Potential revenue streams corresponding CHP technology using BTC process

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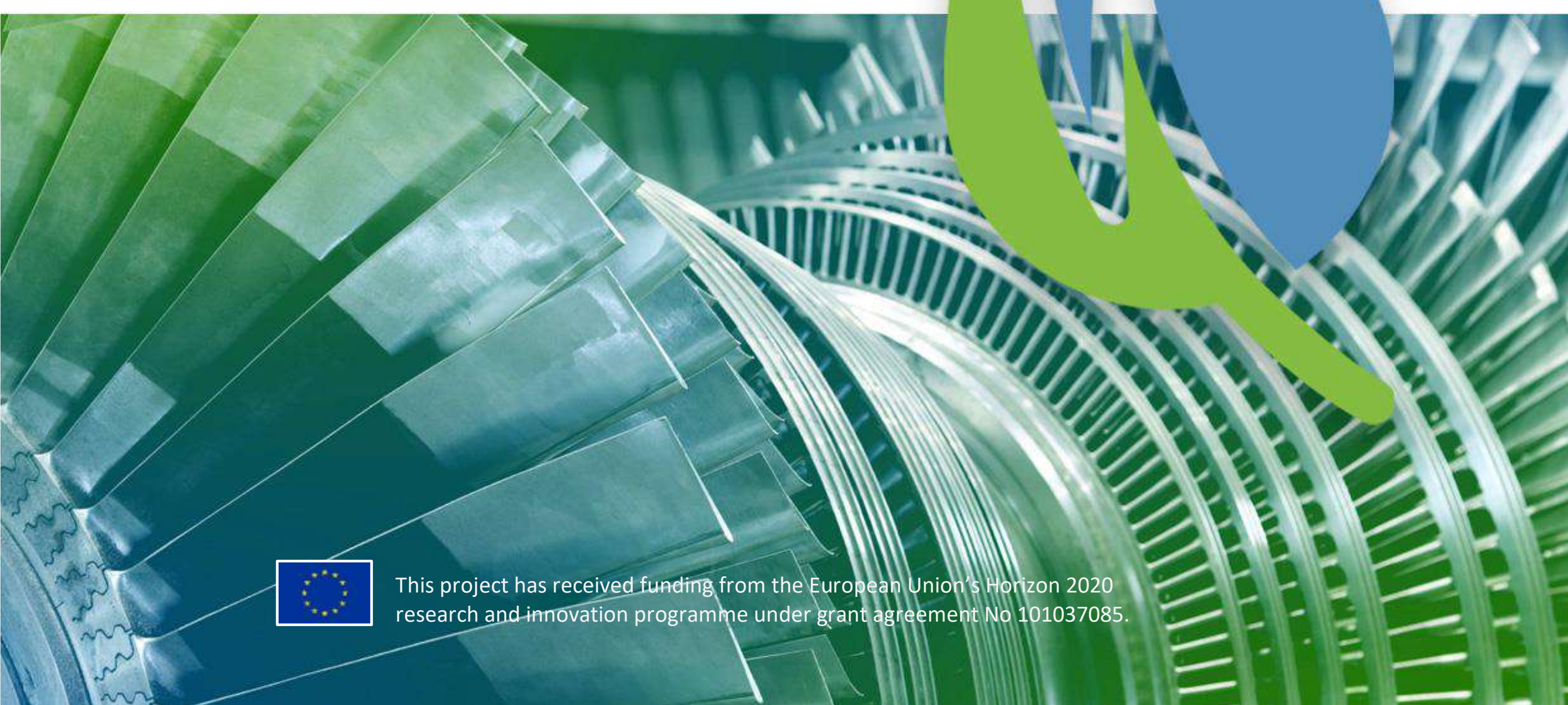

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[1] PU = Public
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Summary

In this project, we consider CHP technology using BTC process resulting in four different products: Electricity, Heat, Hydrogen and CO2.
Hydrogen and CO2 are new type of products currently under the research. No markets are available yet for these products and accordingly no historical prices are existing to use while conducting some investigations towards revenue streams analyses. Many countries have just started to develop hydrogen roadmaps and legislations, thus it will require deeper investigation to predict how hydrogen looks like in the medium or long term, since the market is recently under design. Deeper modelling and optimal planning of all four products of CHP technology using BTC process will take place in WP 4, precisely under the Task 4.1. Under that WP and Task, it has been dedicated proper amount of time to investigate hydrogen and CO2 as a product for the long run, to develop optimization models for further evaluation of all four types of products and determination of optimal operation and planning of CHP plants with BTC process.

In this deliverable electricity is considered as the main product to have simple touch upon revenue analyses, since we have mature markets and historical price time series. Therefore, the revenue stream of the current set-up of electricity and ancillary service markets in Sweden and Spain has been identified and analyzed in this report, using very simple and naive methodology.
Short knowledge about heat and hydrogen as products of CHP plant with BTC process is also provided. However, as it has been stated above, these investigations should be continued later under the Task 4.1.

First, for each country, a review of the electricity markets is introduced and historical data for different market prices collected from various resources are presented. The hourly historical activation prices, procurement prices (for other ancillary services), and day-ahead prices in SE3 and Spain for 2021 are shown in different forms for comparison.

Second, a simplified model has been developed to calculate the potential revenues of the markets. To evaluate the potential revenues for participating with 1 MWh on the difference ancillary service market, some assumptions are considered to simplify the calculations, because only prices (excluding production cost) are included in the analysis. The revenue streams are estimations of the extra hourly revenues per MWh for the different ancillary service markets for 2021. The extra means that it is compared to only participating in the day-ahead market. The results are presented in the figures for each month of the year and are discussed. They reflect the variation and differences in the hourly prices. The revenues correspond to the level of the prices each month. For example, in the hours in

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which there are higher values for the selected market price, the revenue also is high in comparison with lower prices.

Finally, the main conclusions are discussed in the last section to summarize the findings of the report and determine the following works for further operational planning of the heating sector in addition to the electricity market.

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Table of contents

List of tables

List of figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grand agreement N° 101037085.

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1 Introduction

The transition to high shares of intermittent renewable production will create a larger need for grid services to securely operate the electricity system at lower costs. The European and Nordic electricity and the markets of grid services will undergo large changes in the coming years. The flexibility of the electricity sector can be enhanced by district heating systems in different ways; changing the electricity consumption/production of heat production units, thermal storage, etc. A review of the research about the participation of district heating systems in the electricity and ancillary service markets shows that many units in the district heating systems can fulfil the requirements for delivering ancillary services in combined heat and power (CHP) plants (Energiföretagen, 2020). Many research works have evaluated possible economical gains by participating in more markets on the electricity side (for example in ancillary service markets) (Energiforsk, 2015), (Solvina AB, 2014).

For the Nordic region, a new balancing model will be introduced and entail many changes to the current balancing setup (Nordic transmission system operators, 2021). The market for fast-frequency reserves has already been introduced in 2020 and new markets such as products for frequency-containment and frequency-restoration reserves will come. Therefore, it is better to understand the current and future markets on the electricity side in which district heating and CHP units can participate.

Regarding electricity, the current electricity and ancillary service markets in Sweden and Spain are analyzed in this report. A simplified model has been developed to capture the potential revenues from day-ahead (DA) and ancillary markets based on statistical and historical data and prices for 2021 for both countries. An overview of the heating and hydrogen markets is also presented afterwards.

To assess the profitability of the district heating market participation in the electricity sector, operational planning and operations model will be developed in the following tasks of the Bio-FlexGen project. It also needs to capture the effects of the hydrogen market on the revenue of the electricity market. The impacts of both production and consumption of hydrogen in the CHP topping cycle on the revenue streams will be investigated by applying the optimal planning model using collected data from use cases in the other parts of the project or developing some use cases for hydrogen. This development will be implemented in Work Package 4 tasks.

1.1 Overview of case studies

In the following, an overview of the current setup of electricity markets and electricity ancillary services are presented in Sweden and Spain. The historical hourly market prices collected for 2021 are introduced with their references for one biding zone of Sweden (SE3) and Spain. Statistical analyses for the prices of different DA and ancillary services are shown in the following sections. Second, the potential revenues are presented in figures to see how much extra revenue is gained by participating in different ancillary service markets in comparison with participating in only the DA market. The results are discussed in each section. In the end, the main conclusions are presented.

1.2 European electricity markets

Electricity markets facilitate the commercial transactions between generation, consumption and storage such that a reliable electricity supply is maintained at a minimum economic cost. Electricity markets trade not only energy, but also capacities and ancillary services. Even though most electricity grids need almost the same products and services for safe functioning, the procurement method for these products changes depending on the national regulations. In Europe, the Single European Act of 1986 laid the foundations for a competitive internal electricity market without trade restrictions

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(European Economic Community 1987). The idea behind a single electricity market was to increase the cooperation between the member states, allow free trading across different European markets, reduce the prices through competition and increase supply reliability. However, electricity cannot be easily stored and transported like other commodities. The trade of electricity assumes a different form than other market commodities, requiring years of preparatory work before establishing an integrated European market.

The following years conditioned the isolated national markets to prepare for complete integration. The first Energy Package (1996), liberalized the state-owned or state-controlled utilities and was soon followed by the Second Energy Package (2003) which unbundled the distribution and transmission sectors (Meeus 2020)(European Union 2021). These steps were vital in creating competitive markets. The Third Energy Package (2009) further liberalized the markets and started implementing the internal energy market. Finally, the Fourth Energy Package (2019) and the Fifth Energy Package (2021) broke down the entry barriers for the integration of new technologies like renewables, demand response and storage, thereby increasing the competition further (European Union 2021).

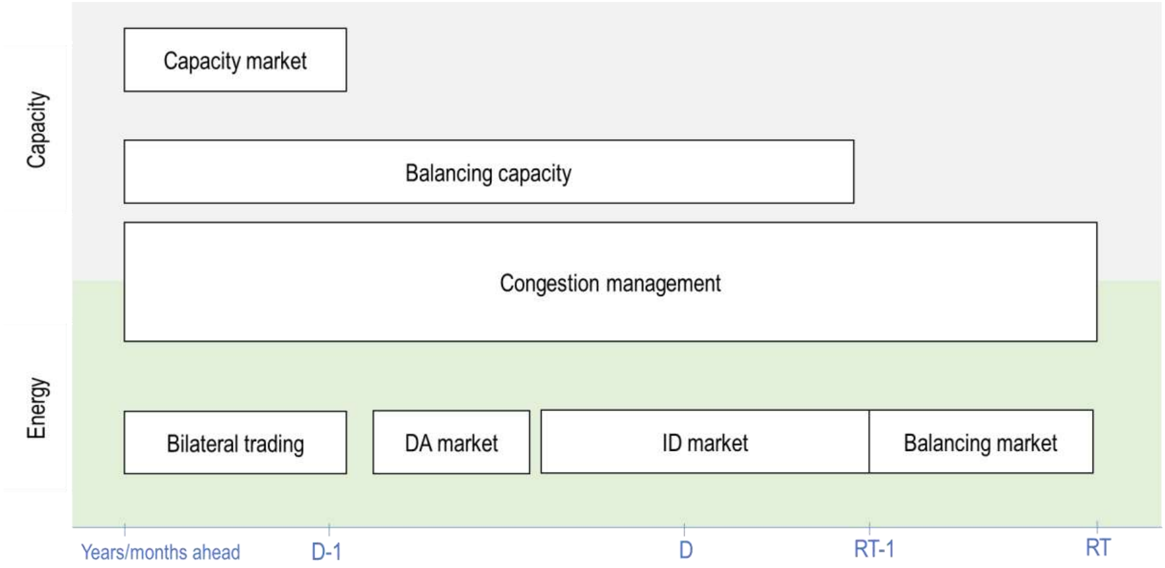

Figure 1: Generic schedule of energy and capacity markets in Europe

Although there are still differences between the market models across Europe, roughly all markets follow the same structure (given in Figure 1). European electricity markets are organized as sequential sub-markets offering products and services needed for a specific delivery day. The capacity markets ensure the availability of enough resources for needs in future. Hence, it takes place much before the actual delivery. On the other hand, the energy trade is conducted close to the actual delivery so that the market participants can accurately predict the possible energy production. The market players can participate in over-the-counter trading to create bilateral contracts much before the actual delivery (years or months ahead) or participate in the DA wholesale market which takes place at noon on the day before delivery. After the DA market, participants can correct their positions in intraday (ID) markets if they cannot ensure their agreed positions due to unforeseen events. Hence, if there is an imbalance between generation and demand levels in real-time operations, it will result in frequency deviations. To prevent it, the system operators have to reserve a predetermined capacity to respond if there is a loss of generation or demand. This is done in balancing (BA) markets.

A markable feature of European electricity markets is the use of zonal markets. The electricity markets in Europe consider the market zone (mostly within the national borders) as a copper plate,

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ignoring the transmission capacities within the zone (Weibelzahl 2017). Such a model treats units in all parts of the zone as equals, thereby creating a uniform price. This is in contrast to the nodal systems, where the price of generation or consumption depends on the node to which it is connected. Nodal systems can easily provide location-based investment signals. However, it might be discriminatory towards certain users or selling units located in deficit areas and also computationally complex. Currently, the technical constraints in most of the zonal European markets are dealt using post-market remedial actions.

The DA and ID markets are currently completely integrated at the European level. The next level of integration is the integration of balancing markets which is rapidly progressing. Nevertheless, to achieve price convergence between the member states, the interconnector capacities have to be increased multifold. To address this, the EU has set a target of 15% interconnector capacity by 2030, which means that every country should set aside at least 15% of its domestic electricity production for transporting across its borders (EC 2020).

Due to various technical and political factors such as rising gas prices, decarbonization policies, rising number of prosumers, etc., the energy markets are continuously transitioning. The electricity market is becoming more decentralized with new market models emerging even at low voltage levels (e.g. local congestion management market). It is tough to identify what market elements are rigid and what are susceptible to change in this context. However, certain trends can be identified in the market model's development that will help identify possible future developments. A comprehensive description of both electricity and heating markets of Sweden and Spain have been presented in Deliverable 3.3 (D3.3). In the next section, the main submarkets of the European model are discussed in detail, with a focus given on recent developments.

2 Potential Revenue Streams of Electricity Market in Sweden

2.1 Statistical Analysis of Electricity Markets Prices

The historical market prices for Sweden have been collected from different sources for the year 2021. In the following, the market prices and ancillary services are introduced shortly.

Day-ahead (DA) price: The DA spot market is a marketplace where a competitive auction takes place based on which the next day price is calculated. The DA electricity market is operated in three steps: 1) bidding, 2) market clearing and 3) pricing. In step 1, all market players (producers and consumers) submit their production or consumption bids in the respective price area before the gate closure. Bids can be single or block bids. The pricing is based on marginal pricing. Most of the trading is done via Nord Pool. Some historical volumes and prices in these markets are available on Nord Pool's website (Nord Pool, 2021).
TSO (Svenska kraftnät in Sweden) maintains the balance between production and consumption during operations by running ancillary services. The current ancillary services used for balancing purposes in Sweden are listed in the following:

Fast Frequency Reserves (FFR): It is an automatically activated service that handles the initial rapid and deep (transient) frequency deviations that can occur in the case of low-level rotational energy errors in the Nordic power system (Svenska Kraftnät, 2021). FFR is intended to be fast to respond to a frequency deviation.

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Frequency Containment Reserve (FCR): FCR are products activated automatically (in the time frame of seconds to minutes) to stabilize the frequency in case of small changes in consumption or production. It is symmetrical. FCR-Normal (FCR-N) and FCR-Disturbance (FCR-D) products are considered as operating reserves, which contain the deviation of the frequency from the nominal value. The historical data are available in (Svenska kraftnät, 2021).

Frequency Restoration Reserves (FRR)

- **Annual Frequency Restoration Reserves (aFRR up/down):** It is an automatically activated service which restores the frequency to 50 Hz. aFRR has a faster response than mFRR. The aFRR product is an automatic complement to mFRR in the FRR process. The data for 2021 are available in (Svenska Kraftnät, 2021).
- **Manual Frequency Restoration Reserves (mFRR up/down):** It is a manually activated service which relieves the automatic services and restores the frequency to 50 Hz. Manual Frequency Restoration Reserves (mFRR) aims at providing replacement of the remaining frequency deviation after FCR and aFRR reserves are applied. The mFRR market is sometimes called the regulating market. The mFRR data are collected from (ENTSO-E , 2021).

Figure 2 shows a comparison of the historical activation prices (for mFRR), procurement prices (for other ancillary services) and DA prices in SE3 for 2021. Each box plot gives information about the distribution of hourly prices in a specific month for a specific market.

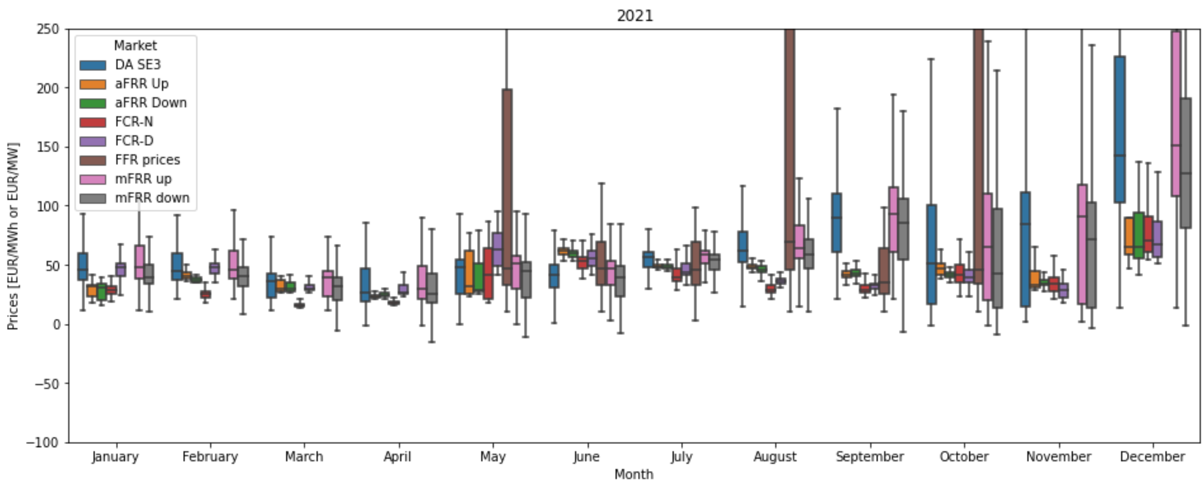

Figure 2: Comparison of all procurement prices in 2021 for Sweden. The y-axis has been capped at 250 EUR/MW for better readability. Note that mFRR up and down is only procured in up- and down-regulated hours, respectively; the hours with no procurement (corresponding to zero revenue) in these markets are not included in the box plots.

Figure 3 shows, for each market, the number of hours per month during which the price in this market was higher than on any other market. For example, DA market prices in SE3 have been higher than in any other markets during 500 hours in September.

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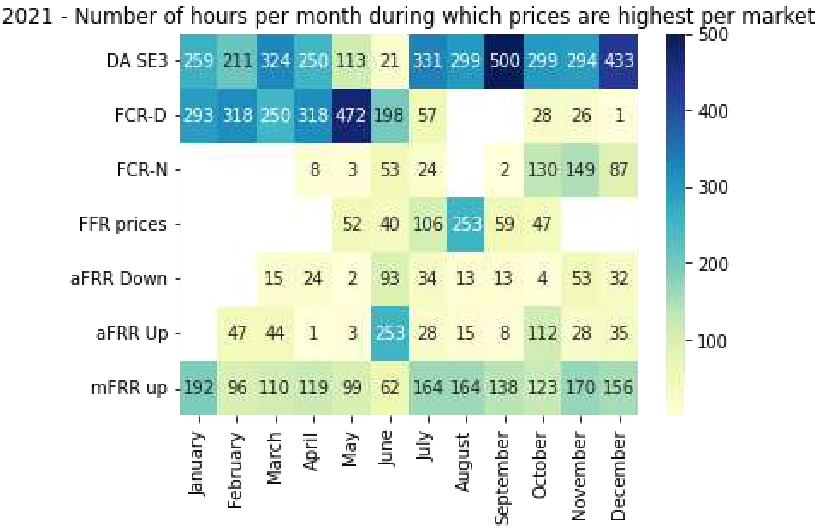

Figure 3: Number of hours per month for each market during which the price on this market was higher than in any other market in Sweden.

2.2 Revenue of Ancillary Service Markets

To evaluate the potential revenue for participating with 1 MWh on the difference ancillary service market, looking at prices only is misleading because it does not capture the full potential revenue. For example, a market participant can offer the same capacity on the DA market and in down-regulation markets. However, offering the capacity to up-regulation markets requires withholding capacity from the DA market. Furthermore, the price distributions in Figure 2 do not consider that some ancillary services are only procured during some hours. Finally, for mFRR down, the prices correspond to the price that producers must pay to buy back their production, and therefore is not a direct measure of revenue.

Figure 4 gives an estimation of the sum of the extra hourly revenues per MWh for 2021 for the different ancillary service markets (“extra” means compared to only participating in the DA market) with the assumptions below:

- Up-regulation markets (FCR-D, aFRR up and mFRR up): 1 MW of capacity is offered in the up-regulation markets only.
- Down-regulation markets (aFRR down and mFRR down): 1 MW of capacity is offered to the down-regulation markets and 1 MWh of energy to the DA market.
- FFR: Same as for down-regulation markets (no need to withhold capacity since FFR is extracted from the kinetic energy in rotating masses).
- Symmetrical markets (FCR-N): 0.5 MW of capacity is offered to the symmetrical markets and 0.5 MWh of energy to the DA market.
- mFRR down has been excluded because the revenue depends on the production costs and, therefore, it requires a more advanced analysis.

Note that Figure 4 shows extra revenue and not extra profit, since the costs (such as fuel costs) of providing the ancillary services have not been considered. In the case of district heating, the costs of delivering ancillary services depend on the flexibility available in the entire system. For example, if it is necessary to also down-regulate heat production when down-regulating the electricity production, this has to be compensated somewhere else in the system so as to deliver the required amount of heat. Therefore, the costs of down-regulation will depend on the cost of flexibility available in the system.

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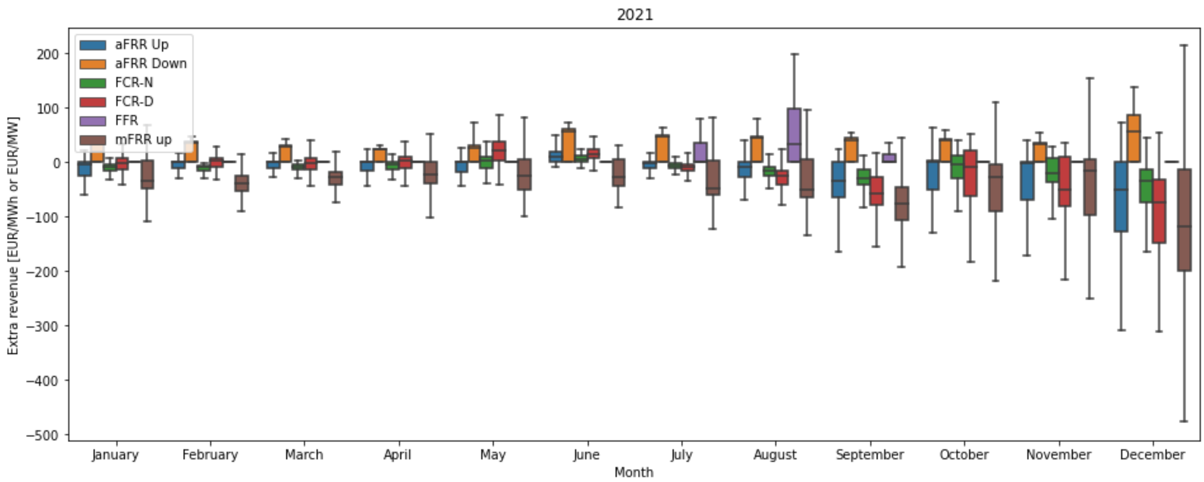

Figure 4: Extra hourly revenues from participation in ancillary services in 2021, per MWh of offered capacity for Sweden. The baseline 0 EUR/MWh corresponds to revenues on the day-ahead market.

Figure 5 indicates how often the extra revenues for each ancillary market were higher than any of the other market.

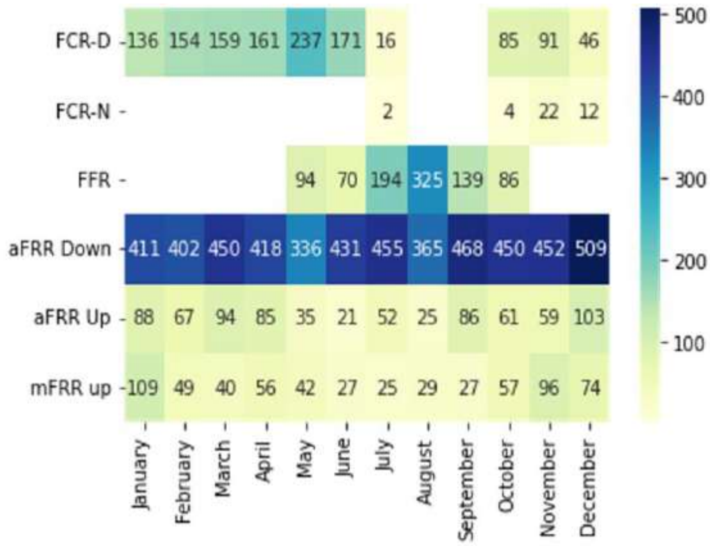

Figure 5: Number of hours per month for each market during which the extra revenues are higher than in any other market for Sweden (total number of hours per month: 672 hours for 28 days, 696 hours for 29 days, 720 hours for 30 days and 744 hours for 31 days).

Finally, Figure 6 shows the total revenues of 1 MWh of capacity for 2021.

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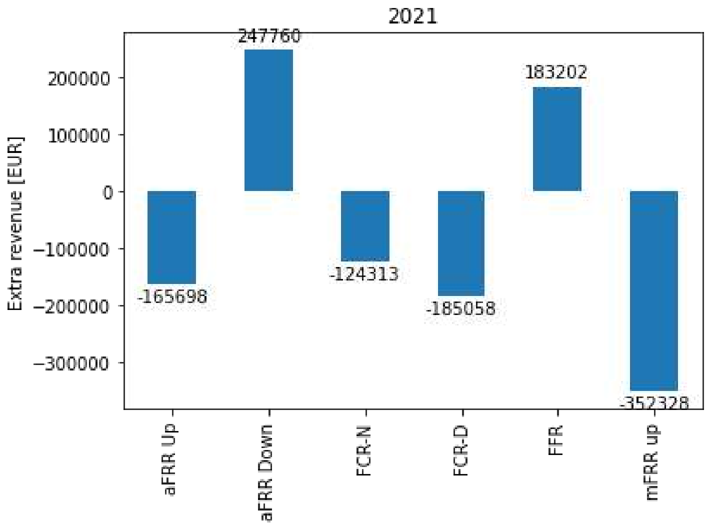

Figure 6: Total extra revenues for 1 MWh of capacity for 2021 in Sweden.

In the estimation above, no smart bidding strategy has been used. Instead, when participating in an ancillary service, 1 MWh is reserved for it irrespective of the price differences between that ancillary service market concerning selling energy only in the DA market.
It can be seen that up-regulation and to a lesser extent the symmetric service FCR-N, lead to a loss compared to only participating in the DA market. This is due to prices on these markets being lower, on average than the prices on the DA market. Still, Figure 5 shows that these markets are the most profitable ones during some hours each month.

aFRR down and FFR are profitable markets since producers get paid for the capacity and do not have to withhold capacity from the DA market. In the case of FFR, the production resource has to be fast enough to deliver 1 MW in about 1 second. Despite FFR only being procured during the summer months, the yearly extra revenue is the second highest of all ancillary services.

3 Potential Revenue Streams of Electricity Market in Spain

3.1 Statistical Analysis of Electricity Markets Prices

The Spanish market data used in this study is from the year 2021 and is collected from the transparency portal of the Spanish system operator[1]. A brief description of the electricity markets considered in this study is given below:

Day-ahead (DA): DA markets are wholesale markets where the market players trade electricity for each hour (or market time unit) of the next delivery day. As the Spanish DA market is coupled with the other European DA markets through the Single Day-Ahead Coupling (SDAC) market, the rules of the market are comparable to the other European DA markets. The market players submit their bids to the local market operator, OMIE, who forwards the bids to the pan-European platform (All NEMO Committee n.d.). The market is conducted as a uniform-pricing auction, at 12:00 CET on the day before the delivery (OMIE 2019). The clearing algorithm, called PCR-EUPHEMIA, calculates the cross-border capacities between the bidding zones and searches for an optimal result that maximises social

[1] https://www.esios.ree.es/en

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welfare. The Spanish DA markets allow simple bids as well as complex bids (Herrero, Rodilla, and Batlle 2020).

Congestion management: In Spain, the congestions arising due to the zonal DA clearance are handled separately in technical constraints markets[2]. The congestions after the DA scheduling are managed in the DA congestion management market (DA CM) and the congestions during the real-time (RT) dispatch are managed in a real-time congestion management market (RT CM). The congestion management market is operated by the TSO. The DA CM uses simple bids submitted by the market players whereas RT CM allows the use of aFRR bids for RT CM (Gobierno de España 2020).

Balancing market: In Spain, the standard balancing market products that are used are Frequency Containment Reserves (FCR), automatic Frequency Restoration Reserves (aFRR), manual Frequency Restoration Reserves (mFRR) and Replacement Reserves (RR). When a frequency deviation event occurs, FCR intervenes automatically within 30 seconds, after which, if the disturbance persists, aFRR gets activated. aFRR can contain the deviations for a maximum of 15 minutes. If the disturbance still exists, the mFRR is activated manually. Finally, to restore the reserves, the replacement reserve (RR) will be manually activated.

In Spain, FCR does not have a market-based procurement. The provision of FCR is a mandatory, unpaid service for a certain set of generators. The procurement of balancing products is done by the TSO, Red Eléctrica de España (REE). As balancing products have to meet specific system needs, only prequalified generators/demand can bid in the balancing markets. A summary of balancing market product requirements is given below.

Table 1. Product requirements for balancing market participation in Spain (Gobierno de España 2020)

	aFRR	mFRR	RR
Market Characteristics			
Procurement of capacity	Yes	No	Yes
Bidding frequency - capacity	Daily	N/A	Daily
Bidding frequency-energy	N/A	15 min	N/A
Technical Characteristics			
Preparation time	30 s	10 min <= x <= 15 min	x <= 30 min
Full Activation Time (FAT)	5 min	15 min	30 min

[2] *'Mercado de restricciones técnicas'* in Spanish

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Bid Characteristics			
Minimum capacity bid	1 MW	N/A	1 MW
Minimum energy bid	N/A	10 MW	1 MW
Bid symmetry	Asymmetrical	N/A	N/A
Minimum duration	15 min	2 hrs	15 min
Product resolution	1 hour	15 min	15 min
Settlement			
Settlement - capacity	Marginal Pricing	N/A	N/A
Settlement - energy	Hybrid	Marginal Pricing	Marginal Pricing

The market prices for different Spanish electricity submarkets for 2021 are given in Figure 7. The rise in prices towards the end of the year can be attributed to two main events: 1) the economic slowdown during the COVID lockdown during the first half of 2021, 2) the gas price hike intensifying during the second half of 2021 (ACER 2022). The prices in most of the ancillary service markets in Spain are set by combined cycle plants which explains the rise in ancillary service prices towards the end of the year (Red Eléctrica de España 2022a).

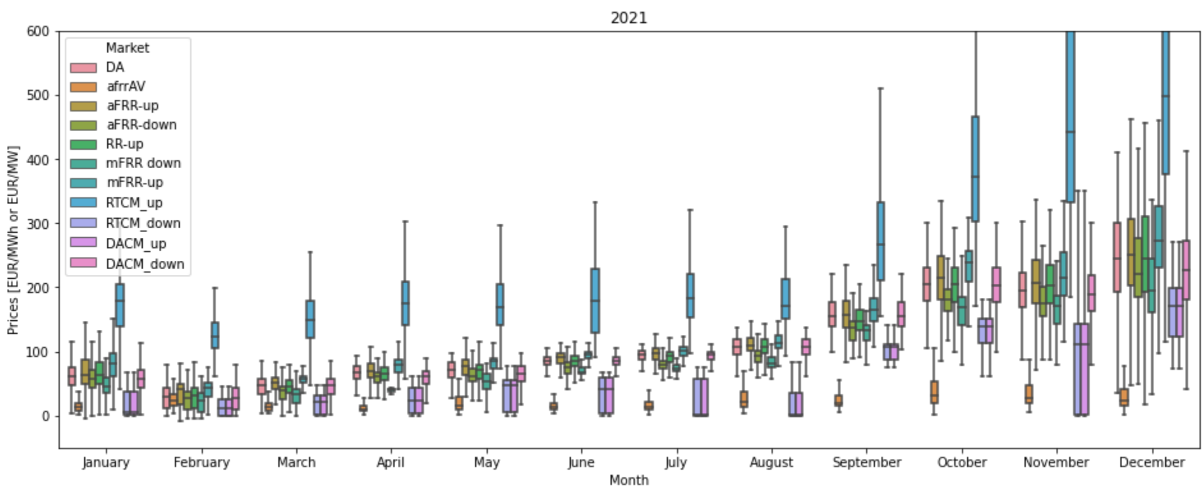

Figure 7: Comparison of all procurement prices in 2021 for Spain. The y-axis ("real- time congestion management up (RTCM up)") has been capped at 600 EUR/MW for better readability. Note that mFRR up and down are only procured in up- and down-regulated hours, respectively; the hours with no procurement (corresponding to zero revenue) in these markets are not included in the box plots.

Fehler! Verweisquelle konnte nicht gefunden werden. shows the distribution of peak prices in different markets. Higher numbers signify a higher possibility of the generator earning more price for a unit of energy. However, this data cannot be interpreted independently. For example, even though the congestion management market creates high prices for a unit of energy, if the generator is located upstream of a congested line (high generation, low demand), there is lower probability that it gets cleared in a congestion management upwards market. Additionally, the reduced pool in the

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balancing market due to prequalification criteria will increase the possibilities of bid mark-ups (Poplavskaya, Lago, and de Vries 2020).

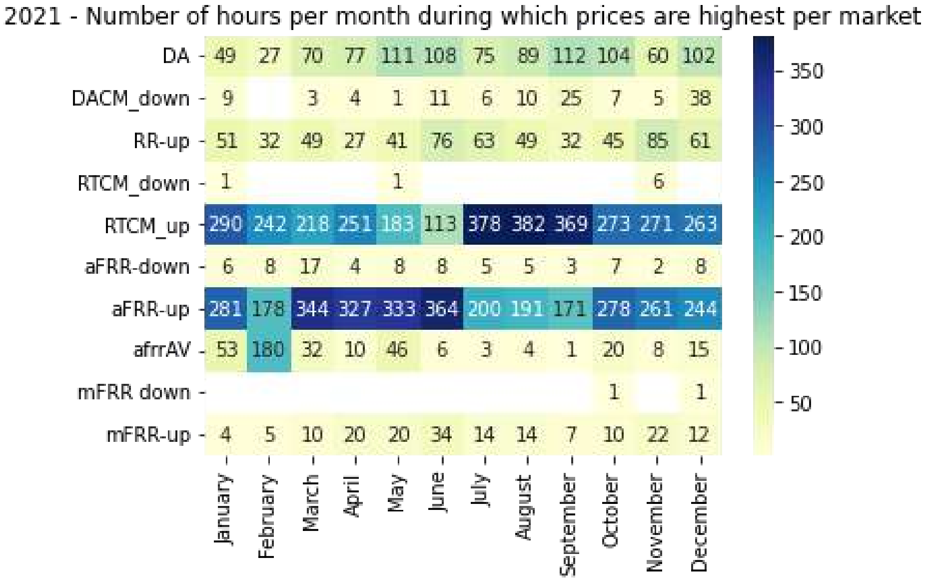

Figure 8: Number of hours per month for each market during which the price on this market was higher than in any other market for Spain.

3.2 Revenues of Ancillary Service Markets

A great advantage of the sequential market model applied in the EU is that the market players can themselves decide to participate in any market (that allows their participation) considering their opportunity costs. This is in contrast to centralized systems where the system operator optimizes their schedule based on the system needs (Ahlqvist, Holmberg, and Tangerås 2019). Thus, an important step in understanding the revenue streams of a potential market player is to estimate the opportunity costs of participating in one market instead of another.

Figure 9 shows the extra revenues that can be earned from participating in the ancillary service markets regarding DA. The assumptions used for the calculations are given in Section 3.2.

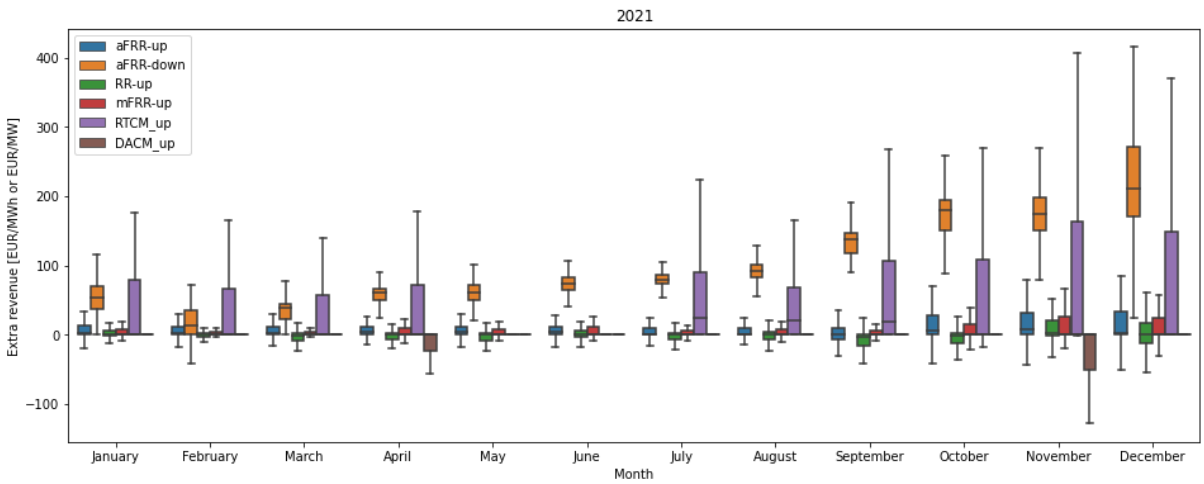

Figure 9:Extra hourly revenues from participation in ancillary services in 2021 for Spain, per MWh of offered capacity. The baseline 0 EUR/MWh corresponds to revenues on the day-ahead market.

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Figure 10 shows the distribution of peak extra revenues throughout the year. aFRR-down is seen to have the maximum revenues among all the other products. This result can be due to the consideration of the opportunity costs here. Compared to the upward reserves, the decision to participate in a downward deviations market might be less risky for the market players. The upward reserves have to reserve a specific capacity to offer it in the capacity market and the activation of the energy is uncertain. At the same time, the downward reserves can offer their available reserve in the market and even if it is not activated for balancing energy, it can still earn the DA price. However, if activated, the upward reserves earn the difference between the upward deviation and the DA market as extra revenue. From the market players' side, these risks can be hedged through portfolio optimization strategies (Faia et al. 2021; Liu and Wu 2007).

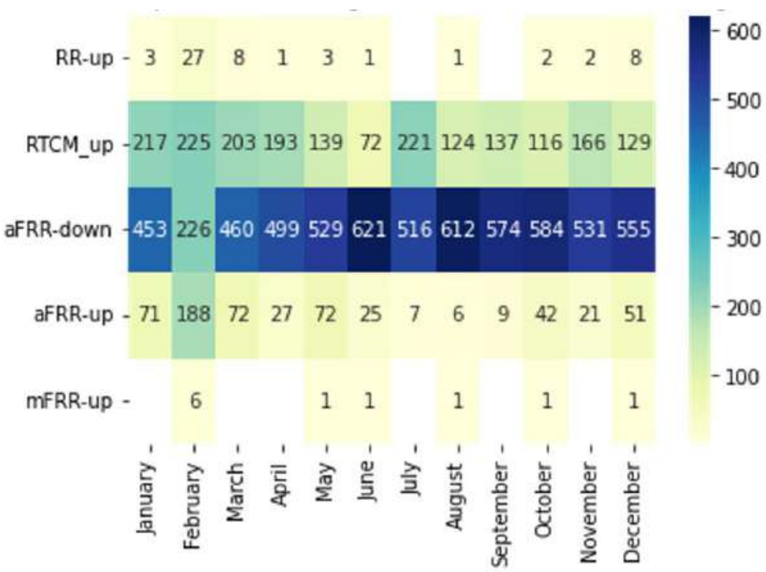

Figure 10: Number of hours per month for each market during which the extra revenues are higher than any other market for Spain (total number of hours per month: 672 hours for 28 days, 696 hours for 29 days, 720 hours for 30 days and 744 hours for 31 days).

The total extra revenues for 1 MW of capacity are given in Figure 11. The quantity activated for real-time congestion management has been increasing recently in Spain due to the large influx from the renewables (REE 2020). The zonal model used for balancing markets excludes network constraints for market clearing, requiring expensive redispatch during real-time operation. However, it is doubtful that these revenues are a long-term stream for generators. The network planning activities at the national level (every 4 years) and bidding zone configuration review process at the European level (every 3 years) track the systemic congestions in the grids and use it as an investment or reinforcement signal (ENTSO-E 2018). On the other hand, the non-copper-based investments undertaken at the national and the European level are encouraging more market models for extracting the flexibility of the connected resources (for example, fast frequency containment reserve, inertia, black-start and voltage response). This might be a potential income source for the new generators.

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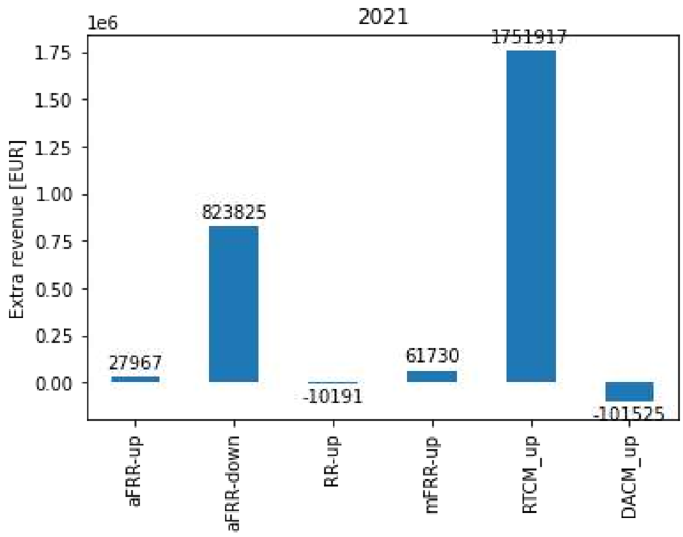

Figure 11: Total extra revenues for 1 MWh of capacity for 2021 for Spain.

Although in this analysis, market gaming is not considered, the market data used for the analysis might not be free from gaming. Sequential markets allow the market players to deduce the best strategies to increase their profits. For instance, from historical data, the market players can know the probability of getting cleared in each market. Within the congestion management markets, energy for upward redispatch was 31 times higher than the downward redispatch in 2021 (Red Eléctrica de España 2022b). This means a market player with a big portfolio can deliberately use the generators that cause congestion in the upward direction to be redispatched in the congestion management market. To understand the effect of gaming in sequential markets, advanced market equilibrium models or agent-based simulations can be used. This is currently out of scope for this study.

4 Heating Market

Sector coupling is a great opportunity for decarbonization of energy systems, and delivering reliable and efficient energy services with the least possible cost. CHP plants, individual heat-only boilers, and electric heating are the main heat production technologies in heat networks expected to provide an increasing share of domestic heating. However, there is a broad range of low-carbon technology options for networks. Heat networks are a crucial aspect of the path towards decarbonising heat and achieving net-zero commitment. Heat networks can utilize renewable or residual heat to achieve climate targets (EZK , 2019). On the other hand, because CHP plants generate simultaneously heat and electricity, they are highly efficient that can deliver additional carbon savings. Approaching 2050, a transition from gas-fired networks to lower carbon technologies such as hydrogen, biomass, or waste-heat recovery are needed (BEIS, 2022). In the Nordic countries, district heating networks are generally used to cover the heating demand. When district heating is coupled with CHP (DH/CHP), it can balance the fluctuations of the power system and support the integration of renewable production. Some technologies can improve the flexibility of the DH/CHP systems. For example, in some CHP plants, using bypass of turbines can help to avoid generating electricity when there is

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excess electricity in the system. Therefore, the flexibility of DH/CHP is important regarding integrating renewable power into the energy system (DEA, 2017).

Unlike gas and electricity, generally, there is no competition within the heat market because district heating systems are local and not connected. Heat cannot be transferred for long distances. The heat network is characterized as a natural monopoly leading to a requirement for supervision and regulation of heat suppliers. Customers cannot choose between different DH providers. The characteristics of the heat market depend on geographical and technical differences. The regulatory framework protects customers against excessive tariffs set by district heating companies and encourages the suppliers toward efficient operations and investments (BEIS, 2022) (EZK , 2019). There are two main models for price regulations: liberalised price in which there is ex-post price control on request (e.g., Sweden, Finland, Germany); regulated price in which there is mandatory price control (e.g., Denmark, Netherland, Bulgaria, Lithuania) (EC, 2021g). In most European countries, suppliers have the freedom to set tariffs. In Denmark, two ways are used to set tariffs. When the supplier owns the CHP plant (many heat companies do), power production income is included in the budget, and the heat tariff will be lowered corresponding to income. When the heat company does not own the CHP plant, the heat delivery tariff is negotiated. In the CHP cost-allocation methodology, CHP can maximize its profit by selling electricity. However, for small-scale CHP plants, there is a regulation preventing them to earn profit from electricity generation (USAID, 2021).

5 Hydrogen Market

Another key element of decarbonization of energy systems is the use of low-carbon fuels. European Commission published a strategy and identified clean hydrogen as a priority for investment in Europe to boost the economy and energy resilience. It emphasizes using renewable hydrogen, which is hydrogen produced by water electrolysis and using electricity stemming from renewables. The strategy target is the installation of 6 GW of electrolysers by 2024 and 40 GW by 2030. This leads to the production of 10 million tonnes of renewable hydrogen in Europe until 2030 (EC, 2022c). The technology of this project can utilize hydrogen as a feedstock for fast-start capability and also produce renewable hydrogen either through the gasification of biomass and catalytic steam reforming, or the process of water electrolysis driven by the electricity produced in the biomass-fired top cycle (BTC) CHP plant. The plant will be active in both the demand and supply sides of the hydrogen market. In addition, the emphasis of the European Commission on renewable hydrogen is beneficial for this technology, because both hydrogen modes rely on renewable sources. Some regulatory aspects have been discussed broadly, i.e. how to classify hydrogen (low-carbon, renewable, green, etc.), and how to design a scheme of guarantees of origin. However, the design of the hydrogen market or regulation of the hydrogen network has not been specified practically. Under the proposal (EC, 2021b), the European Commission outlines a regulatory framework to help the growth of the sector and allow a large degree of flexibility and exceptions until 2030.

6 Conclusion

The revenue stream of current electricity and ancillary service markets in Sweden and Spain have been identified and analyzed in this report. It captures the hourly variability of prices of the

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electricity and ancillary service markets and compares the revenues of each market. The hourly historical prices for electricity and ancillary services have been collected for the year 2021 for both countries and the features of different markets with their purposes have been introduced. A statistical model has been developed to economically assess the potential revenues of participation of 1 MWh of electricity in different markets. The method that calculates the potential revenues are presented based on some assumptions to simplify the model e.g., the reserved capacity for activation of the ancillary services, and the effects of different markets on each other. The results show that the probability of each analyzed market varied in different months. For example, for Sweden, it is more profitable to participate in FCR-D up market sometimes in cold seasons, however, FFR up has higher hourly distributions in warmer months (due to higher FFR prices in the summer). Therefore, selecting the optimal revenue depends on different factors such as the other market prices and hourly electricity consumption. In general, the profitability of each market highly corresponds to the price level.

In Spain, participation in real-time congestion management and aFRR down markets are seen as the most profitable markets. The unused aFRR bids are used for real-time congestion management in Spain. Hence, when real-time congestion management is required, the prices in that market tend to be higher than in all other markets. The findings indicate a new revenue stream for medium-cost and high-cost generators in markets with heavy penetration of low-cost technologies: system services/ancillary services. The provision of system services like balancing and congestion management can reduce the dependency of investment return of high-OPEX technologies on scarcity prices and improve system adequacy. From the Spanish market analysis, it is challenging to draw conclusions about the seasonal revenue streams as the studied year, 2021, was full of disruptions in the Spanish electricity markets. Although peak demands in the Spanish electricity grid generally occur during the cold months, the winter of 2021 was also marked by abnormally high gas prices. Gas power plants represent a sizeable share of the generation mix in the balancing and congestion management markets, creating a huge spike in the market prices. On the other hand, the gas dependency also shows a possible market entry gap. The European Union is adopting different measures to decouple the electricity and gas markets in Europe through REPowerEU plan. A part of the plan is to replace the non-renewable generation in all electricity markets with domestic, renewable-based technologies. Hence, technologies like biomass can be expected to take over the share of gas power plants in near future.

In addition, the order in which decisions have to be taken on the electricity and ancillary service markets should be considered for optimal operational planning. To evaluate the profitability of the participation of district heating in the electricity sector, an operational planning and operation tool will be developed in the next research of Bio-FlexGen project. Moreover, it is important to capture the effects of the hydrogen market on the revenue of the electricity market in top cycle CHP plants. Therefore, the operational planning and operations tool must be able to capture both the heat and hydrogen markets in addition to the electricity market. Such tools can build upon existing work in coming work packages (WP4) in which revenues are estimated from participating in the potential markets including both hydrogen and district heating markets.

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7 References

BEIS. (2022). *Combined Heat and Power: pathway to decarbonisation - summary of call for evidence responses.* Retrieved from Department for Business, Energy & Industrial Strategy: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1062478/chp-pathway-to-decarbonisation-summary-cfe-responses.pdf

Byman, K. (2016). *Electricity production in Sweden.* Stockholm: Royal Swedish Academy of Engineering Sciences.

DEA. (2017). *Regulation and planning of district of district in Denmark.* Retrieved from Danish Energy Agenacy: https://ens.dk/sites/ens.dk/files/Globalcooperation/regulation_and_planning_of_district_heating_in_denmark.pdf

EC. (2021b). *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on common rules for the internal markets in renewable and natural gases and in hydrogen.* Retrieved from European Commission: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0803

EC. (2021g). *Overview of markets and regulatory frameworks under the revised Renewable Energy Directive.* Retrieved from European Commission: https://op.europa.eu/en/publication-detail/-/publication/5e1fd499-eabf-11ec-a534-01aa75ed71a1/language-en

EC. (2022c). *A hydrogen strategy for a climate-neutral Europe.* Retrieved from European Comission: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

Energiföretagen. (2020). *Färdplan för fossilfri konkurrenskraft - Elbranschen.* Retrieved from Energiföretagen: https://www.energiforetagen.se/globalassets/dokument/fardplaner/ffs_elbranschen_webb-200123.pdf

Energiforsk. (2015). *El och fjärrvärme - samverkan mellan marknaderna.* Retrieved from Energiforsk: https://energiforskmedia.blob.core.windows.net/media/19560/el-och-fjarrvarme-energiforskrapport-2015-223.pdf

Energimyndigheten. (2022). *Energy in Sweden Facts and Figures 2021.* Retrieved from https://www.energimyndigheten.se/en/facts-and-figures/statistics/

ENTSO-E . (2021). *Prices of Activated Balancing Energy*. Retrieved from ENTSO-E Transparency Platform: https://transparency.entsoe.eu/balancing/r2/pricesOfActivatedBalancingEnergy/show?name=&defaultValue=false&viewType=TABLE&areaType=MBA&atch=false&dateTime.dateTime=22.06.2022+00:00|CET|DAYTIMERANGE&dateTime.endDateTime=22.06.2022+00:00|CET|DAYTIMERANGE&re

EZK . (2019). *Tariff regulation of district heating for small users .* Retrieved from Management summary of report for the Dutch Ministry of Economic Affairs and Climate (EZK): https://www.sirm.nl/docs/Publicaties/190219-District-heating-tariff-regulation-management-summary.pdf

Nord Pool. (2021). Retrieved from Nord Pool: https://www.nordpoolgroup.com/en/Market-data1/data-downloads/historical-market-data2/

Nordic transmission system operators. (2021). Retrieved from Nordic Balancing Model: https://nordicbalancingmodel.net/

Solvina AB. (2014). *Investigation of possibilities for Swedish cogeneration plants to supply frequency control, FCR-N.* Retrieved from Energiforsk: https://energiforskmedia.blob.core.windows.net/media/18821/undersokning-av-mojligheter-for-svenska-kraftvarmeverk-att-leverera-primar-frekvensreglering-varmeforskrapport-1261.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grand agreement N° 101037085.

Svenska Kraftnät. (2021). *Behov av FFR*. Retrieved from Svenska Kraftnät: https://www.svk.se/aktorsportalen/systemdrift-elmarknad/information-om-stodtjanster/ffr/behov-av-ffr/#:~:text=Svenska%20kraftn%C3%A4t%20och%20%C3%B6vriga%20nordiska,18%20%25%20och%20Energinet%208%20%25.

Svenska Kraftnät. (2021). *Mimer ("Automatisk frekvensåterställningsreserv")*. Retrieved from Mimer SVK: https://mimer.svk.se/AutomaticFrequencyRestorationReserve

Svenska kraftnät. (2021). *Mimer ("Primärreglering")*. Retrieved from Mimer SVK: https://mimer.svk.se/PrimaryRegulation/PrimaryRegulationIndex

USAID. (2021). *TARIFF SETTING IN THE DISTRICT HEATING SECTOR: RECOMMENDATIONS BASED ON INTERNATIONAL EXPERIENCE.* Retrieved from United States Agency for International Development (USAID): https://www.osti.gov/servlets/purl/1826858

AveBiom 2022. https://www.avebiom.org/sites/default/files/ipb/IPB-Indice-precios-pellet-AVEBIOM.pdf

Ahlqvist, Victor, Par Holmberg, and Thomas Tangerås. 2019. 'Central- versus Self-Dispatch in Electricity Markets'. SSRN Electronic Journal, no. 1257. https://doi.org/10.2139/ssrn.3302569.

All NEMO Committee. n.d. 'SDAC'. Accessed 4 April 2022. https://www.nemo-committee.eu/sdac.

Elia. 2018. 'Study on the Review of the Black Start Ancillary Services', 66.

ENTSO-E. 2018. 'First Edition of the Bidding Zone Review', 238.

ENTSO-E. 2019. 'Fast Frequency Reserve – Solution to the Nordic Inertia Challenge'.

ENTSO-E. 2021. 'ENTSO-E Bidding Zone Configuration Technical Report 2021'.

Faia, Ricardo, Tiago Pinto, Zita Vale, and Juan Manuel Corchado. 2021. 'Portfolio Optimization of Electricity Markets Participation Using Forecasting Error in Risk Formulation'. International Journal of Electrical Power & Energy Systems 129 (July): 106739. https://doi.org/10.1016/J.IJEPES.2020.106739.

Gobierno de España. 2020. 'Resolución de 10 de Diciembre de 2020, de La Comisión Nacional de Los Mercados y La Competencia, Por La Que Se Aprueba La Adaptación de Los Procedimientos de Operación Del Sistema a Las Condiciones Relativas al Balance Aprobadas Por Resolución de 11'. Boletín Oficial Del Estado.

Herrero, Ignacio, Pablo Rodilla, and Carlos Batlle. 2020. 'Evolving Bidding Formats and Pricing Schemes in USA and Europe Day-Ahead Electricity Markets'. Energies 13 (19): 1–21. https://doi.org/10.3390/en13195020.

Liu, Min, and Felix F. Wu. 2007. 'Portfolio Optimization in Electricity Markets'. Electric Power Systems Research 77 (8): 1000–1009. https://doi.org/10.1016/J.EPSR.2006.08.025.

National Grid ESO. 2019. 'Stability Pathfinder RFI Technical Performance and Assessment Criteria'.

OMIE. 2019. 'DAY-AHEAD AND INTRADAY ELECTRICITY MARKET OPERATING RULES'. Vol. 11.

Poplavskaya, Ksenia, Jesus Lago, and Laurens de Vries. 2020. 'Effect of Market Design on Strategic Bidding Behavior: Model-Based Analysis of European Electricity Balancing Markets'. Applied Energy 270 (May): 115130. https://doi.org/10.1016/j.apenergy.2020.115130.

Red Eléctrica de España. 2022a. 'Boletín Mensual de Energía Eléctrica - Diciembre'.

Red Eléctrica de España. 2022b. 'The Spanish Electricity System: Ancillary Services and International Exchanges 2021'. Madrid.

Red Eléctrica de España. 2020. 'The Spanish Electricity System. 2020'.

Red Eléctrica de España. REE. System Operator Information System (e·sios): https://www.esios.ree.es/en

ACER. 2022. 'ACER's Final Assessment of the EU Wholesale Electricity Market Design'.

Ahlqvist, Victor, Par Holmberg, and Thomas Tangerås. 2019. 'Central- versus Self-Dispatch in Electricity Markets'. *SSRN Electronic Journal*, no. 1257. https://doi.org/10.2139/ssrn.3302569.

All NEMO Committee. n.d. 'SDAC'. Accessed 4 April 2022. https://www.nemo-committee.eu/sdac.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grand agreement N° 101037085.

EC. 2020. 'Electricity Interconnection Targets [Last Update: 17.03.2020]', 9–11.
ENTSO-E. 2018. 'First Edition of the Bidding Zone Review', 238.
European Economic Community. 1987. 'Single European Act'. *Official Journal of the European Communities* L 169: 1–28.
European Union. 2021. 'Internal Energy Market'. *Fact Sheets on the European Union - 2021*. https://doi.org/10.4135/9781412971850.n78.
Faia, Ricardo, Tiago Pinto, Zita Vale, and Juan Manuel Corchado. 2021. 'Portfolio Optimization of Electricity Markets Participation Using Forecasting Error in Risk Formulation'. *International Journal of Electrical Power & Energy Systems* 129 (July): 106739. https://doi.org/10.1016/J.IJEPES.2020.106739.
Gobierno de España. 2020. 'Resolución de 10 de Diciembre de 2020, de La Comisión Nacional de Los Mercados y La Competencia, Por La Que Se Aprueba La Adaptación de Los Procedimientos de Operación Del Sistema a Las Condiciones Relativas al Balance Aprobadas Por Resolución de 11'. *Boletín Oficial Del Estado*.
Herrero, Ignacio, Pablo Rodilla, and Carlos Batlle. 2020. 'Evolving Bidding Formats and Pricing Schemes in USA and Europe Day-Ahead Electricity Markets'. *Energies* 13 (19): 1–21. https://doi.org/10.3390/en13195020.
Liu, Min, and Felix F. Wu. 2007. 'Portfolio Optimization in Electricity Markets'. *Electric Power Systems Research* 77 (8): 1000–1009. https://doi.org/10.1016/J.EPSR.2006.08.025.
Meeus, Leonardo. 2020. *The Evolution of Electricity Markets in Europe*. *The Evolution of Electricity Markets in Europe*. https://doi.org/10.4337/9781789905472.
OMIE. 2019. 'DAY-AHEAD AND INTRADAY ELECTRICITY MARKET OPERATING RULES'. Vol. 11.
Poplavskaya, Ksenia, Jesus Lago, and Laurens de Vries. 2020. 'Effect of Market Design on Strategic Bidding Behavior: Model-Based Analysis of European Electricity Balancing Markets'. *Applied Energy* 270 (May): 115130. https://doi.org/10.1016/j.apenergy.2020.115130.
Red Eléctrica de España. 2022a. 'Boletín Mensual de Energía Eléctrica - Diciembre'.
———. 2022b. 'The Spanish Electricity System: Ancillary Services and International Exchanges 2021'. Madrid.
REE. 2020. 'The Spanish Electricity System. 2020'.
Weibelzahl, Martin. 2017. 'Nodal, Zonal, or Uniform Electricity Pricing: How to Deal with Network Congestion'. *Frontiers in Energy* 11 (2): 210–32. https://doi.org/10.1007/s11708-017-0460-z.

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