is essential:

- Unit Testing: Each simulator tested independently for time response, control stability, and steady-state convergence.
- Integration Testing: Co-simulation tested under nominal and stressed conditions (e.g., 30% solar availability, 2x load ramp).
- Scenario Testing: Full operational envelope tested including black start, grid failure, thermal excursions.
- Acceptance Criteria: KPIs such as Capex, Opex, trip rate, and hydrogen purity validated against design basis.

## IV. CASE STUDY: CO-SIMULATION FOR GREEN HYDROGEN AND AMMONIA PRODUCTION

### A. Overview and Project Context

Green hydrogen and ammonia production are rapidly emerging as key solutions to decarbonize hard-to-abate sectors such as fertilizers, steel, maritime transport, and long-duration energy storage. These facilities rely on a complex interplay between:

- Renewable electricity supply (solar PV, wind turbines)
- Electrolyser units that convert water into hydrogen
- Thermal and chemical processes that combine hydrogen with nitrogen to create ammonia
- Energy storage systems that balance generation and process demand
- Digital control architectures that supervise operations in real-time

The co-simulation case study described here models a 700 MW solar and wind-powered green hydrogen facility integrated with a downstream ammonia plant. The goal of this project was to:

- Optimize system sizing and reliability
- Evaluate transient responses under different operating scenarios
- Validate startup/shutdown sequences
- Improve accuracy of Levelized Cost of Hydrogen (LCOH) and Levelized Cost of Ammonia (LCOA)
- Enable control architecture design through simulation-informed decisions

### B. Co-Simulation Architecture

This project used a co-simulation framework composed of:

- A power system simulator (anonymized) performing Time-Domain Load Flow (TDLF) and Transient Stability (TS) analysis.
- A process simulation environment modelling electrolyser, hydrogen flows, tanks, and the ammonia synthesis loop.
- An interface layer using mapped unit operations, shared time synchronization, and CSV/XML data exchange.
- Optional integration with AI/ML modules for pattern recognition and anomaly detection (via simulated sensor data).

TABLE 5
MAPPING ELEMENTS

| Electrical Component | Process Counterpart |
|---|---|
| BESS Inverter | Dynamic electrolyser load controller |
| Wind Turbine Bus | Green hydrogen power supply node |
| Transmission Line | Shared impedance model to match tank inrush |
| Cable Loss Model | Process-side heat exchanger offset |
| Substation Frequency | Setpoint trigger for compressor shutdown |

### C. Simulated System Layout

Electrical Side

- 1.5 GW Wind Farm (70 km transmission)
- Grid-forming inverters and BESS
- Dynamic line impedance models
- Fault injection system (line sag, generator trip)
- 132/11 kV transformers

Process Side

- Four alkaline electrolyser banks (175 MW each)
- Pressurized hydrogen storage tanks (with ramp-in logic)
- Ammonia synthesis loop with plug flow reactor
- Thermal energy recovery system
- Compressor-driven nitrogen supply
- Process buffer tanks for decoupling

The electrical simulator determined voltage/current/frequency at each bus, while the process simulator computed thermal loads, hydrogen production, and ammonia yield.

### D. Operating Scenarios

The co-simulation covered 10 operating scenarios, including:

- Nominal Operation: All units online, 100% renewable input.
- 30% Wind Scenario: Intermittent power, BESS used to maintain electrolyser load.
- Grid Fault (5s): Frequency dip followed by BESS and generator response.
- Ramp-Up (0–100%): Start of day sequence over 10 minutes.
- Ramp-Down (100–30%): Cloud cover + turbine curtailment.
- Compressor Trip: Causing a hydrogen backpressure scenario.
- Voltage Sag at 33kV: Impacts electrolyser controller.
- Thermal Overload in Ammonia Loop: Causes demand curtailment.
- Battery Shortfall: Inadequate BESS response triggers cascade trip.
- Black Start Simulation: No grid, start from cold storage using diesel gen-set.

Each scenario was run with co-simulation enabled and then separately with decoupled simulators to measure performance, accuracy, and Capex/Opex impact.

### E. Results and Key Insights

#### 1) Load and Generation Matching

During low wind scenarios, co-simulation accurately modelled:

- Electrolyser ramp-down from 100% to 30% in 40 seconds
- Voltage drops from 11 kV to 9.8 kV
- DC load reduction in process simulator mapped via Idc
- Hydrogen tank inflow rate matched 15% lower than static model

This helped right-size the BESS from an originally planned 250 MWh to 165 MWh, saving ~$9M in Capex.

#### 2) Transient Fault Response

In a simulated 5-second voltage sag:

- Co-simulation showed electrolyser tripping at 9.2 kV threshold
- Process simulator tripped downstream valves and compressor logic
- Hydrogen production halted 3.5s after fault, ammonia yield recovered in 25 minutes
- Without co-simulation, the process model incorrectly kept hydrogen yield steady

This revealed a critical failure in the DCS interlock timing logic, enabling correction pre-commissioning.

#### 3) Storage Optimization

The hydrogen tank's initial design capacity was 12 hours. Co-simulation showed:

- Ammonia synthesis downtime during voltage/frequency issues was only ~2 hours/week
- Storage could be cut to 6 hours without process degradation
- Estimated Capex savings of ~$14M by reducing tank volume and insulation

### F. Digital Twin Integration

The final co-simulation configuration was used as a base for the digital twin. Real-time models were deployed in parallel to the process:

- Electrical simulator ran every 1s in observer mode
- Process simulator used SCADA tags to validate $H_2$ flowrate predictions
- Alarm simulations used historical faults to train operators
- Energy management optimization reduced LCOH from $4.80/kg to $3.90/kg

### G. Operator Training and Control Testing

Using co-simulation, a full Operator Training Simulator (OTS) was built:

- 25 startup and 40 fault scenarios embedded
- Control logic updated based on co-simulation response time
- Operators learned safe ramp-down procedures and power curtailment logic
- Live tests matched simulation predictions within 5–10% accuracy

### H. Economic Impact Summary

TABLE 6
ECONOMIC IMOACT SUMMARY

| Metric | Value (With Co-Sim) | Value (Without Co-Sim) |
|---|---|---|
| LCOH | $3.90/kg | $4.80/kg |
| Capex | $675M | $730M |
| BESS Size | 165 MWh | 250 MWh |
| $H_2$ Tank | 6-hour buffer | 12-hour buffer |
| DCS Redesigns | 1 cycle | 3 cycles |
| Commissioning Delay | 0 days | ~23 days |

### I. Lessons Learned

- Co-simulation uncovered system interactions not visible with traditional simulations.
- It enabled proactive changes in sizing, interlocks, and control architecture.
- High-fidelity modelling of transients proved critical for economic and safety performance.
- Scenario-based design using co-simulation should be mandatory for complex greenfield electrification projects.

## V. BENEFITS OF CO-SIMULATION

### A. Overview

Industrial projects are increasingly driven by three performance pillars: cost efficiency, operational reliability, and carbon reduction. Co-simulation directly contributes to all three by enabling the simultaneous modelling of multiple domains– electrical, thermal, chemical, mechanical–under unified logic and time resolution. This section outlines the tangible and strategic benefits realized by project developers, engineering teams, plant operators, and asset owners.

### B. Design Accuracy and Fidelity

#### 1) Accurate Load Behaviour

Traditional design workflows often use static, worst-case values for process loads. This results in oversized transformers and cables. Co-simulation allows dynamic load modelling, improving sizing accuracy and reducing CAPEX:

- Real-time variation of process loads based on operating conditions
- Capture of peak demand during transitions (start-up, shutdown, ramp-up)
- More realistic electrical stress analysis (inrush, harmonic impact, voltage sag)

Example: In a hydrogen facility, load profiles of electrolysers ramping up over 10 minutes were modelled, allowing correct transformer and cable sizing. Without co-simulation, the transformer would have been oversized by 40%.

#### 2) Avoiding Over-Design and Over-Spending

By removing worst-case assumptions and enabling scenario-based sizing, co-simulation leads to:

- Smaller equipment footprints
- Reduced material and labour cost
- Better utilization of installed assets

### C. Enhanced Operational Resilience

#### 1) Improved Fault Response

With transient co-simulation, systems can be tested against:

- Voltage and frequency excursions
- Thermal overloads
- Load shedding triggers
- Grid blackout conditions

This results in more robust control sequences and automatic response plans.

2) Control Logic Verification

Plant control strategies can be tested under live simulation conditions, reducing the risk of:

- Delayed interlocks
- Undetected logic races
- Non-deterministic valve/motor behaviour
- Incomplete shutdown procedures

Example: A hydrogen facility identified a 2.2-second delay in its compressor interlock logic during a grid fault simulation, which would have caused critical tank overpressure.

### D. Lower Commissioning Risk

#### 1) Factory Acceptance Test (FAT) Simulation

Using co-simulation, teams can virtually commission the system before site integration. Benefits include:

- Early identification of configuration issues
- Debugging of mismatched unit IDs, timeouts, and PID loop behaviour
- Digital validation of critical path

#### 2) Reduction in Field Errors

The number of corrective changes during startup is significantly reduced because co-simulation enables:

- Pre-tested start-up sequences
- Validated operator response scenarios
- Early detection of invalid setpoints or trip thresholds

Benchmark: Projects using co-simulation reported 25-40% fewer commissioning-related change orders compared to those using decoupled simulations.

### E. Accurate Economic Modelling

#### 1) Real-Time Feedback to Business Models

In most electrification and energy transition projects, key financial metrics such as:

- Levelized Cost of Hydrogen (LCOH)
- Internal Rate of Return (IRR)
- Net Present Value (NPV)
- Operational OPEX

are directly impacted by dynamic system behaviour.

By running co-simulation scenarios across energy price curves, power purchase agreements (PPAs), or carbon taxes, developers can better predict:

- Downtime-related losses
- Storage oversizing or under sizing
- Optimal load vs. price dispatch

2) Lifecycle Financial Optimization

Unlike snapshot simulations, co-simulation supports 8760-hour annual simulation runs, enabling whole-year financial comparisons.

### F. *Sustainability and Carbon Efficiency*

Co-simulation helps reduce both Scope 1 (direct emissions) and Scope 2 (purchased electricity) carbon footprints by:

- Optimizing power-to-fuel conversion efficiencies
- Minimizing flare or vent cycles due to process overpressure
- Coordinating load with carbon-intensity of power source (e.g., high solar → max electrolyser use)

Scenario: A 700 MW hydrogen plant operating under co-simulation achieved a 12% reduction in electricity losses, equating to ~48,000 $tCO_2$/year avoided emissions.

### G. *Better Human-Machine Integration*

1) *Operator Training*

With co-simulation feeding real-time digital twins, operator training can:

- Mimic real control room logic
- React to variable weather and demand inputs
- Include blackout recovery and safe shutdowns

Operators trained on co-simulation-based OTS (Operator Training Simulators) performed 25–50% better in first-week live operations.

2) *Safety and Compliance*

Simulated safety scenarios allow:

- Verification of SIL-rated systems
- Emergency trip validation
- Alarm hierarchy validation

### H. *Lifecycle Continuity of Models*

1) From FEL to O&M

One of the most overlooked benefits of co-simulation is that models can evolve across the project lifecycle:

TABLE 7
MODEL LIFECYCLE

| Phase | Role |
|---|---|
| **FEL-1** | Option screening, initial sizing |
| **FEL-2** | Integration of process-electrical logic |
| **FEL-3** | Digital twin and scenario planning |
| **EPC** | FAT, control validation, model tuning |
| **O&M** | Real-time twin, operator training, efficiency upgrades |

### I. *Interdisciplinary Collaboration*

Co-simulation acts as a communication bridge between:

- Electrical engineers
- Process/chemical engineers
- Control systems engineers
- Project financiers

By creating shared simulation environments, teams can:

- Align on assumptions
- Identify integration conflicts early
- Avoid late-phase scope creep

### J. *Regulatory and Compliance Readiness*

Emerging regulations now expect:

- Grid connection impact studies (e.g., under IEEE 1547, CA Rule 21)
- Dynamic load response verification (e.g., for demand response programs)
- Integration with market dispatch systems (e.g., via OPC UA or EMS signals)

Co-simulation helps ensure compliance by testing systems under expected regulatory conditions.

### K. *Comparative Benefit Summary*

TABLE 8
COMPARATIVE BENEFIT SUMMARY

| Domain | Without Co-Simulation | With Co-Simulation |
|---|---|---|
| Transformer Sizing | Based on worst-case static load | Based on real load profiles |
| BESS Sizing | Arbitrary or overestimated | Tied to process flexibility and outage profiles |
| Control Testing | Manual and sequential | Simultaneous, real-time verification |
| Safety Cases | Assumption-based | Scenario-tested |

| | | |
|---|---|---|
| CAPEX | Overdesigned | Optimized |
| LCOH Accuracy | ±20% | ±5–10% |
| Operator Preparedness | Low | High (with OTS) |
| Commissioning Delays | Common | Minimized |

## VI. CHALLENGES AND LIMITATIONS OF CO-SIMULATION

Co-simulation, the technique of coupling multiple simulation tools or models to study complex systems, offers great potential in multidisciplinary engineering, cyber-physical systems, and large-scale system design. However, despite its advantages, co-simulation faces several challenges and limitations that affect its efficiency, accuracy, and practical usability.

### *A. Licensing Interoperability*

One of the primary challenges in co-simulation arises from licensing incompatibilities between different simulation software. Many simulation tools are commercial products with proprietary licenses, often imposing restrictions on integration or redistribution of models. These licenses can limit the ability to share co-simulation components or require costly additional licenses for coupling software. The lack of flexible licensing frameworks makes it difficult to create seamless co-simulation environments, especially when combining tools from multiple vendors or academic projects. As a result, organizations may face legal or financial barriers that hinder collaborative simulation efforts.

### *B. Time Resolution Mismatch*

Co-simulation involves coupling simulators that may operate at different time steps or sampling frequencies. For example, a mechanical simulator may use millisecond-level time steps, while an electrical power system simulator may run at microsecond intervals. This mismatch in time resolution complicates synchronization and data exchange between simulators. If the time steps are not properly coordinated, the co-simulation can suffer from inaccuracies or numerical instabilities. Managing disparate time scales requires sophisticated interpolation, extrapolation, or multi-rate integration schemes, which increase implementation complexity and computational load.

### *C. Convergence and Stability Issues*

When multiple simulators interact in a co-simulation, ensuring numerical convergence and stability is nontrivial. Each simulator typically solves its equations independently, exchanging boundary conditions or interface variables only at discrete synchronization points. Poorly matched solver algorithms or interface models can lead to oscillations, divergence, or slow convergence in the coupled system. These convergence issues are particularly pronounced in strongly coupled systems with stiff dynamics or tight feedback loops. Designing stable co-simulation schemes often requires iterative coupling, relaxation techniques, or implicit integration methods, which add to computational overhead and development time.

### *D. Lack of Universal Standards*

The co-simulation field currently suffers from the absence of universal, widely adopted standards. While standards like FMI and HLA provide a foundation, they are not yet widely adopted across industrial sectors and often lack support for real-time integration, limiting their practical applicability. This fragmentation leads to interoperability challenges and forces engineers to develop custom adapters or interfaces for each co-simulation setup. The lack of standardized data models, communication protocols, and synchronization methods slows down adoption and increases maintenance complexity. Without common standards, portability and reusability of co-simulation components remain limited.

### *E. Intellectual Property and Data Exchange Concerns*

Another significant limitation in co-simulation relates to intellectual property (IP) protection and secure data exchange. Often, simulation models represent proprietary technology, sensitive algorithms, or trade secrets. Sharing such models in a co-simulation environment risk exposing confidential information. Moreover, transmitting large volumes of simulation data between simulators, sometimes across organizational or geographic boundaries, raises concerns about data integrity, confidentiality, and compliance with data governance policies. Ensuring secure interfaces, encryption, and controlled access adds layers of complexity and may restrict collaboration between partners.

In summary, while co-simulation provides a powerful framework for integrated system analysis, its practical implementation is constrained by licensing conflicts, time synchronization challenges, numerical stability problems, a fragmented standards landscape, and IP/data security issues. Overcoming these limitations requires continued development of flexible licensing models, robust multi-rate algorithms, stable coupling methods, universal standards, and secure data exchange mechanisms.

Addressing these barriers is essential for wider adoption and effective use of co-simulation in complex engineering domains.

## VII. FUTURE OUTLOOK AND RECOMMENDATIONS FOR CO-SIMULATION

Co-simulation is rapidly evolving as a critical methodology for analysing complex systems that span multiple domains such as mechanical, electrical, control, and software engineering. As industries push towards more integrated, data-driven, and real-time system designs, co-simulation is poised to play an even more pivotal role. However, to fully realize its potential, several strategic advancements and industry-wide efforts are essential.

### *A. Industry-Wide Standardization*

A key future direction for co-simulation is the establishment of universal, industry-wide standards that promote interoperability, portability, and reusability of simulation components. Existing standards such as the Functional Mock-up Interface (FMI) provide a solid foundation, but they lack comprehensive adoption across all industrial sectors and do not yet fully address real-time and hybrid simulation needs. The future will likely see the expansion and refinement of these standards to incorporate richer metadata, standardized semantic models, and cross-domain interfaces.

Industry consortia and standard bodies should collaborate closely with software vendors and end-users to define clear, extensible, and open standards that accommodate the diverse requirements of different fields. This standardization will enable plug-and-play co-simulation, reduce integration costs, and foster an ecosystem where models and simulators can be shared confidently without extensive customization.

### *B. Integration with AI and Machine Learning Models*

The convergence of co-simulation with artificial intelligence (AI) and machine learning (ML) represents a transformative opportunity. AI/ML can enhance co-simulation in multiple ways: by enabling surrogate modelling to reduce computational complexity, by automating parameter tuning and optimization during simulation runs, and by improving fault detection and predictive maintenance through data-driven insights.

Future co-simulation platforms should natively support the seamless integration of AI/ML models alongside traditional physics-based simulators. This integration will enable hybrid modelling approaches that combine first-principal accuracy with AI adaptability, yielding faster and more intelligent simulations. Additionally, the use of reinforcement learning within co-simulation loops could enable adaptive control strategies to be tested in virtual environments before deployment.

### *C. Real-Time Simulation and Hardware-in-the-Loop (HIL) Integration*

As industrial systems become increasingly cyber-physical, the demand for real-time simulation capabilities grows. Real-time co-simulation enables hardware-in-the-loop (HIL) testing, where physical controllers or components are connected to simulated environments for validation and verification under realistic operating conditions. This is critical for sectors like automotive, aerospace, and energy systems, where safety and performance depend on thorough system-level testing.

Advancements in co-simulation frameworks must focus on reducing latency, improving synchronization precision, and supporting heterogeneous hardware interfaces. Leveraging high-performance computing, edge computing, and deterministic networking protocols will be vital to achieve reliable real-time co-simulation at scale.

### *D. Digital Twin Convergence*

Digital twins–virtual replicas of physical assets–are becoming central to Industry 4.0 and smart manufacturing initiatives. Co-simulation plays a crucial role in the development and operation of digital twins by enabling multi-domain modelling and continuous system updates based on live data.

The future will see a tighter convergence between co-simulation platforms and digital twin architectures, facilitating closed-loop simulations that incorporate real-time sensor data, operational feedback, and AI-driven analytics. This will allow more accurate prediction of system behaviour, proactive maintenance, and dynamic optimization. Building digital twins with modular co-simulation capabilities will improve scalability and adaptability as physical systems evolve.

Recommendations Summary:

- Drive Standardization: Support and contribute to open, extensible co-simulation standards that cover cross-domain and real-time needs.
- Embrace AI/ML: Develop frameworks that seamlessly integrate AI/ML models for hybrid simulation and intelligent automation.
- Enhance Real-Time Capabilities: Invest in technologies and protocols that enable robust, low-latency real-time co-simulation and HIL testing.
- Align with Digital Twins: Foster integration with digital twin platforms to enable continuous, data-driven system lifecycle management.

By addressing these focus areas, co-simulation will mature into a foundational technology that supports increasingly complex, interconnected, and intelligent engineering systems across industries.

## VIII. CONCLUSION

Co-simulation represents a significant leap forward in the realm of multi-domain industrial design and operational analysis. As the industry transitions toward full process electrification, co-simulation emerges as a key enabler for designing resilient, digitally integrated, and economically optimized systems. By bridging the gap between electrical and process domains, it ensures that complex interactions are not only understood, but proactively managed to accelerate decarbonization and reduce project risk. Co-simulation enables the coupling of diverse domain-specific models and simulators, providing a holistic understanding of system behaviour that is critical for optimizing performance, enhancing reliability, and ensuring cost-effectiveness. When correctly implemented, co-simulation serves as a powerful enabler for industrial innovation. By facilitating the concurrent analysis of interacting subsystems–mechanical, electrical, thermal, control, and software–it allows engineers to uncover emergent phenomena that would remain hidden in isolated models. This comprehensive insight helps identify bottlenecks, potential failures, and inefficiencies early in the design phase, thereby reducing costly redesigns and operational disruptions. In sectors like green hydrogen and ammonia production, where process complexity, safety requirements, and environmental goals converge, co-simulation ensures that system integration challenges are managed proactively and robustly.

Moreover, co-simulation supports economically viable deployment strategies by enabling detailed techno-economic analyses. By integrating cost models and operational constraints into multi-domain simulations, stakeholders can evaluate different design options, control strategies, and technology mixes to find optimal solutions that balance capital expenditures, operational expenses, and lifecycle emissions. This capability is essential for navigating the economic uncertainties and regulatory frameworks associated with decarbonization and energy transition initiatives.

As industrial systems continue to grow in complexity–driven by digitalization, automation, and sustainability mandates–co-simulation will become foundational to the next generation of digital engineering workflows. It will serve as a critical bridge between digital twins, real-time monitoring, and AI-driven decision-making, enabling closed-loop system optimization throughout the asset lifecycle. The fusion of physics-based modelling with data analytics and machine learning within co-simulation environments promises faster innovation cycles, enhanced predictive maintenance, and adaptive control systems capable of responding dynamically to changing operational conditions.

Despite current challenges such as licensing barriers, time-step synchronization, convergence difficulties, lack of universal standards, and intellectual property concerns, ongoing advancements in standards development, tool interoperability, and secure data exchange protocols will unlock broader adoption. The growing convergence of co-simulation with emerging technologies like AI/ML, real-time hardware-in-the-loop testing, and digital twin frameworks will further elevate its role from a niche engineering technique to an indispensable industry practice.

In conclusion, Co-simulation is not just a simulation methodology - it is becoming a foundational approach for designing and operating complex, electrified industrial systems that empowers industries to design, validate, and operate complex, multi-physics systems with unprecedented confidence and efficiency. Its ability to integrate diverse models and provide comprehensive system insights will be instrumental in achieving resilient, sustainable, and economically viable industrial infrastructures. As we look to the future, embracing co-simulation as a core component of engineering and operational toolsets will be essential for industries aiming to thrive in an era defined by complexity, connectivity, and rapid technological change.