QANTIC

Success Factors in Revenue Modelling for Large-Scale Energy Storage

White Paper

Qantic is a software provider offering applications for optimized design of energy systems – visit us on www.qantic.com

Executive Summary

What to expect from this white paper?

Dear reader,

In this white paper, we examine the success factors for modelling the revenues of utility-scale energy storage systems. These systems participate in multiple markets and **stack revenues** from trading, ancillary services, and grid-support functions.

Robust models must reflect **technical constraints** like degradation and system losses, while also accounting for realistic **dispatch strategies**. One case study illustrates how **foresight assumptions** impact revenue projections in continuous **intraday trading**. Another highlights the role of **market depth** when estimating aFRR revenues, especially for large systems. Furthermore, case studies are provided to assess technical aspects, **grid restrictions** and **hybridization.**

It is demonstrated how PV-battery **co-location** helps to cope with limited grid access. Finally, we provide a **structured checklist** and practical examples to help developers, investors, and utilities evaluate whether their models are fit for purpose.

Have a valuable read.

Best regards

Thomas Kalitzky | Managing Director | Qantic GmbH

Content

Introduction

Situation

Energy storage is a key enabler in the energy transition.

Applications range from small behind-the-meter systems to large front-of-the-meter installations.

Systems may be standalone BESS or integrated with PV and wind in hybrid configurations.

To assess profitability and develop solid business cases, detailed financial modelling is essential—including all cost elements and revenue streams.

Challenge

Revenue models often involve multiple value streams across several markets.

In large-scale systems, multi-market optimization is typically required.

Capturing complexity without sacrificing transparency is difficult.

Key Question

What are the success factors for modelling revenue streams in large-scale energy storage projects?

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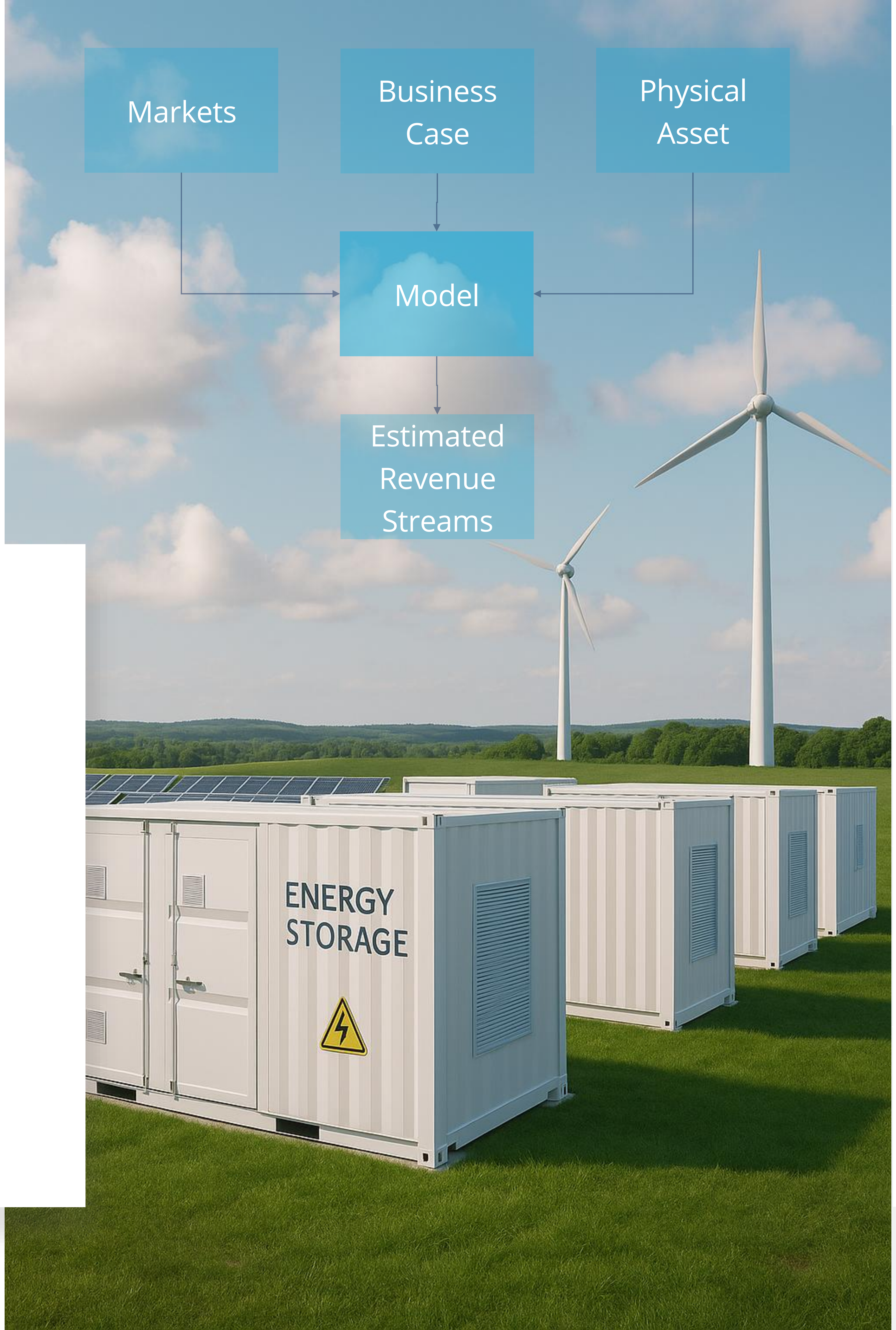


Core Requirements for Robust and Reliable Modelling

Technical Model

– Technology-specific **parameters** must be reflected realistically

– Accurate representation of **battery degradation** and system limitations

– Technical model must be **integrated** into market optimization model

Optimization Strategy

– Multi-market optimization and realistic **trading strategies**

– Explicit treatment of **foresight** (perfect vs. limited) and **market liquidity**/depth

– **Backtesting** against real portfolio performance and battery indices is essential

Flexibility and Future Readiness

– Easy adaptation to changes in **market design** and regulation

– Ability to model **grid constraints** evolve over time (e.g. curtailment, redispatch)

– Support for **hybrid systems,** including PV, wind, heat, and hydrogen integration

Technical Model:
From Physical Behavior to Financial Impact

Battery Operation	Physical Effects	Financial Outcomes
– Charge/Discharge – State of Charge – Cycle Count – Power Limits	– Efficiency Loss – Capacity Fade – Degradation Rate – Temperature Limits	– Revenues – O&M Costs – Lifetime and Replacement Investment

Situation

- A sound technical model is the foundation of any revenue projection for storage systems
- System performance and degradation directly impact financial outcomes
- Accurate modelling of technical behavior ensures credible and reliable results

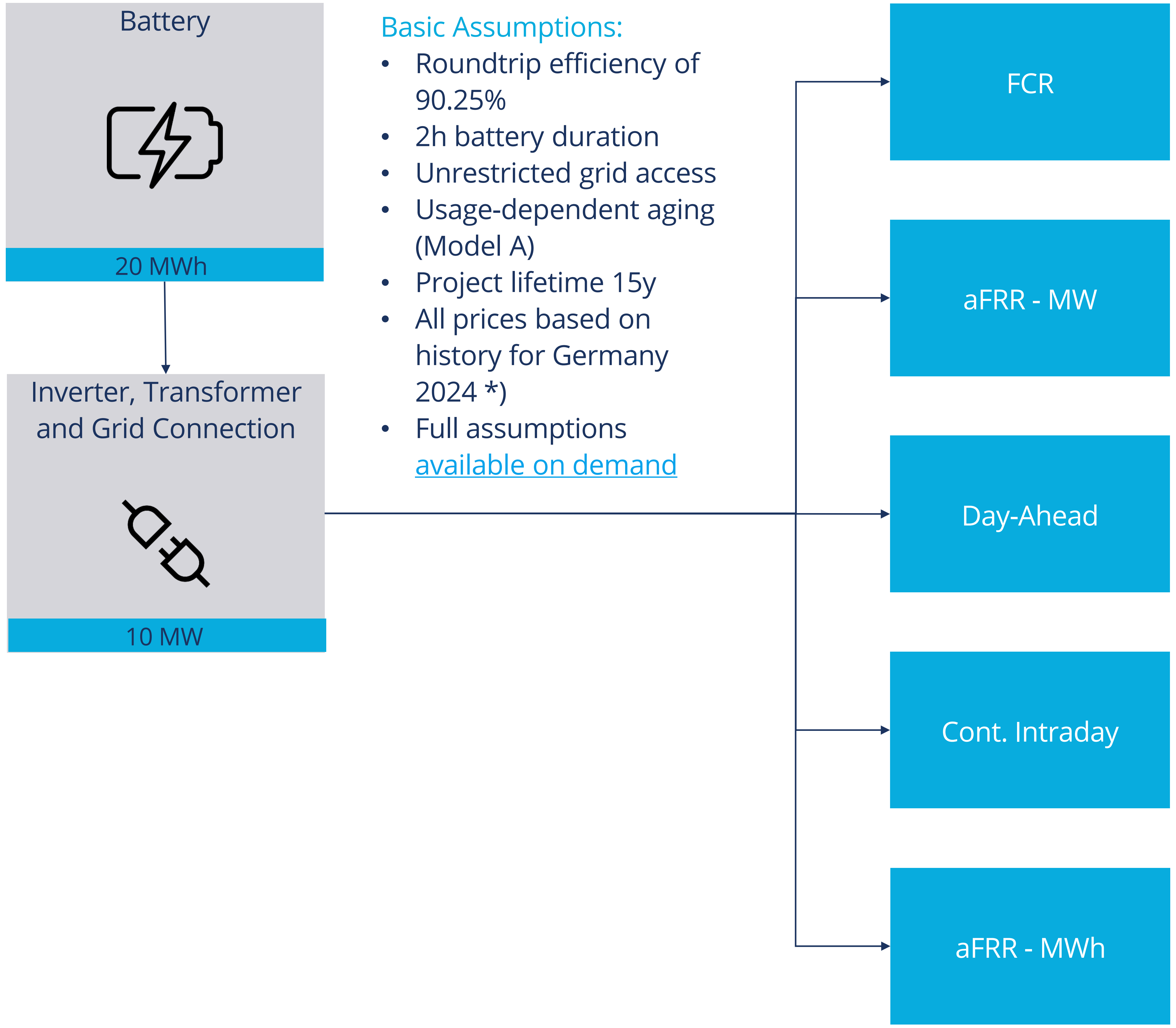
Challenge

- Battery degradation is complex and highly usage-dependent
- Simplified assumptions often lead to unrealistic projections of lifetime, performance, and costs
- Neglecting technical constraints undermines the quality of decision-making
- The chosen degradation model must be suited for integration into the optimization strategy—otherwise, revenue projections may not justify the increased battery aging caused by cycling

What a Good Model Looks Like

- Includes realistic, usage-based degradation modelling
- Reflects roundtrip efficiency, capacity fade and power limits
- Captures system-specific parameters such as inverter limits and efficiencies
- Embeds the technical model (incl. degradation) into the business case, trading logic, and optimization strategy

Technical Model – Example:
Impact of Degradation-Aware Optimization on Revenue



Basic Assumptions:

- Roundtrip efficiency of 90.25%
- 2h battery duration
- Unrestricted grid access
- Usage-dependent aging (Model A)
- Project lifetime 15y
- All prices based on history for Germany 2024 *)
- Full assumptions available on demand

Model A

With Degradation

Revenue: 100%

Model B

No Degradation

Revenue: 141%

Technical model has strong influence on revenues

- Failing to account for battery degradation in the revenue model can lead to a significant **overestimation** of revenues. It not only inflates the expected capacity available at end-of-life, but also distorts the optimization logic itself.
- If the model ignores degradation-related opportunity costs and does not limit the number of allowed cycles, it may result in **excessive throughput** and overtrading. The model may then target small price spreads that don't justify the additional aging.
- While neglecting the battery aging in the optimization can increase short-term revenues, the long-term cost of accelerated battery wear—especially **cell replacement**—can outweigh the gains.
- Even with constraints on the maximum number of cycles per day, revenues may still not justify the degradation incurred. Hence, the model should reflect both **degradation cost** and warranty related **cycle limits** within the optimization

*) All case studies are based on historical German market data and model configurations that reflect German market rules and regulation. Q-System provides flexibility to adjust configurations to various international market designs, trading rules and regulations. Model comparison is derived by configuring two differently parameterized model runs in our Q-System tool.

Optimization Strategy:
The Right Market, at the Right Time

Dispatch Decision

Day-Ahead Market
- Price Forecasting
- Cycle Restrictions
- Expectation other Markets

Intraday Market
- Limited Foresight
- Rolling Optimization
- SoC-Constraints
- Backtested

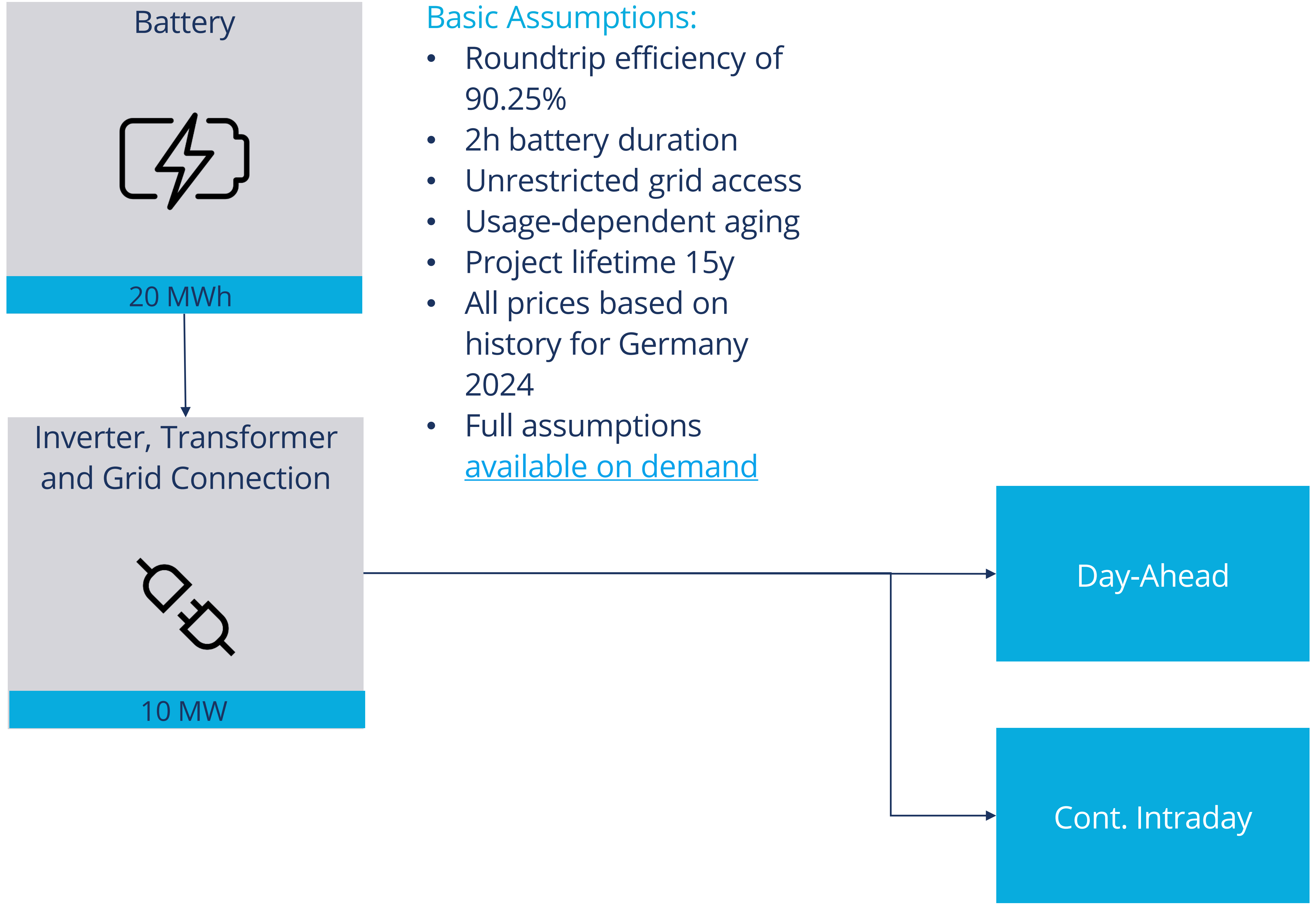
Ancillary Services (FCR, aFRR, ...)
- Limited Liquidity
- SoC-Management
- Expected Degradation
- Capacity vs. Energy

Situation
- Revenue optimization is at the core of financial modelling for storage systems
- It must reflect real-world operations across energy and reserve markets (ancillary services)
- A robust optimization framework ensures realistic and actionable revenue projections

Challenge
- Technical constraints (e.g. degradation) must be embedded in the strategy
- Continuous intraday trading requires modelling under limited foresight—perfect foresight produces unrealistic results
- Reserve market revenues depend on accurate state-of-charge (SoC) management; market depth and liquidity constraints must be accounted for, especially in large systems
- Model quality must be balanced with data availability, particularly if the model is used for long-term projections

What a Good Model Looks Like
- Incorporates realistic limitations and trading strategies (e.g. imperfect foresight)
- Includes robust SoC management, especially for reserve markets
- Models liquidity and scalability limits for market participation
- Backtested against historical trades, real portfolio performance, or battery benchmarks

Optimization Strategy – Example 1/2:
Limited Foresight vs. Perfect Foresight in Intraday Trading



Basic Assumptions:

- Roundtrip efficiency of 90.25%
- 2h battery duration
- Unrestricted grid access
- Usage-dependent aging
- Project lifetime 15y
- All prices based on history for Germany 2024
- Full assumptions available on demand

Model A
Limited Foresight

Revenue: 100%

Model B
Perfect Foresight (Delivery Day)

Revenue: 125%

Realistic foresight model is important to avoid overestimation of intraday revenues

- Accurately modelling foresight is especially important when estimating revenues from **continuous intraday trading**. Assuming perfect foresight can significantly overstate expected revenues.
- In our simulations, we apply a rolling intrinsic optimization using a limited foresight window. Our approach has been **backtested** against actual trading portfolio performance and shows deviations of **less than 5%.**
- In this analysis, we compare our standard limited foresight setup with a benchmark case that uses perfect foresight based on the **ID1 index** of all 96 (24×4) 15-minute intraday contracts. All other assumptions remain identical.

Optimization Strategy – Example 2/2:
Limited vs. Unlimited Market Liquidity

Battery
200 MWh

Inverter, Transformer and Grid Connection
100 MW

aFRR - MW
Day-Ahead
Cont. Intraday
aFRR - MWh

Basic Assumptions:

- Roundtrip efficiency of 90.25%
- 2h battery duration
- Unrestricted grid access
- Usage-dependent aging
- Project lifetime 15y
- All prices based on history for Germany 2024
- Full assumptions available on demand

Model A
Limited Market Liquidity aFRR
Revenue: 100%

Model B
Unlimited Market Liquidity aFRR
Revenue: 157%

Accounting for market liquidity constraints can be crucial

- To highlight the importance of modelling **market liquidity**, we analyzed an extreme case of a100 MW battery system under two scenarios: actual market conditions vs. unlimited liquidity.
- In 2024, the **aFRR market** in Germany was especially attractive for batteries and contributed significantly to the revenue stack. However, aFRR energy volumes are often limited, meaning large systems can only access a small share of those opportunities.
- Despite high prices and attractive spreads compared to intraday markets, a 100 MW system may only benefit with a small fraction of its capacity, respectively it will only be **occasionally activated** with the full output power.
- While this clearly matters for larger systems, it's also relevant for smaller ones when assessing whether expected revenues rely on market segments that may be **cannibalized** as storage deployment grows.

Flexibility and Future Readiness:
As Specific as Needed, as General as Possible

Situation
- The energy market is changing rapidly—new regulations, market mechanisms, and technologies emerge continuously
- Revenue models must be adaptable to remain valid throughout a project's lifetime
- Companies needs and focus markets evolve over time

Challenge
- Regulatory frameworks differ across countries and change frequently
- Grid access may be temporarily limited due to curtailment or redispatch
- Hybrid systems (PV, wind, heat, hydrogen) increase modelling complexity
- Static models become obsolete and limit long-term planning

What a Good Model Looks Like
- Modular and adaptable to different national regulations and evolving policy frameworks
- Supports modelling of grid access restrictions and curtailment events
- Enables integration of hybrid configurations and multi-sector systems
- Easily extendable to new market products, bidding formats, or technical requirements

Flexibility and Future Readiness – Example 1/2:
Impact of Changing Curtailment Rules on Standalone Storage

Battery

100 MWh

Inverter, Transformer and Grid Connection

Basic Assumptions:
- Roundtrip efficiency of 90.25%
- 2h battery duration
- Unrestricted grid access
- Usage-dependent aging
- Project lifetime 15y
- All prices based on history for Germany 2024
- Full assumptions available on demand

Grid Restriction:

Restriction for Model A:
- Grid-withdrawal (charge) is limited to zero in 12% of all hours (mostly during 8-18)
- Grid-infeed (discharge) is limited to zero in 7% of all hours, predominantly on sunny summer days
- Otherwise grid access is unlimited

No restriction for Model B

FCR

aFRR - MW

Day-Ahead

Cont. Intraday

aFRR - MWh

Model A
With Grid Restriction

Revenue: 100%

Model B
Without Grid Restriction

Revenue: 119%

Evolving limitations in grid access need to be handled by the model

- Obviously, the results of this comparison strongly depend on the **extent of curtailment**. The more grid access is restricted, the greater the reduction in revenues.
- Interestingly, the impact on revenues is **not linear** with the amount of curtailed energy. It also depends on when curtailment occurs and which market the battery would otherwise serve.
- Multi-market optimization can partially compensate by **shifting dispatch** to second-best opportunities that align with grid limits—but this effect is hard to predict.
- Therefore, grid restrictions must be carefully reflected in the model—including how they may **evolve over the lifetime** of the project.

Flexibility and Future Readiness – Example 2/2:
co-location as an Option to Address Grid Restrictions

Battery

100 MWh

Inverter, Transformer and Grid Connection

Solar panels

50 MWp

Basic Assumptions:
- Roundtrip efficiency of 90.25%
- 2h battery duration
- Unrestricted grid access
- Usage-dependent aging
- Project lifetime 15y
- All prices based on history for Germany 2024
- German PV profile
- Full assumptions available on demand

Grid Restriction:

Restriction for Model A:
- Grid-withdrawal (charge) is limited to zero in 12% of all hours (mostly during 8-18)
- Grid-infeed (discharge) is limited to zero in 7% of all hours, predominantly on sunny summer days
- Otherwise grid access is unlimited

No restriction for Model B

FCR

aFRR - MW

Day-Ahead

Cont. Intraday

aFRR - MWh

Model A
With Grid Restriction

Revenue: 100%

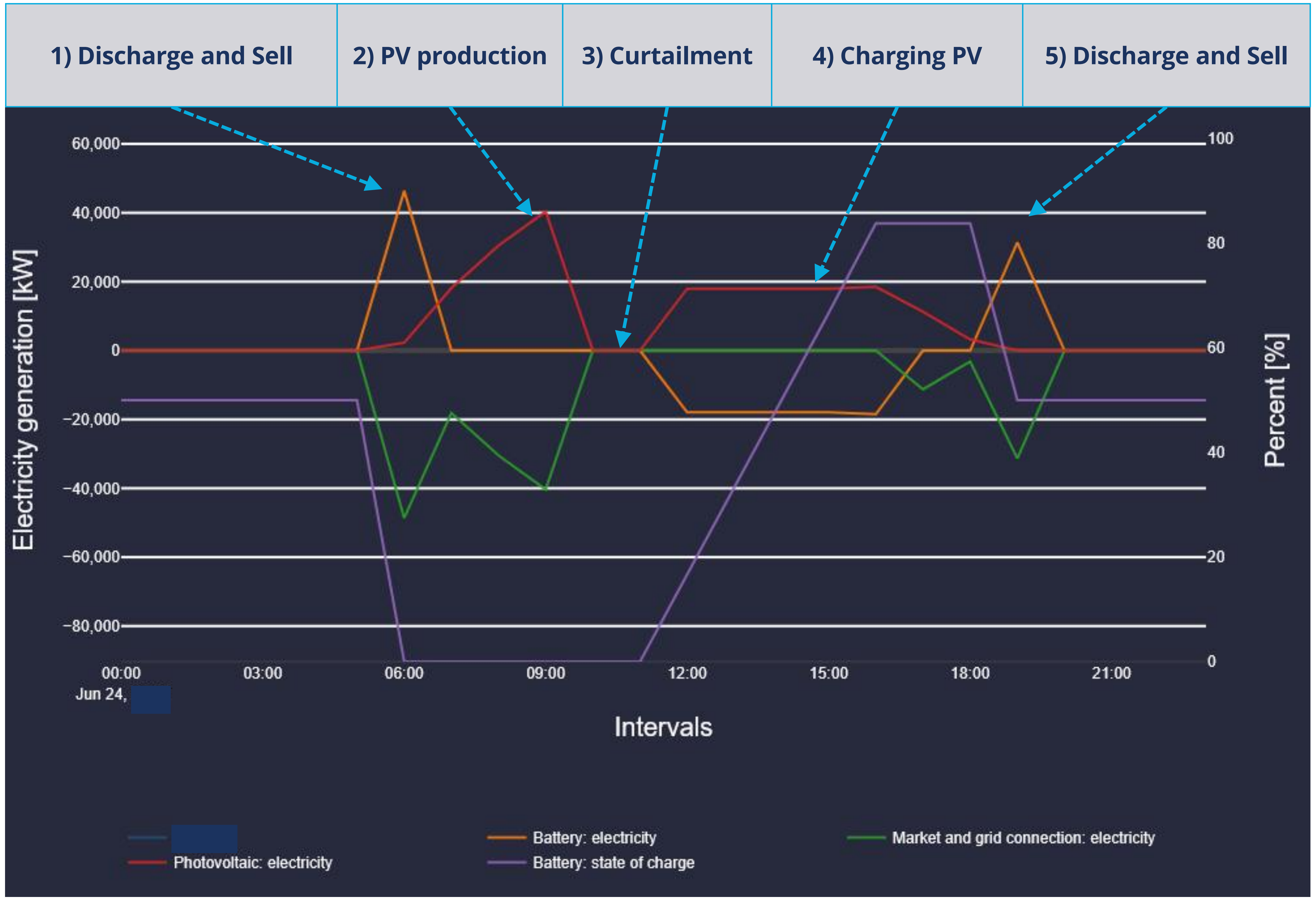
Model B
Without Grid Restriction

Revenue: 115%

A hybrid design can partially avoid revenue losses from grid restrictions

- In the hybrid configuration, revenue is also reduced by grid restrictions. However, their impact on the hybrid system is **smaller than on the standalone system**.
- In this setup, the battery can be (partially) **charged from the PV**. This is especially useful during hours when grid infeed is restricted and the PV would otherwise be curtailed, leading to lost revenues for the PV asset.
- Also when grid withdrawal is limited, the battery benefits from being co-located with the PV, as it can still charge directly from the PV if generation is available and can **avoid withdrawal** from the grid.
- However, there are still times when battery or PV cannot be freely operated optimally from the asset owners perspective due to grid restrictions. Their impact also depends on the available markets and the chosen **multi-market-optimization** strategy.

Flexibility and Future Readiness – Background:
How a Hybrid System handles Restrictions to Grid Access



In the displayed time sample, the hybrid system is able to **charge PV production that would otherwise have been curtailed** and sell it at relatively high prices in the evening. <u>The strategy on that day is as follows</u>:

1. **Empty the battery** by discharging in the morning hours. Realize relatively high prices **and bring the SoC down** to zero to have full capacity available to charge the PV production later in the day that would otherwise be curtailed.
2. In the morning hours, grid-infeed is still allowed (due to relatively high residual load of the grid). The **system produces and sells to the market**, similar to a PV-only case.
3. Since the battery capacity will not be sufficient to store the entire curtailed PV production on that day, there must be hours with actual **PV curtailment (no infeed, no charging)**.
4. The battery is able to **charge parts of the PV production** that would otherwise be curtailed.
5. The stored PV energy, which would otherwise be curtailed, is **sold on the marke**t at relatively high prices in the evening.

The actual daily pattern **varies significantly** depending on market prices, production profiles, and the extent of curtailment.

If grid consumption/withdrawal is also limited at some hours (due to high residual load) there can also be a pattern observed, where the battery charges PV production to **avoid withdrawal from the grid**.

Flexibility and Future Readiness – Comparison of Examples: Impact of Grid Restrictions Depends on System Configuration

50 MWp

PV only

Change in revenues (limited vs. unlimited grid access):

-16.5%

50 MW / 100 MWh

Battery only

Change in revenues (limited vs. unlimited grid access):

-15.9%

50 MWp & 50 MW/ 100 MWh

Hybrid system

Change in revenues (limited vs. unlimited grid access):

-13.0%

Revenues of hybrid systems are less sensitive to restricted grid access

- We compare the different systems under the same restriction of grid access. For each hour of the year, one of the following three situations may apply:
  1. **Grid-withdrawal (charge) is limited to zero**. This restriction is relevant in 12% of all hours (during high residual load of the grid)
  2. **Grid-infeed (discharge/generation) is limited to zero**. This restriction is relevant in 7% of all hours, predominantly on sunny summer days (with low residual load)
  3. **Grid access is unlimited**. This is the case during most of the hours
- For each system we calculate the revenues under the grid restriction and **compare** them to the revenues under unlimited grid access.
- Under **unlimited grid access**, the PV can fully sell its entire production to the market and the battery is optimally dispatched towards market prices. Under this unrestricted grid access the hybrid system dispatch is basically similar to the standalone dispatches
- Under **limited grid access,** the PV loses revenues as it is curtailed in peak production hours. The battery is temporarily restricted both in charge and discharge.
- Under limited access the **hybrid system provides additional value** as it can charge the battery with otherwise curtailed PV production. In some hours of limited grid withdrawal the battery of the hybrid system can still (partially) charge from the PV.

Checklist

Important Features of a Revenue Modelling Solution

Asset Representation

☐ Models power, energy, and efficiency limits accurately

☐ Includes usage-based degradation with lifecycle impact

☐ Considers inverter limits and auxiliary load

☐ Links technical specs to dispatch and revenue

Market Modelling

☐ Adapts to country-specific market rules and products

☐ Accounts for liquidity limits and market depth

☐ Includes ancillary markets (e.g. aFRR, mFRR)

☐ Extendable to future services without overhaul

Data & Validation

☐ Compatible with actual data granularity and scope

☐ Backtested against real trades or benchmarks

☐ Clear for technical and financial stakeholders

☐ Outputs suitable for planning and validation

Operational Logic & Strategy

☐ Dispatch respects technical and market constraints

☐ Avoids uneconomic cycling via degradation-aware logic

☐ Includes realistic foresight assumptions

☐ Supports multi-market coordination and SoC limits

Adaptability & Scalability

☐ Models curtailment, redispatch, hybrid logic

☐ Supports PV, wind, H_2 and heat integration

☐ Regulatory changes can be easily updated

☐ Reusable across regions and technologies

Performance & Usability

☐ Fast enough for planning and sensitivity testing

☐ Transparent, traceable, and well-documented

☐ User-friendly scenario setup and output handling

☐ Integrates into broader analysis workflows

Q-System: Energy System Design Software

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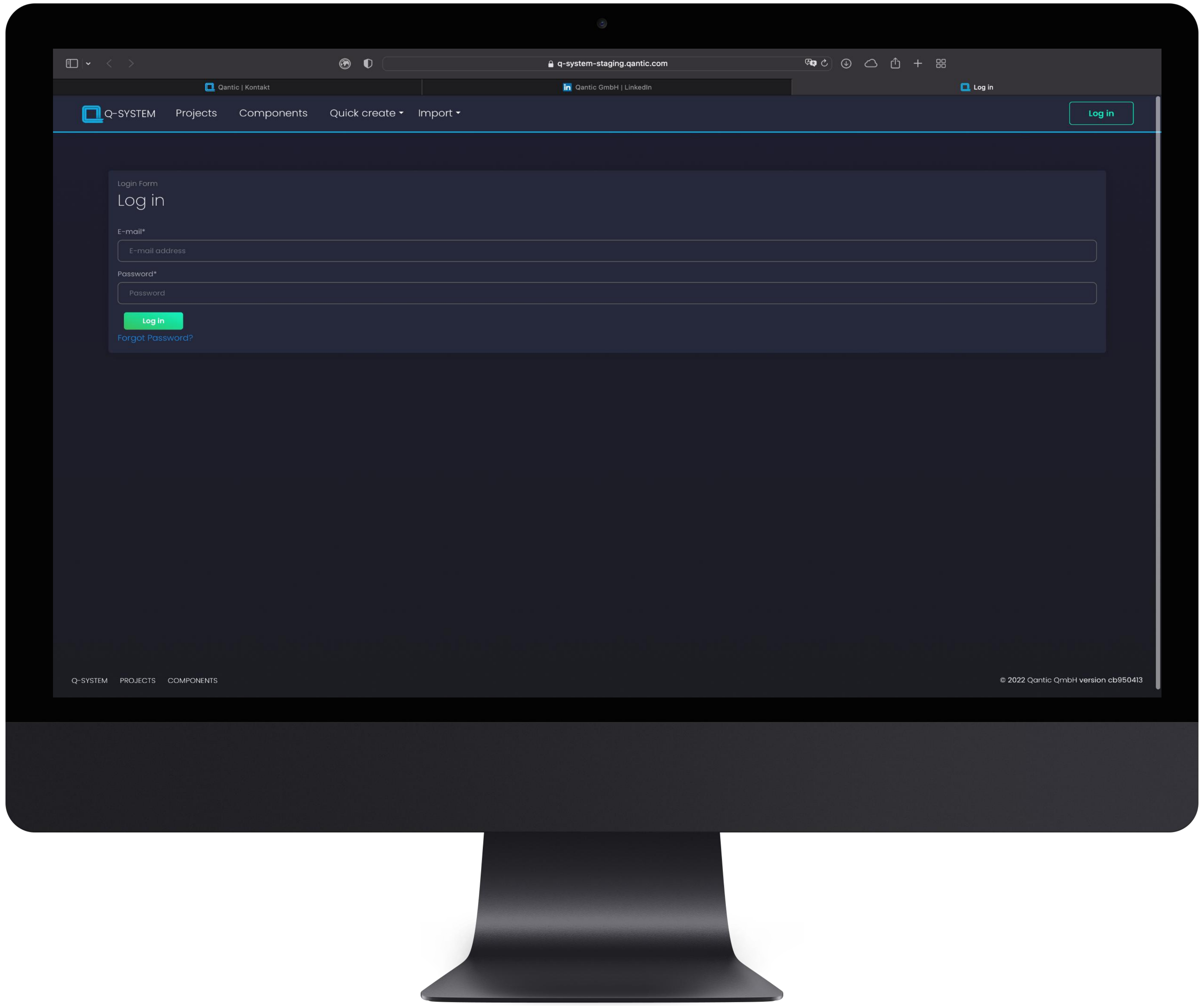

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