

# Integrated Operation of Combined Heat and Power, Underground Thermal Energy Storage, and Batteries in Nordic Electricity Markets<sup>#</sup>

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## ABSTRACT

The growing share of renewables in the power system has increased the risk of supply and demand imbalances, leading to more frequent grid frequency deviations. To manage this, flexible resources are needed to help close this gap. Batteries have already proven to be a mature technology for energy arbitrage and are financially rewarded for providing reserves that support grid balancing. At the same time, the rising penetration of renewables into the power system has reinforced the link between heat and electricity sectors. Combined Heat and Power (CHP) sits at the intersection of these two systems and plays a key role in supporting this interaction. However, these two technologies operate differently, and their joint potential remains underexplored. This paper presents a mixed-integer linear optimization (MILP) model that maximizes revenue from multi-market participation under current market rules. Two case studies of different system configurations are compared. The results highlight the significance of high-value frequency markets and complementary roles of CHP and batteries in market participation.

**Keywords:** sector coupling, combined heat and power, batteries, flexibility, multi-market participation

## NOMENCLATURE

### Indexes and sets

|           |                                |
|-----------|--------------------------------|
| $i \in I$ | Index for CHP unit             |
| $t \in T$ | Index for optimization horizon |

### Symbols

|                      |   |
|----------------------|---|
| $\lambda_t^{DAM}$    | Day-ahead price at time $t$                 |
| $P_{t,i}^{chp,grid}$ | Power from CHP unit $i$ to grid at time $t$ |
| $P_{t,i}^{chp}$      | Power produced by CHP unit $i$ at time $t$  |
| $Q_{t,i}^{chp}$      | Heat produced by CHP unit $i$ at time $t$   |
| $\lambda_t^X$        | Frequency market X price at time $t$        |

|                  |  |
|------------------|--|
| $P_t^{bat,sell}$ | Power from battery to grid at time $t$ |
| $P_t^{bat,buy}$  | Power from grid to battery at time $t$ |

## 1. INTRODUCTION

The power grid must maintain a fixed frequency by balancing supply and demand. The electricity demand in Sweden is expected to double by 2045 [1], placing pressure on the grid to meet this demand. Meanwhile, the increasing share of renewable energy sources in the energy mix has introduced greater risk of unbalanced supply and demand, leading to grid frequency deviations. To address this, a source of flexibility needs to be introduced to close the gap between supply and demand.

Electricity is traded between producers and suppliers through various electricity markets. Most of the electricity trading takes place ahead of time, such as day-ahead market (DAM) and intraday market (IDM). While these markets aim to match supply and demand, they are not responsible for real-time balancing [2]. Instead, balancing markets exist to compensate the deviations of grid frequency, comprising Fast Frequency Reserve (FFR), Frequency Containment Reserve (FCR), and Frequency Restoration Reserve (FRR). These markets are operated by the Swedish transmission system operator (TSO) Svenska kraftnät (SvK).

One of the technologies supporting system balance is energy storage. Frequency regulation services are designed for fast ramping resources, such as batteries, due to their ability to respond quickly [3]. Moreover, batteries can be coupled with renewables to increase their dispatchability and mitigate fluctuations [4]. Owing to this same advantage, batteries can earn revenue by exploiting price fluctuations in multiple markets [5]. This creates new opportunities for producers to benefit from multiple services in the electricity markets [6].

Several studies have explored the profitability of batteries participating in electricity markets. Casla et al.

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[7] explored bidding strategies for batteries not originally designed for balancing in FCR-N, FCR-D, and FFR markets. The results revealed profitable participation, with seasonal and market-specific impacts. Alavijeh et al. [8] developed a model maximizing battery profits across Swedish FCR markets by accounting for degradation and technical requirements to improve practicality. While these studies compare the value of participating in different electricity markets, they focus exclusively on the electricity sector.

At the same time, the rising penetration of renewables into the power system has increased the interdependencies between heat and electricity systems [9]. This raises questions about how these sectors can jointly enhance the operational flexibility of the whole system. Combined Heat and Power (CHP) plants are widely utilized in Sweden for the co-production of electricity and district heating (DH) [10]. However, due to regulations and operational barriers, CHP plants are unable to leverage their full flexibility capabilities [11,12]. CHP plants are traditionally operated to follow the heat demand profile, making heat as the main product and electricity the by-product that gives extra revenues [13]. The optimal capacity allocation involves scheduling heat and power generation to minimize costs, typically formulated as a unit commitment problem solved using Mixed-Integer Linear Programming (MILP) [14]. Therefore, CHP operation is largely governed by heat demand, making the CHP unit itself relatively inflexible from an electricity market perspective.

Several studies explored the flexibility potential of CHP plants. Beiron et al. [10] explored different flexibility measures of CHP plants and quantified their impact, among them are boiler load control and flexible power-to-heat ratio. One study investigated how different types of turbines can offer more product flexibility, namely backpressure and extraction units [15].

To the best of the author's knowledge, only few studies explore the interaction between heat and electricity systems. One study investigated the role of batteries in providing a source of flexibility to the operation of CHP plants, leading to reduced cost of the overall system [16]. However, it did not explore how assets in heat and electricity systems can together add flexibility by interacting with each other in the electricity markets.

The coupling of CHP plants and batteries could add financial value to the batteries by leveraging CHP-generated electricity and capturing more market opportunities. CHP plants are characterized by low operational cost, but has limited ramping flexibility,

while batteries deliver power quickly, but are costly for endurance [17]. Given the volatility of electricity market prices and the heat-driven operation of CHP, selling electricity as a cost-reduction strategy is not always straightforward.

Existing research reveals a limited focus on the joint operation of heat and electricity systems, particularly in the context of increasing opportunities for multi-market participation. To fill the gap identified in the literature, this paper aims to study the interaction of CHP plants and batteries in maximizing the revenues from different electricity markets using MILP.

## 2. OVERVIEW OF SWEDISH BALANCING MARKETS

In Nordic and Baltic regions, the trading of electricity is facilitated by Nord Pool, which clears the day-ahead market and intraday market. Traders submit bids one day ahead of delivery. On the day of delivery, the power system must remain balanced, with supply and demand matched at every moment. When grid frequency deviations occur, SvK will procure reserves that are traded in the balancing markets. Fig. 1 illustrates the frequency activation range of different balancing markets [18]. In this paper, only FCR markets are explored.

Batteries are classified as Limited Energy Resources (LER) according to SvK, so LER-specific rules apply in this study. SvK requires a minimum bid size of 0.1 MW for participation in the selected markets. FCR-N (Normal) and FCR-D (Disturbance) both include up and down regulation. Technical requirements set by SvK, specifically power and endurance, ensure that units can supply and sustain power in response to frequency changes. Batteries must sustain power for 20 minutes in FCR-D and 1 hour in FCR-N.

FCR-N and FCR-D are compensated differently through capacity and energy activation payments. In both markets, accepted bids are remunerated at the marginal price, and traders must make the offered reserve available regardless of activation, which occurs automatically based on real-time frequency. Only in FCR-N do traders receive additional payment for actual energy activation. Based on the real-time frequency data observed from the Finnish TSO Fingrid, FCR-D is rarely activated due to the infrequent events within its

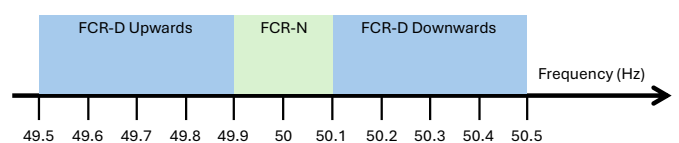


Fig. 1 Frequency activation range

activation range, with only 0.48% and 0.98% of occurrences in 2024 [19].

### 3. METHODOLOGY

The system used in the model is shown in Fig. 2. Section 3.1 describes the system model; Section 3.2 outlines the MILP multi-market optimization and case study.

#### 3.1 System layout description

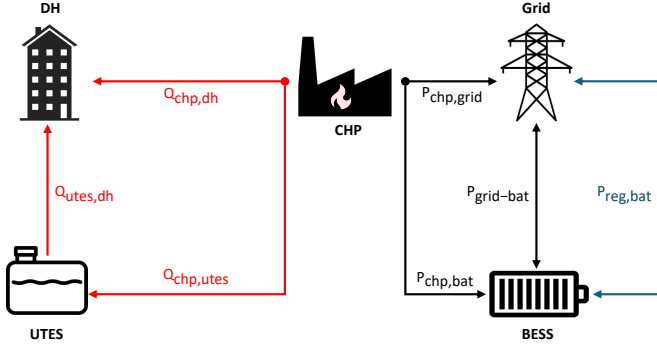


Fig. 2 System layout

The modelled heat system consists of waste-fired and biomass-fueled CHP units, a DH network, and an underground thermal energy storage (UTES). The system configuration is inspired by the DH network in Västerås, Sweden. In this system, UTES is integrated into the DH network with CHP plants that operate with varying fuel costs. UTES has a maximum capacity of 13 GWh<sub>th</sub>.

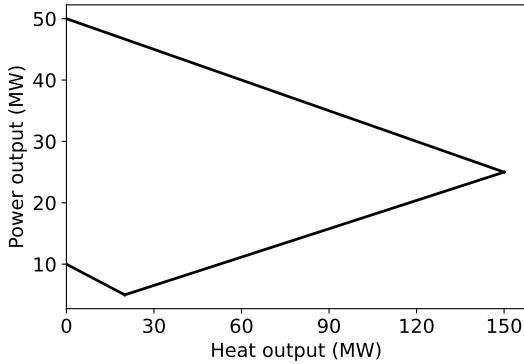


Fig. 3 Simplified FOR of an extraction unit

The CHP units are modeled as extraction units, providing more flexibility between electricity and heat production. Fig. 3 illustrates the simplified feasible operating region (FOR) of an extraction unit. These units have a heat output of 150 MW<sub>th</sub> and a power output of 50 MW<sub>el</sub>. It is important to note that the coordination of the operation of CHP units and UTES aim to allow CHP to be more flexible in its electricity production [20].

Battery energy storage system (BESS) interacts with the grid primarily to exploit electricity price fluctuations by charging when prices are low and discharging when prices are high. As shown in Fig. 2, batteries participate in both the day-ahead market through energy arbitrage and in balancing markets by providing reserves. Batteries can be charged using electricity from the CHP unit, giving the CHP the flexibility to allocate its output either to the grid or to the battery, depending on price signals. In this model, the battery has a 100 MWh capacity, with a power rating of 50 MW and has an efficiency of 95%.

Two system configurations are considered in this study. In the baseline setup, batteries and CHP operate independently. In this study, an alternative configuration is proposed where CHP and batteries are integrated within one system. Another possible sub-system in this type of sector-coupling is heat pump, often referred to as power-to-heat units. However, because heat pumps are typically smaller in scale and individually owned in the studied region, they are not included in this context.

#### 3.2 Optimization and case study

##### 3.2.1 MILP multi-market optimization

The model is optimized using MILP under chosen scenarios. For a fair comparison, this study assumes that the system has perfect information about future electricity prices in each market. These assumptions are considered reasonable, as the goal is to compare the profits of an integrated plant of CHP units, UTES and BESS versus BESS-only across different markets.

Overall, the objective function maximizes total revenues minus costs. As seen in Eq. (1), CHP revenues come from DAM electricity sales, while costs include fuel, startup, and shutdown costs. Meanwhile, batteries earn profits from DAM and FCR markets, as shown in Eq. (2). CHP units are modelled with several constraints such as a ramping rate and minimum up and down time, and the heat system must be able to fulfill the heat demand first before CHP sells power to the grid.

$$\max \sum_{t \in T} \left[ \sum_{i \in I} \lambda_t^{DAM} \cdot P_{t,i}^{chp,grid} - Cost(Q_{t,i}^{chp} + P_{t,i}^{chp}) \right] \quad (1)$$

$$\max \sum_{t \in T} [(\lambda_t^{DAM} + \lambda_t^X) \cdot (P_t^{bat,sell} - P_t^{bat,buy})] \quad (2)$$

##### 3.2.2 Case study

To compare system configurations, two case studies are evaluated. In Case 1, an integrated plant is optimized while Case 2 optimizes a BESS-only system. To evaluate

how the case studies perform under varying conditions, two sensitivity analyses are conducted:

1. Heat demand variation

Three representative weeks are selected to represent winter, spring and summer heat demand profiles, based on patterns from Gadd & Werner [21]. Fig. 4 shows that the representative weeks clearly exhibit distinct patterns, illustrating how the model responds to different heat loads.

2. Battery C-rate variation

Simulations are run with battery C-rates of 0.5C and 1C to assess how the charging and discharging rate impacts market participation. C-rate of 0.5C is used as the benchmark, as the battery is designed for a 2-hour duration according to an industrial partner.

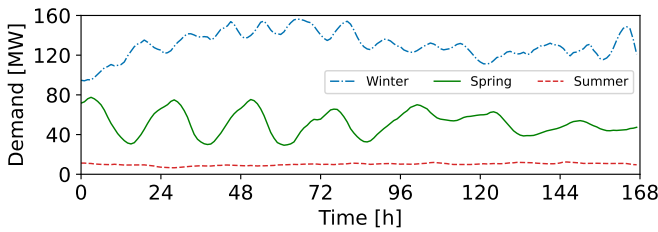


Fig. 4 Weekly heat demand by season

3.2.3 Market data

The model is simulated using electricity price data for zone SE3 in 2024, with DAM prices sourced from ENTSO-E [22] as well as FCR-N, FCR-D, and mFRR prices obtained from Mimer [23]. Fig. 5 shows the variation in price in different electricity markets across seasonal weeks (winter, spring and summer). It can be observed that DAM prices overall show moderate volatility with noticeable pattern. FCR-N and FCR-D down prices are

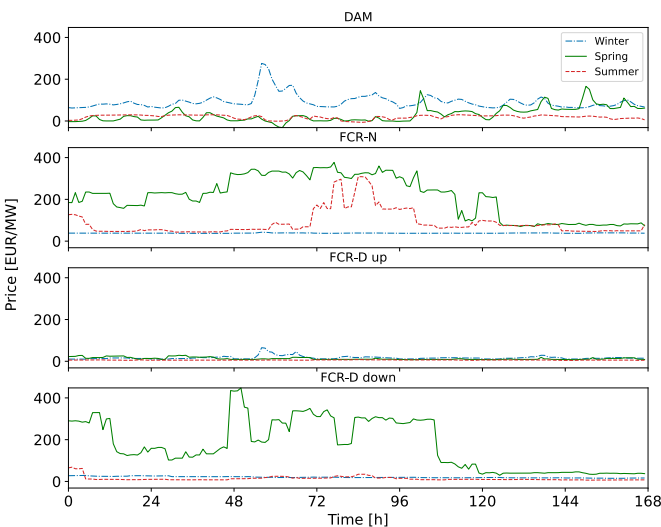


Fig. 5 Electricity price in DAM, FCR-N and FCR-D

significantly higher and exhibit more variability, especially in spring, which reflect greater balancing needs. Particularly, FCR-D up prices remain low and stable across all seasons.

4. RESULTS AND DISCUSSION

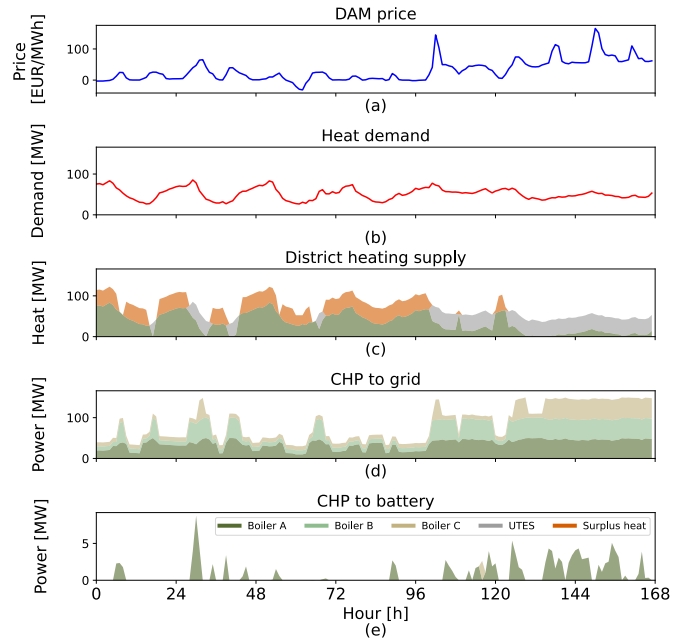


Fig. 6 CHP and battery operation for spring week

The optimization results for Case 1 under different seasons, with a detailed focus on a particular representative week are presented to show how the system operates. The optimization is performed on a weekly timescale, using market price and frequency data from 2024.

Fig. 6c shows that the CHP unit with the lowest fuel cost (waste unit) mainly covers the heat demand. Moreover, CHP electricity production generally follows the DAM price profile, with a noticeable increase during periods of high electricity price. When price is low, CHP operates at minimum electricity production and instead produces surplus heat that is stored in UTES. This stored heat is then utilized during hours of favorable electricity price, allowing CHP to shift its focus toward electricity generation and decreases heat production.

In this model, waste is assumed to have zero fuel cost. In reality, utilities are typically compensated to receive waste while being subject to waste incineration tax. This is a known limitation and should be addressed in future work when the reference for the values is available for the study. However, it could be expected that any negative net fuel cost would only increase CHP electricity production.

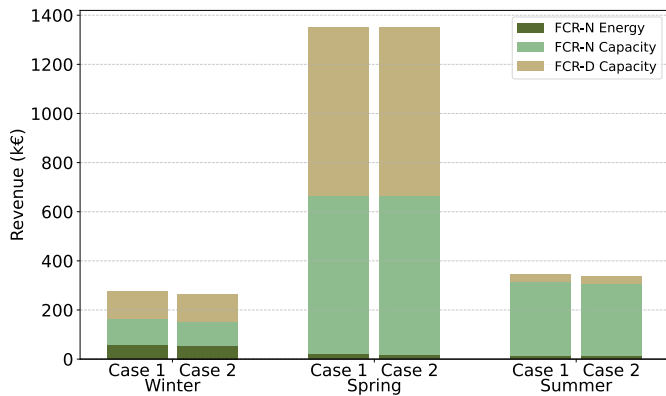


Fig. 7 Seasonal revenues of a 0.5C battery

Fig. 7 compares the financial outcomes of a BESS with that of an integrated CHP-UTES-BESS system across multiple markets. Generally, looking at the share of revenues, FCR markets contribute the largest share of total revenues, but the contribution varies significantly across seasons, due to noticeable seasonal variations in price as seen in Fig. 5. For instance, in spring, FCR-N and FCR-D down offer the highest prices, driving the optimization to prioritize reserve, as seen in Fig. 8. Since the battery starts with a minimum state-of-energy, it will begin by buying electricity from the grid to accommodate future participation. This shows that the system maximizes total revenue by favoring high-value frequency markets over day-ahead arbitrage.

Looking at Fig. 6d and Fig. 6e, the results also show that, while CHP units primarily prefer to dispatch power to the grid, there are instances where they charge the battery. As a result, the total revenues of the integrated plant in Case 1 are higher compared to the BESS-only in Case 2. DAM revenues are present in Case 1, but absent in Case 2, especially during winter where DAM prices are high. However, most of the share is taken up by other markets, with the DAM accounting for only 2% in comparison. This observed behavior supports future reserve bids and satisfies headroom constraints, particularly during periods of high FCR-D up bids and higher power output from CHP 1.

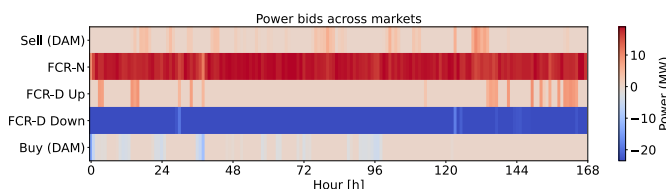


Fig. 8 Power bids across markets for spring week

When battery has a duration of 1 hour (1C), Fig. 9 shows that the battery shifts its participation by allocating more capacity to the FCR-D market, particularly in winter. This leads to substantial increase

in FCR-D revenues, while revenue from FCR-N decreases, since both prices are competitive with each other in winter. This shift is largely driven by the maximum bid size limits in FCR markets, with FCR-D up allowing the highest bids. Moreover, since FCR-D requires reserving headroom without activating energy, it becomes more attractive at higher power rating.

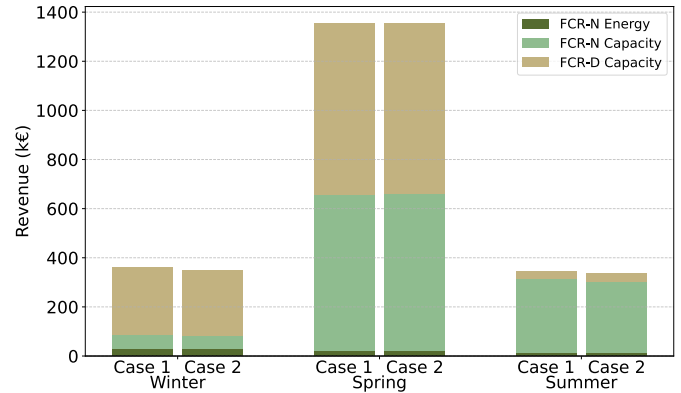


Fig. 9 Seasonal revenues of a 1C battery

## 5. CONCLUSION

This study shows that the presence of UTES enables the operation of CHP to be more electricity-driven. On the other hand, the battery is aggressively revenue-driven, especially in FCR markets, which then prioritizes preserving headroom. This could be translated as a strategy to contribute to resilience by ensuring available capacity when frequency deviates. In an integrated plant, a power exchange between batteries and CHP would reduce that headroom, so the model generally avoids doing it. These results highlight the importance of understanding the complementary roles of CHP and batteries in electricity markets to fully exploit operational flexibility that translates into improved resilience of the grid by providing balancing services.

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