DIVISION SAFETY AND TRANSPORT
ELECTRIC POWER SYSTEMS

Potential profits from ancillary service markets

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RISE Report 2023:31

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Abstract

In this deliverable from the SeCoHeat project, profits that can be made with 1 MWh of electricity production capacity on existing ancillary service markets are evaluated in 2020 and 2021. Profits are evaluated for four different marginal production costs corresponding to the following fuels for a CHP power plant: waste (assumed fuel price: 0 kr/MWh), recycled wood (10 kr/MWh), wood chips (20 kr/MWh) and wood pellets (30 kr/MWh).

The results show that except for wood chips and wood pellets in 2020, the most profitable ancillary service markets are FFR (fast-frequency response) and aFRR down (automatic frequency restoration reserves for down-regulation). The reasons are that (1) producers don't have to withhold capacity from the day-ahead market when their participate in these two markets and (2) producers get compensated for the capacity reserved for the ancillary service markets.

For wood chips, the FFR market was the most profitable in 2020, followed by the mFRR down market (manual frequency restoration reserves for down-regulation). The reason for the mFRR down market to be more profitable than the aFRR down market for this fuel is that the profits from mFRR down depend on the avoided fuel costs, which are higher for wood chips than for waste and recycled wood. In 2021, all prices started increasing significantly, which decreased the relative profitability of the mFRR down compared to other markets.

For wood pellets, the mFRR down market was also the second most profitable market in 2020, for the same reasons. The most profitable one in 2020 was the mFRR up market (manual frequency restoration reserves for up-regulation). The reason is that the higher fuel price of these two fuels entails low participation in the day-ahead market. Therefore, withholding capacity from the day-ahead market to be able to participate on the mFRR up market brings additional profits. In 2021, however, day-ahead prices started increasing significantly (a trend that continued into 2022) and the mFRR up market became the least profitable market for these two fuels.

The profit evaluation performed in this deliverable is purely economic. It does not include the sector coupling to the heat sector (which entails limitation of the available electricity production capacity but also a possibility to store heat if storage is available) nor does it include other technical limitations such as ramp rates. These aspects will be considered in follow-up work in this project.

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Key words: district heating, ancillary services, electricity markets, sector coupling

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Content

1 Introduction

The SeCoHeat project aims at investigating potential incomes from ancillary service and local flexibility markets that can be made by district heating systems. In this deliverable, a statistical analysis of historical prices in 2020 and 2021 from the different ancillary services is performed to get some insights into the price formation in the different markets (Section 3). Furthermore, an evaluation of potential profits that could have been done in 2020 and 2021 on the different markets by offering 1 MW/MWh of capacity is performed for different fuels (Section 4).

2 Scope and limitations

A detailed description of all ancillary service and local flexibility market was performed in a previous deliverable in this project (Deliverable D2.1.1: Review of current and future heat- and electricity-related products and their relevance for district heating companies) and will not be repeated here. We refer the interested reader to the previous deliverable for more detail. In particular, the pricing structure of each market was described in detail.

Most of the numerical evaluations performed in this deliverable are limited to ancillary service markets because historical prices are publicly available with hourly resolution. This is not the case for local flexibility markets, which is why only a limited evaluation was performed for these markets in which procurement prices are compared to the prices on ancillary services.

The numerical evaluations are limited to the possibility to offer 1 MW/MWh of electrical capacity for either up- or down-regulation, or both. Technical limitations that would limit this capacity are not considered. No consideration of coupling between heat and electricity sector is taken here. This will be done in future work in this project.

The evaluations performed here aim at answering the question: “On which market could 1 MW/MWh of electrical production capacity have been offered in 2020 and 2021 to maximize profits?”.

3 Statistical analysis of prices on ancillary service markets and local flexibility markets

Figure 1 shows a comparison of the historical procurement prices for ancillary services and day-ahead prices in SE3[1] for 2020. Procurement prices correspond to capacity compensation, i.e., a payment to producers to reserve capacity. The exception is mFRR for which the procurement prices are energy prices, i.e. payment for activated

[1] Day-ahead prices and mFRR prices depend on the price zone. SE3 was chosen because a more detailed analysis of the revenues from district heating systems in Gothenburg and Nyköping (both located in SE3) will be performed later

energy[2]. Some ancillary services receive compensation for both capacity and activation, but this is not considered in this section. Figure 2 shows the same information for 2021. Each box plot gives information about the distribution of hourly prices in a specific month for a specific market. Observe that the scales for the y-axis are different in the two figures. FCR-D refers to FCR-D up since the FCR-D down market did not exist before 2022.

Prices in 2021 are higher than prices in 2020. A clear increase of prices can be seen from September 2021. This trend continued in 2022 (not shown here). Prices for DA, FFR, and mFRR up and down have generally the largest variance. Possible reasons for this include that other ancillary services have historically been provided by hydropower to a larger extent with more stable prices as a result. Also, mFRR prices are tightly coupled to the DA prices and DA prices are more volatile because they depend on more factors such as transmission capacity and marginal prices in other countries. As far as FFR is concerned, it is a recent market with limited volume, which may explain the volatility in its prices.

FFR is only procured during the period of the year with low system inertia, which corresponds to the period between the end of spring and middle of autumn. FFR started to be procured in 2020 in Sweden.

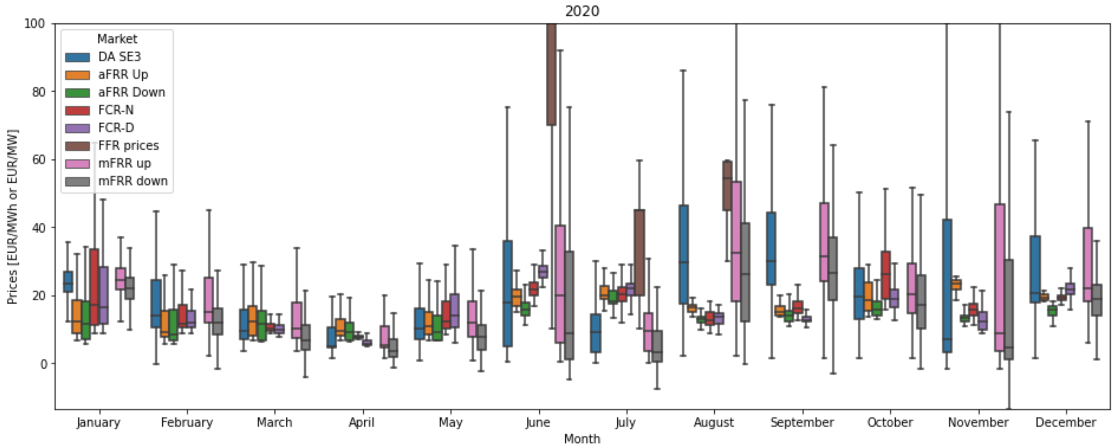

Figure 1: Comparison of all procurement prices in 2020. The y-axis has been capped at 100 EUR/MW for better readability. The brown box for FFR prices extends up to 300 EUR/MWh in June. Note that mFRR up and down is only procured in up- and down-regulated hours, respectively; the hours with no procurement (corresponding to zero revenue) in these markets are not included in the box plots.

[2] As will be mentioned farther down in the report, prices for mFRR up are payments to the producers for up-regulation whereas prices for mFRR down are payments from the producers to the TSOs to be able to produce less than planned.

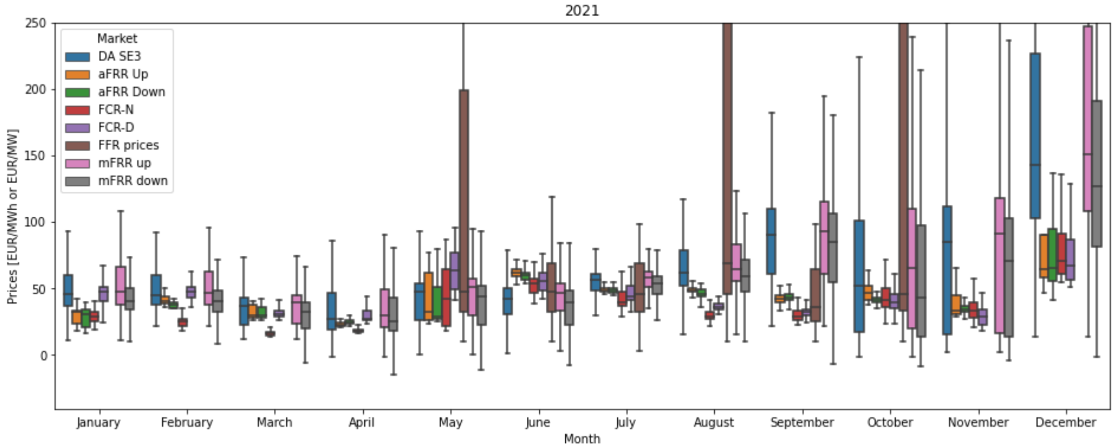

Figure 2: Comparison of all procurement prices in 2021. The y-axis has been capped at 250 EUR/MW for better readability. FRR prices extend up to 500 EUR/MWh in both August and October. Note that mFRR up and down is only procured in up- and down-regulated hours, respectively; the hours with no procurement (corresponding to zero revenue) in these markets are not included in the box plots.

Table 1 provides some price information about the local flexibility market Stockholm Flex from [1], which is the only flexibility market in Sweden with available data for 2021 (no data available for 2020). Prices are originally in SEK/MW*h (prices per 1 MW of capacity that can be sustained for one hour) and were converted to EUR/MW*h using an exchange rate of 10 SEK for 1 EUR.

In weeks 4 to 10 of 2021, volume weighted average prices varied from 30 EUR/MW*h to 88 EUR/MW*h, which align well with prices on ancillary service markets for that period as seen in Figure 2. The market is prices pay-as-bid so market participants may receive more or less than the weighted averages (as is the case for FCR markets and was the case for aFRR markets in 2020 and 2021[3]). Weeks 48 and 49 were at similar price levels whereas weeks 50 and 51 experienced higher averages of 300 to 682 EUR/MW*h. The price levels of these last two weeks are much higher than that of the ancillary service markets in the same period, see Figure 2. By their local nature, the traded volumes on local flexibility markets are small as can be seen in the last column of Table 1.

Due to the limited amount of publicly available data, the analysis in the rest of this report will not consider prices on the local flexibility markets.

Table 1: Average prices and volumes in the local flexibility market Stockholm Flex for 2021.

[3] aFRR markets will move to marginal pricing in 2022.

Week	Volume weighted average price (EUR/MW*h)	Min (EUR /MW*h)	Max (EUR /MW*h)	Net traded volume (MW*h)
51	681.88	15	1000	4.8
50	300.00	300	300	0.1
49	87.04	1	500	777.93
48	84.20	84.20	84.2	20
10	30	30	30	Not available
6	45.71	20	200	Not available
5	87.69	20	500	Not available
4	85	20	85	Not available

Figure 3 shows, for each ancillary market, the number of hours per month during which the price on this market was higher than on any other market in 2020. Figure 4 shows the same information for 2021. For example, in September 2020, day-ahead market prices in SE3 have been higher than on any other markets for 508 hours. Note that prices for mFRR down are never included since they are always lower than day-ahead prices. Conceptually, mFRR down price also must be interpreted differently than other prices: they are prices that market participants pay to buy energy, instead of producing it themselves, so that they can produce less than planned by their day-ahead commitment. In contrast, all other prices are prices that market participants receive as compensation to participate in the markets.

Looking at only prices, the day-ahead market seems to be interesting compensation-wise since it has many hours with the highest prices. FCR-D and FCR-N also both get a large share of hours with highest prices for some of the months. FFR prices are among the highest in the summer months. Although mFRR up never is the market with highest prices in any of the month, it nevertheless has many hours in which prices on this market are the highest. This is due to the relationship that mFRR up prices are always higher than the day-ahead prices when the power system is up-regulated.

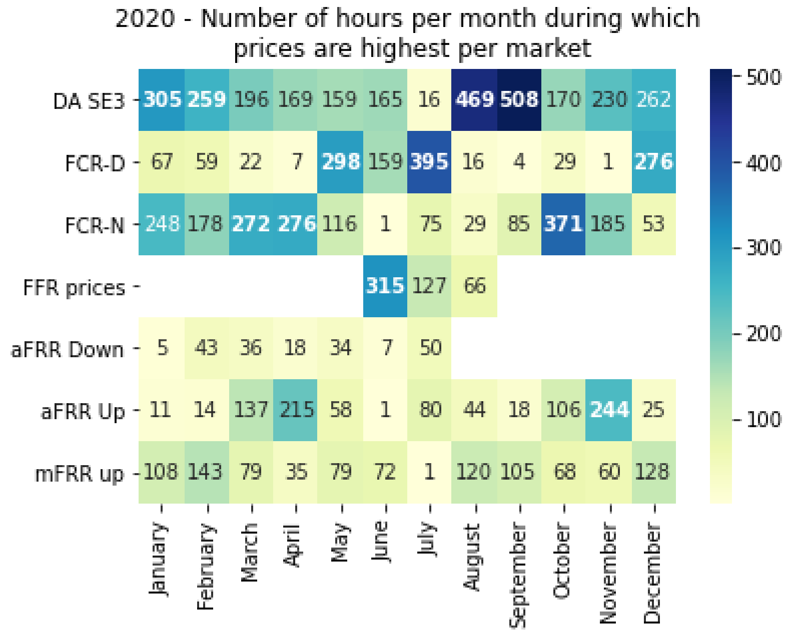

Figure 3: Number of hours per month for each market in 2020 during which the price on this market was higher than on any other market. The market with the most hours with highest prices is indicated by marking its number of hours in bold for each month.

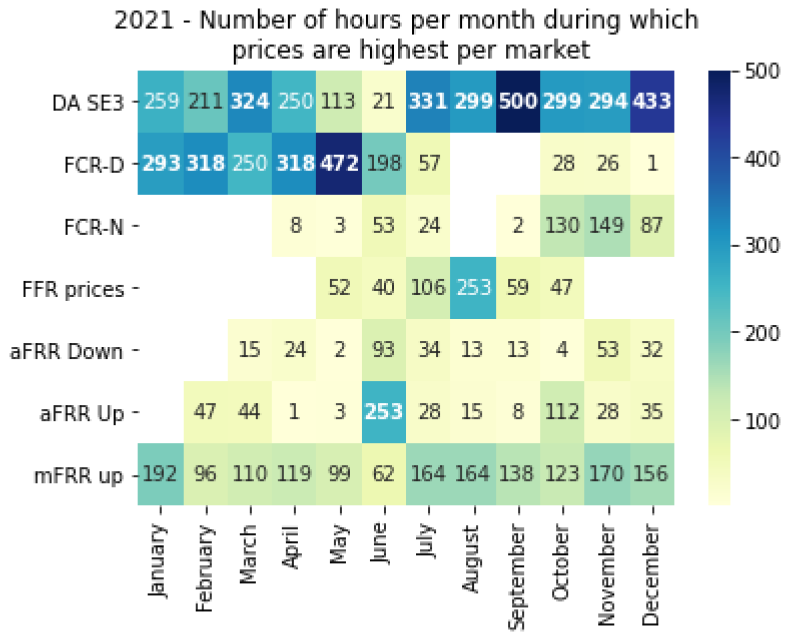

Figure 4: Number of hours per month for each market in 2021 during which the price on this market was higher than on any other market. The market with the most hours with highest prices is indicated by marking its number of hours in bold for each month.

Looking at only prices in the separate markets give limited information about potential revenues from the different markets. It was already mentioned earlier that mFRR down prices cannot be compared directly to other prices. It also is important to keep in mind that, in some cases, a producer can (and, in some cases, must) participate in several markets simultaneously for a certain hour. For example, to participate in pure down-regulation (mFRR down and aFRR down), a producer must first get a bid accepted in the day-ahead market to have some baseline production from which it can down-regulate. This also applies to FFR because a generation unit needs to be running to be able to provide FFR support in line with the fast activation requirements of this service. Another example is FCR-N where a producer needs to be able to both up- and down-regulation and, therefore, needs to have got capacity (but not all its available capacity) accepted on the day-ahead market to perform down-regulation. Some markets are mutually exclusive. For example, a producer cannot offer the same capacity on day-ahead and up-regulation markets (FCR-D, mFRR up, aFRR up) at the same time. Therefore, if a market participant wants to participate in a pure up-regulation market, it must withhold capacity from the day-ahead market.

In the next section, consideration will be taken to this to evaluate the revenues that could have been made with 1 MW/MWh of capacity in the different markets.

4 Potential profits for day-ahead market and ancillary services

In this section, the profit is calculated for participating with 1 MWh in the day-ahead and different ancillary service markets. Profits each market are computed for each market separately. No optimal selection of which market to bid on is done. For some ancillary service markets, it is needed or possible to also participate in the day-ahead market (see explanation farther down). In reality, different capacities will be able to be delivered to the different markets due to, for example, the more stringent activation times of some services. Here, it is assumed that 1 MWh can be delivered to all markets.

For each market, it is assumed that a producer sends 1 bid of 1 MWh and that the bid price is set to the producer's marginal cost. The bid is accepted on a market if the bid price is lower than the market price, except for mFRR down for which a bid is accepted if the bid price is larger than the mFRR down price. Table 2 gives an overview of the conditions under which a bid will be accepted on the different markets.

Table 2: Conditions for a bid to be accepted on the DAM and ASM.

Market	Conditions for a bid to be accepted on the corresponding markets
Day-ahead	Bid price ≤ DA price
mFRR up	(Bid price ≤ mFRR up) and (mFRR price > DA price[4])
mFRR down	(Bid price ≥ mFRR down price) and (mFRR down price < DA price[5])
aFRR up	(Bid price ≤ aFRR up price) and (aFRR up is procured)
aFRR down	(Bid price ≤ aFRR down price) and (aFRR down is procured)
FCR-D up	Bid price ≤ FCR-D up
FCR-N	Bid price ≤ FCR-N price
FFR	Bid price ≤ FFR price

Hourly profits are computed as follow:

[4] This condition means that the TSO performs up-regulation during this hour.
[5] This condition means that the TSO performs down-regulation during this hour.

Profits = Compensation from DA (*when applicable*)
+ Compensation for procured capacity for AS (*when applicable*)
+ Compensation for activated energy for AS (*when applicable*)
- Production costs

Where:

- Compensation from DA: day-ahead price when a bid to the day-ahead market is accepted.
- Compensation for procured capacity for AS: payment received by the producer when a bid for capacity for an ancillary service is accepted. The payment is equal to the AS procurement price for capacity.
- Compensation for activated energy for AS: payment received by the producer for the energy activated for delivering ancillary services. Activated energy for up-regulation, when compensated, is always priced according to mFRR up prices. Correspondingly, activated energy for down-regulation, when compensated is always priced according to mFRR down prices. For down-regulation, the compensation for activated energy is negative: it is a payment from the producer to the TSO, as explained earlier.
- Production costs: production costs for the net production considering both day-ahead plan and activation for ancillary services. The production costs are computed as follows:

Production costs = production * marginal cost

And

production = production according to day-ahead plan
+ activated up-regulation
- activated down-regulation

The profit evaluation is performed for each hour of 2020 and 2021 based on the formula above and the following assumptions:

- Up-regulation markets (FCR-D, aFRR up and mFRR up): a bid of 1 MW of capacity is offered on the up-regulation markets during hours with procurement. For the hours when it is known beforehand that there will not be procurement[6], a bid of 1 MWh is offered to the day-ahead market instead.
- Down-regulation markets (aFRR down and mFRR down): a bid of 1 MWh to the day-ahead market and, if this bid is accepted on the day-ahead market, a bid of 1 MW of capacity is offered to the down-regulation markets.
- FFR: Same as for down-regulation markets
- For mFRR up and down, we assume that a bid is activated during the whole hour if accepted.
- For aFRR up/down regulation, we assume that the half of the bid capacity (i.e. 0.5 MWh for a bid of 1 MW) is activated during hours with up/down regulation. This is a simplification since this activated energy depends on the frequency.

[6] The schedule for hours with procurement for aFRR is published by Svenska kraftnät in advance. In contrast, there are some hours during which mFRR up is not activated but this is not known in advance by market actors.

- Symmetrical markets (FCR-N): a bid of 0.5 MWh of energy to the day-ahead market and, if this bid is accepted on the day-ahead market, a bid of 0.5 MW of capacity is offered to the FCR-N market. For the activation, the same assumption as for aFRR markets is used: activated energy for up-regulation is assumed to be half of the bid size (i.e. 0.25 MWh for a bid of 0.5 MW) during hours with up-regulation, and similarly for down-regulation.
- For FCR-D up, it is assumed that the activated energy is zero. In reality, activation occurs proportionally to the system frequency deviation from 49.9 Hz and bids are fully activated when the system frequency reaches 49.5 Hz. Since the TSO strives at maintaining the frequency above 49.9 Hz, the activated volumes will remain small for most hours.
- For FFR, it is also assumed that the activated energy is zero. This is because FFR is activated only following critical contingencies and its duration is short.
- Hours with up- and down-regulation are assumed to be determined by the mFRR prices. Hours with up-regulation are hours for which the mFRR up price is strictly larger than the day-ahead price. Hours with down-regulation are hours for which the mFRR down price is strictly lower than the day-ahead price.

Table 3 gives an overview of the markets for which profits will be computed, and the hourly production, compensation and profit resulting from the assumptions above depending on whether bids are accepted. The profit calculation for each market is explained in more detail in the next subsections. Note that the producer’s marginal cost impacts the acceptance criterion of a bid (since the bid price is assumed to be equal to the marginal price) and the production costs (which are equal to the product of production and marginal cost).

Table 3: Hourly production, compensation and profit in all investigated markets, depending on whether bids are accepted.

Market	Condition on bid acceptance	(A) Production according to day-ahead plan [MWh]	(B) Activated up-regulation [MWh]	(C) Activated down-regulation [MWh]	Production (A+B-C) [MWh]	Compensation from DA	Compensation for procured capacity for AS	Compensation for activated energy for AS	Profit: Sum of compensations minus (production * marginal cost)
Day-ahead	Bid accepted on DA	1	0	0	1	DA price	0	0	DA price – marginal cost
	Bid not accepted on DA	0	0	0	0	0	0	0	0
mFRR up only	Bid accepted on mFRR up	0	1	0	1	0	0	mFRR up price	mFRR price – marginal cost
	Bid not accepted on mFRR up	0	0	0	0	0	0	0	0
mFRR down & day-ahead	Bid accepted on DA and mFRR down	1	0	1	0	DA price	0	-mFRR down price	DA price - mFRR down price
	Bid accepted on DA but not on mFRR down	1	0	0	1	DA price	0	0	DA price – marginal cost

Market	Condition on bid acceptance	(A) Production according to day-ahead plan [MWh]	(B) Activated up-regulation [MWh]	(C) Activated down-regulation [MWh]	Production (A+B-C) [MWh]	Compensation from DA	Compensation for procured capacity for AS	Compensation for activated energy for AS	Profit: Sum of compensations minus (production * marginal cost)
	Bid accepted neither on DA nor on mFRR down	0	0	0	0	0	0	0	0
aFRR up & day-ahead	Bid accepted on aFRR up	0	0.5 if hour with up-regulation[7] 0 otherwise	0	0.5 up-regulation 0 otherwise	0	aFRR up price	0.5 * mFRR up price	aFRR up price if up-regulation[8]: +0.5*(mFRR up price – marginal cost)
	No aFRR up procurement and bid accepted on DA[9]	1	0	0	1	DA price	0	0	DA price – marginal cost
	Otherwise	0	0	0	0	0	0	0	0
aFRR down & day-ahead	Bid accepted on DA and aFRR down	1	0	0.5 if hour with down-regulation[10]	0.5 if down-regulation	DA price	aFRR down price	-0.5*mFRR down price	DA price + aFRR down price If down-regulation[11]:

[7] As explained above, hours with up-regulation are hours during which the TSO activate mFRR up bids. During these hours, it is assumed that half the bid capacity for aFRR is activated.
[8] In addition to the aFRR price.
[9] Market actors know in advance that there will not be any procurement of aFRR up and can send bids to the DA market.
[10] As explained above, hours with down-regulation are hours during which the TSO activate mFRR down bids.

Market	Condition on bid acceptance	(A) Production according to day-ahead plan [MWh]	(B) Activated up-regulation [MWh]	(C) Activated down-regulation [MWh]	Production (A+B-C) [MWh]	Compensation from DA	Compensation for procured capacity for AS	Compensation for activated energy for AS	Profit: Sum of compensations minus (production * marginal cost)
				0 otherwise	1 otherwise				– 0.5*(mFRR down price+marginal cost)
	Bid accepted on DA but not aFRR down	1	0	0	1	DA price	0	0	DA price – marginal cost
	Bid not accepted on DA	0	0	0	0	0	0	0	0
FCR-D up	Bid accepted on FCR-D up	0	0	0	0[12]	0	FCR-D up price	0	FCR-D up price
	Bid not accepted on FCR-D up	0	0	0	0	0	0	0	0
FCR-N & day-ahead	Bid accepted on DA and FCR-N	0.5	0.25 if hour with up-regulation[13] 0 otherwise	0.25 if hour with down-regulation 0 otherwise	0.75 if up-regulation 0.25 if down-regulation	0.5*DA price	0.5*FCR-N price	0.25*mFRR up price if hour with up-regulation	0.5*(DA price + FCR-N price – marginal cost) if up-regulation[14]:

[11] In addition to DA price + aFRR down price.
[12] Capacity is reserved for FCR-D up but activation is zero according to the assumptions.
[13] It is assumed that half of the bid capacity (i.e. 0.25 MWh) is activated in case of up-regulation (and similarly for down-regulation).

Market	Condition on bid acceptance	(A) Production according to day-ahead plan [MWh]	(B) Activated up-regulation [MWh]	(C) Activated down-regulation [MWh]	Production (A+B-C) [MWh]	Compensation from DA	Compensation for procured capacity for AS	Compensation for activated energy for AS	Profit: Sum of compensations minus (production * marginal cost)
					0.5 otherwise			-0.25*mFRR down price if hour with down-regulation 0 otherwise	+0.25*(mFRR up price – marginal cost) if down-regulation: +0.25*(marginal cost – mFRR down price)
	Bid accepted on DA but not on FCR-N	0.5	0	0	0.5	0.5*DA price	0	0	0.5*(DA price – marginal cost)
	Bid accepted neither on DA nor on FCR-N	0	0	0	0	0	0	0	0
FFR & day-ahead	Bid accepted on DA and FFR	1	0	0	1[15]	DA price	FFR price	0	DA price + FFR price – marginal cost
	Bid accepted on DA but not FFR	1	0	0	1	DA price	0	0	DA price – marginal cost
	Bid accepted	0	0	0	0	0	0	0	0

[14] In addition to the first part of the profit (and similarly for hours with down-regulation).
[15] Capacity is reserved for FFR but it is assumed that the activated energy is negligible compared to the DA production.

Market	Condition on bid acceptance	(A) Production according to day-ahead plan [MWh]	(B) Activated up-regulation [MWh]	(C) Activated down-regulation [MWh]	Production (A+B-C) [MWh]	Compensation from DA	Compensation for procured capacity for AS	Compensation for activated energy for AS	Profit: Sum of compensations minus (production * marginal cost)
	neither on DA nor on FFR								

4.1 Profits from day-ahead market only

The producer participates in the day-ahead market, when the day-ahead price is larger than the bid price, which is assumed to be equal to the marginal cost. For a bid of 1 MWh, the profit is equal to the difference between day-ahead price and marginal cost.

4.2 Profits from mFRR up market only

When a bid is accepted for mFRR, it is assumed that the bid is activated for the whole hour. In addition, the mFRR price is not a capacity price; it is an energy price (price for being activated). mFRR up prices are always equal or greater than the day-ahead prices. If mFRR up price is equal to the day-ahead price, there is no up-regulation and, therefore, no activation of mFRR up. If mFRR up is less than the marginal cost, the producer's bid will not be activated. In both these cases, profit is zero. Otherwise, for 1 MW, profit is equal to mFRR up price minus marginal cost.

4.3 Profits from day-ahead and mFRR down markets

As mentioned in assumptions above, to participate in down-regulation markets, the producer needs to participate in day-ahead market also. In mFRR down, producer buys back the production from the TSO to be able to produce less than its day-ahead commitment. Hence, being activated for mFRR down is a revenue for the TSO and a cost for the producer. That is the reason why, for mFRR down, the bid is selected if the bid price (assumed equal to marginal cost) is larger than the mFRR down price. The profit is the difference between the day-ahead price and the mFRR down price. Note that there is no production cost involved since activation of mFRR down means that the producer does not need to produce the 1 MWh accepted on the day-ahead market. If the marginal cost is less than the mFRR down price, the profit is equivalent to participation in day-ahead market.

4.4 Profits from day-ahead or aFRR up markets

Participation in aFRR up is when the aFRR up price is larger than the bid cost (assumed to be equal to the marginal cost). Note that this assumption is a simplification. In reality, the producer will want to bid on the aFRR up market if it expects to get more than from the day-ahead market. Therefore, its bid price may include an estimation of the expected day-ahead market price for the same hour.

The activation for aFRR up and down depends on the grid frequency and varies from hour to hour. Some hours may not see any activation, some other hours may see a full activation (1 MWh), and some other hours may see partial activation (between 0 and 1 MWh). Here, it is assumed that if an aFRR bid has been accepted, half of the capacity (0.5 MWh) will be activated during hours with up-regulation (hours in which the mFRR up prices are larger than the day-ahead prices). In Sweden, producers get compensated for the activation of aFRR by the mFRR price. The production cost is, in case of activation, equal to the cost for the activated energy (0.5 MWh priced at marginal cost). If a bid to aFRR up has been accepted but not activated, then the production cost is zero.

The Swedish TSO does not procure aFRR up for all hours. The schedule for procurement is published in advance. For the hours with no procurement, it is assumed that the producer bids its 1 MW of capacity to the day-ahead market instead, and the profit is then equal to the profit from day-ahead market if that bid gets accepted.

The profit is zero, when the bid to aFRR up is not accepted or when there is no procurement of aFRR up and the bid to the day-ahead market is not accepted.

4.5 Profits from day-ahead and aFRR down markets

Producers can send bids to the aFRR down only if they expect to have production online from which they can down-regulate. Therefore, they need to send a bid to the day-ahead market and that bid must be accepted. When there is procurement of aFRR down, the bid to aFRR down is then selected when the bid price (assumed to be equal to marginal cost) is lower than the aFRR down price. Like aFRR up, it is assumed that the accepted aFRR down capacity will be activated only during hours with down-regulation (i.e. during which the TSO activated mFRR down bids). In case of activation, it is assumed that half of the bid capacity (i.e. 0.5 MWh) will be activated. Activation of aFRR down is priced by the mFRR down price and it is a cost for the producer. In case of activation, the actual production is 0.5 MWh: it is the day-ahead plan (1 MWh) minus the down-regulation (0.5 MWh). In case the aFRR down bid is accepted but not activated, the production is equal to the day-ahead plan (1 MWh).

The profit is zero in case the bid to the day-ahead market is not accepted (in which case the producer cannot participate in aFRR down either).

4.6 Profits from FCR-D up markets only

In the hours in which a bid for FCR-D is accepted (FCR-D up price is larger than the bid price), the profit is calculated as the difference between the procurement revenues (FCR-D up prices) and the production costs. It is assumed that the activation of FCR-D is zero. Therefore, production costs are zero. If FCR-D up is less than bid price (assumed to be equal to marginal cost), profit is zero.

4.7 Profits from day-ahead and FCR-N markets

Like mFRR down, a producer needs to get a bid accepted in the day-ahead market to participate in the down-regulation part of FCR-N. Therefore, if the day-ahead price is lower than the bid price, the day-ahead bid is rejected and there is no participation in either the day-ahead market or the FCR-N market and the profit is zero.

In case the producer participates in the day-ahead market (day-ahead price larger than bid price), it does so with a capacity of 0.5 MWh to keep capacity for participation in FCR-N in both direction (both up-regulation to 1 MW and down-regulation to 0 MW). It is assumed that the producer also participates in FCR-N when the bid price (assumed equal to marginal cost) is lower than the FCR-N procurement price. When participating in FCR-N, the producer receives compensation for both the procured capacity (FCR-N procurement price) and the activated energy (priced with mFRR up prices for up-regulation and mFRR down prices for down-regulation as for aFRR up and aFRR down). We assume here that half of the bid capacity (i.e. 0.25 MWh) is activated during up- and down-regulated. The actual production is equal to the capacity offered to the day-ahead market (0.5 MWh) adjusted with the activated up- and down-regulation for FCR-N.

If prices are such that the producer only participates in the day-ahead market, the profit is equal to the day-ahead market profit with a capacity of 0.5 MWh.

4.8 Profits from day-ahead and FFR markets

For FFR, the producer is paid for the capacity and at the same time participating in day-ahead market. Therefore, there is no withholding capacity from the day-ahead market and the revenue of day-ahead market also is included in the FFR profit. Corresponding to the price comparison between FFR and marginal cost, the profit is either equal to the profit of day-ahead, or a higher one with addition of FFR price.

5 Profit calculation results

Based on the methodology presented in the previous sections, the profits for participating with 1 MWh in the different markets with a CHP plant are computed for different fuels below. Four types of biomass fuels have been selected with different prices ranging from 0 to 30 EUR/MWh. Based on [2] biofuels and waste are the most common electricity production sources in Sweden, and wood chips are usually the fuel used in biofuel fired CHP plants. Wood chips is considered as main fuel with price 20 EUR/MWh based on data published in Swedish Energy Agency [3]. Table 4 shows the fuel prices, efficiency and resulting marginal production cost for electricity used in the analysis.

Table 4. Selected fuels with different prices for CHP plant

	Waste	Recycled wood	Wood chips	Wood pellets
Fuel price (EUR/MWh) [3]	0	10	20	30
Efficiency [2]	0.9	0.9	0.9	0.9
Marginal production cost for electricity (EUR/MWh)	0	11.11	22.22	33.33

In the following, the results for wood chips are analysed first, and then the results for waste, recycled wood, and wood pellets are presented respectively.

5.1 Fuel: Wood chips

Marginal production cost for wood chips is calculated by dividing the fuel price to efficiency which is considered 0.9 as total efficiency for biofuel CHP plants [2]. The marginal production cost will be 22.22 EUR/MWh.

Figure 5 shows the number of hours with zero and non-zero profit for each market in 2020 and 2021. The wood chip CHP participates in the different markets a limited number of hours in 2020. This is due to a high marginal cost of producing electricity compared to the procurement prices on all the markets during this year. In 2021, a wood chip CHP would participate in all markets much more often as procurement prices were much higher during that year.

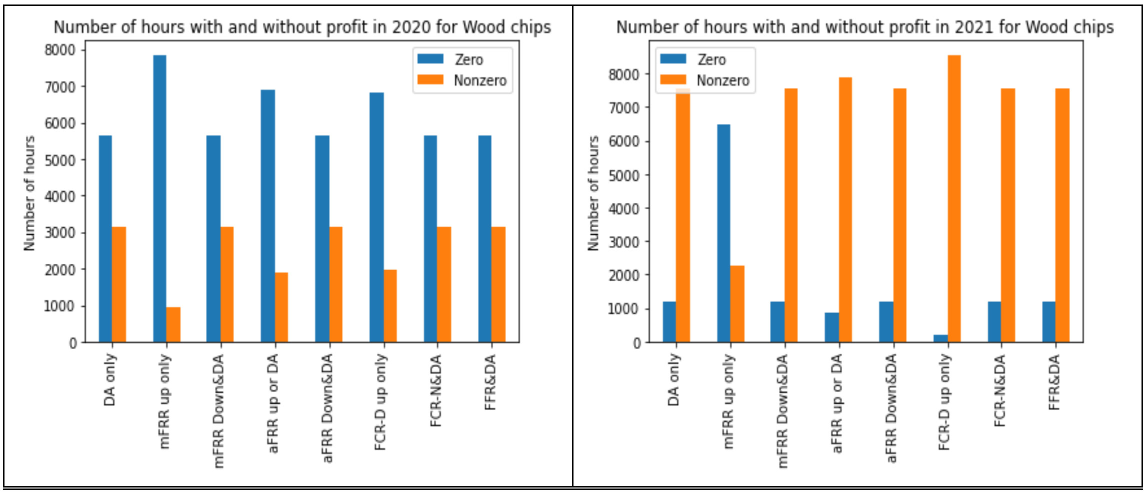

Figure 5: Number of hours with and without profits in each market for wood chips for 2020 and 2021.

The magnitude of the monthly profits for each market is shown in Figure 6 for 2020 and in Figure 7 for 2021. Note that the scales are different in the two figures and the colours on the two graphs cannot be compared directly.

The profits from day-ahead give a baseline to compare participation in the other markets.

In 2020, mFRR up, mFRR down and FCR-D up are the markets that are the most profitable the most often. In 2021, it was aFRR down and FCR-D up has 5 months higher profits than other markets. FCRD-up also has the highest profit for 2021 in Figure 5.

Participating in mFRR up means withholding capacity from the day-ahead market to offer it to the mFRR up market instead. Participating in mFRR up is more profitable than participating in the day-ahead market during hours with up-regulation when mFRR up prices are higher than the marginal production cost. For hours for which the day-ahead price is lower than the marginal production cost, withholding capacity does not entail any loss.

Participating in mFRR down and day-ahead brings substantial additional profits compared to only participating in the day-ahead market. This is due to the marginal price being usually higher than the mFRR down price during hours of down-regulation when the wood chip unit already participates in the day-ahead market. It gets the highest profit in August, September, November and December 2020. Participating in mFRR down does not bring any risk of losing profits from the day-ahead market, as opposed to mFRR up.

The profit of participating in aFRR up is higher than that of the day-ahead market for a few months in 2020 and for almost all months in 2021. Capacity offered to aFRR up is remunerated. However, it is seldom that this capacity is fully activated. It is assumed here that half of this capacity is activated. This activation leads to extra incomes. Furthermore, since not all capacity is activated, the production costs are lower than if the same capacity was sold on the day-ahead market (in which case, it would have been fully activated). Therefore, for aFRR up (and similarly for FCR-N), a simple comparison between procurement prices and day-ahead prices does not capture the whole difference in profits.

The profit of aFRR down and day-ahead in 2020 is equal to the profit of participation in day-ahead market only except in January, February, June, and October. This is due to higher marginal cost than aFRR down prices, which means that a unit that uses wood chips would never participate in the aFRR down market. Profits for aFRR down in 2021 are higher than day-ahead only in the whole year. In February 2021 and from September to December, aFRR down is the market with highest profit.

Profits from FCR-D up are the highest in three months in 2020 and five months in 2021. Offered capacity is remunerated and is seldom activated for FCR-D up. This is due to the system frequency staying outside the activation band for FCR-D up most of the time. Therefore, production costs can be assumed to be zero when capacity has been accepted for FCR-D. This is a difference compared to the day-ahead market where production needs to match the accepted capacity.

Reserving half of the capacity to participate in FCR-N in addition to the day-ahead market decreases the profits in all months of 2020 except January and October, and 2021 except for January, May, June, and July compared to only participating in the day-ahead market. As for aFRR up, not all accepted capacity is activated (it is assumed here that half is activated). When capacity is activated for the down-regulation part of FCR-N, it is priced at the mFRR down price, which entails a loss when the mFRR down price is higher than the marginal production cost.

In 2020, participating in FFR in addition to the day-ahead market brought additional profits only during June and August when the FFR prices were the highest. However, no additional profits were made during any other months, either because no FFR capacity was procured or because the marginal cost of wood chip units is too high. In contrast, in 2021, FFR capacity was procured more often, and prices were higher than in 2020. Participating in FFR in addition to day-ahead therefore brought additional profits in May to October. FRR gets the highest profits of all markets for July and August 2021.

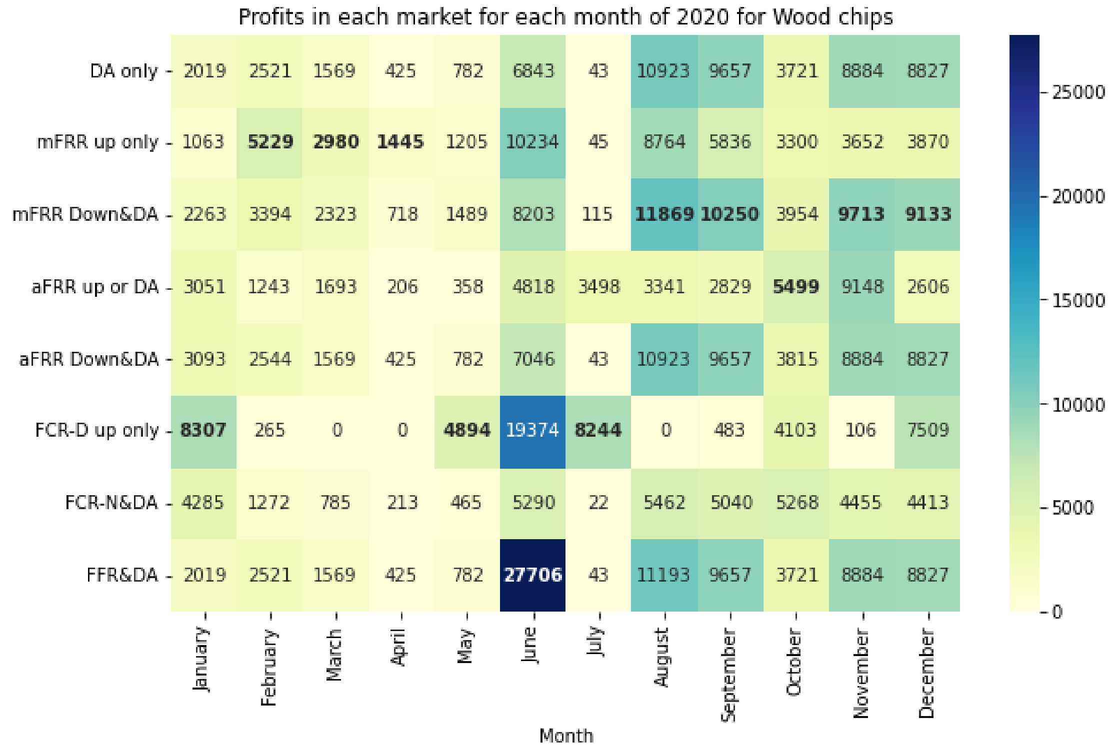

Figure 6: Monthly profits from each market in 2020 for wood chips.

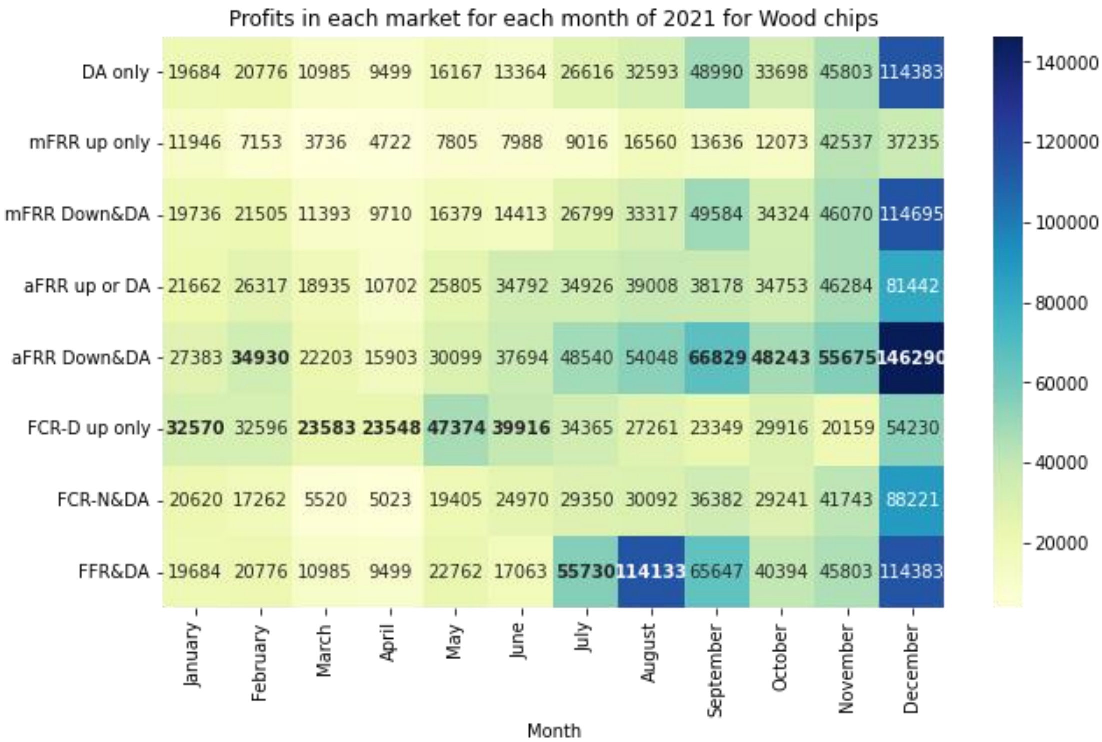

Figure 7: Monthly profits from each market in 2021 for wood chips.

Figure 8 shows the total (annual) profit of 1 MWh of capacity participating in different markets for 2020 and 2021. Profits in 2021 are much higher than in 2020 due to higher prices in 2021. Figure 8 shows that participating in FFR and day-ahead market has the highest total profit in the year 2020. mFRR down and day-ahead market also has a high total profit in 2020 because there is profit from day-ahead market in addition to buying energy with lower cost from mFRR down instead of producing it with a higher marginal cost. In 2021, participating in aFRR down and day-ahead market brings the highest profit of all markets. FFR and day-ahead market has the second highest profits. The profitability of the aFRR up market is higher than that of DA only in 2021 whereas it was much lower in 2020. The relative profitability of mFRR up compared to other markets decreased substantially in 2021, probably due to the fact that the higher prices in 2021 enabled the wool chip unit to participate more often in all markets. Reserving capacity from the DA to participate in FCR-N is an economic loss both in 2020 and in 2021.

All in all, the down-regulation markets and the FFR markets are consistently among the most profitable markets because no capacity needs to be withheld from the day-ahead market. Note that in the analysis performed here, no consideration of the technical possibility to down- or up- regulate was taken. In reality, the coupling with the heat sector through the need to deliver a certain amount of heat entails limitations on the amount of capacity that can be offered for down- or up-regulation. This will be considered in future work.

Interestingly, although the profits from FCR-D up were often the highest in the first half of 2021, the total yearly profits for the whole year from that market are still lower than the profits from day-ahead markets.

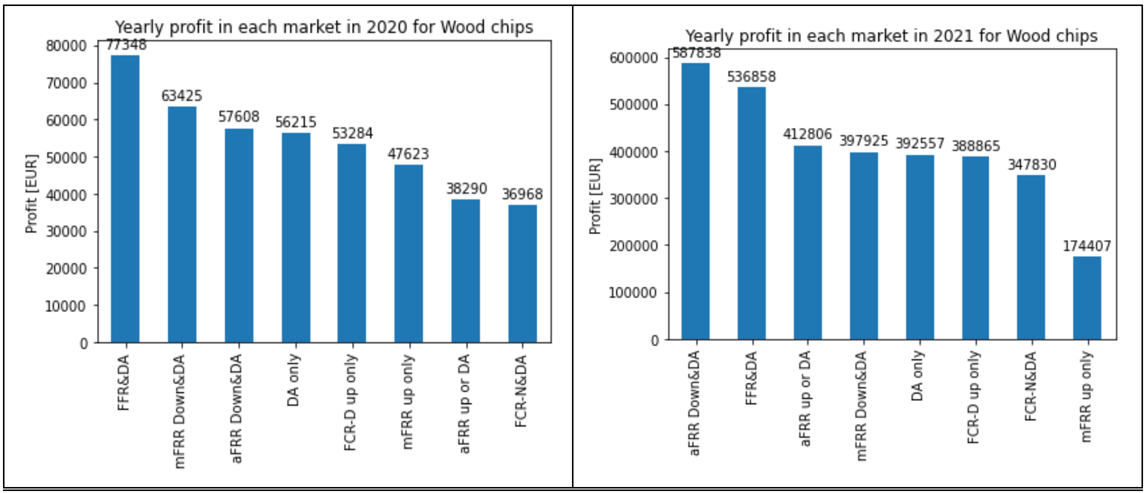

Figure 8: Annual profits for 1 MWh of capacity participating in different markets in 2020 and 2021 for wood chips. Note that the scale of profits extends to 80 kEUR in 2020 and to 600 kEUR in 2021.

5.2 Fuel: Waste

The second fuel selected for analysis is waste with the lowest price among all studied fuels (0 EUR/MWh). Figure 9 presents the number of hours with zero and non-zero profit for each market in 2020 and 2021. According to this figure, a waste unit will make profits in all markets during most hours. It can be compared with the corresponding figure for wood chips Figure 5. Note that, although not visible on the figures, there are a few numbers of hours with zero profit in almost all markets due to negative day-ahead prices (in which case a waste unit would not participate in day-ahead). mFRR up is the only market for which a generating unit using waste would not make profits for all hours. This is because mFRR up is only activated during up-regulated hours. During the rest of the hours, the unit would have kept capacity for mFRR up in vain. The only difference between 2020 and 2021 is the number of hours for mFRR up, which is due to the number of hours with up-regulation being different between 2020 and 2021.

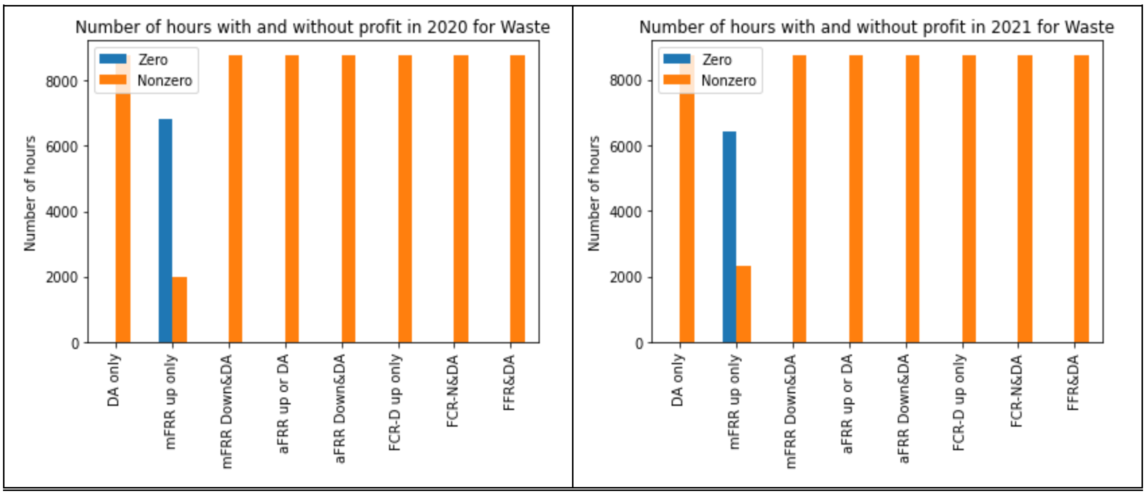

Figure 9: Number of hours with and without profits in each market for waste for 2020 (right) and 2021 (left).

Figure 10 gives the monthly profit for each market for 2020. Figure 11 gives the same information for 2021.

For 2020, FFR has the highest prices in June according to Figure 1 and Figure 3. Based on Figure 10, FFR has the highest profit in June. Opposite to wood chips in Figure 6, there are difference between profits of “aFRR down& DA” and “DA only” markets in Figure 10. This is because there are some hours in which aFRR down price is higher than the marginal cost, so a waste-based unit would participate in aFRR down. aFRR down is the most profitable market during most of the time (10 months out of 12). The exceptions are June with FFR and July with FCR-D up. Participating in mFRR down brings very small additional profits compared to participating in the DA only. The reason is that with waste having a zero marginal costs, it is only profitable to participate in mFRR down when mFRR down prices are negative, which occurs very seldom.

In 2021, aFRR down and day-ahead is the most profitable market in all months except the summer months when FFR is the most profitable market.

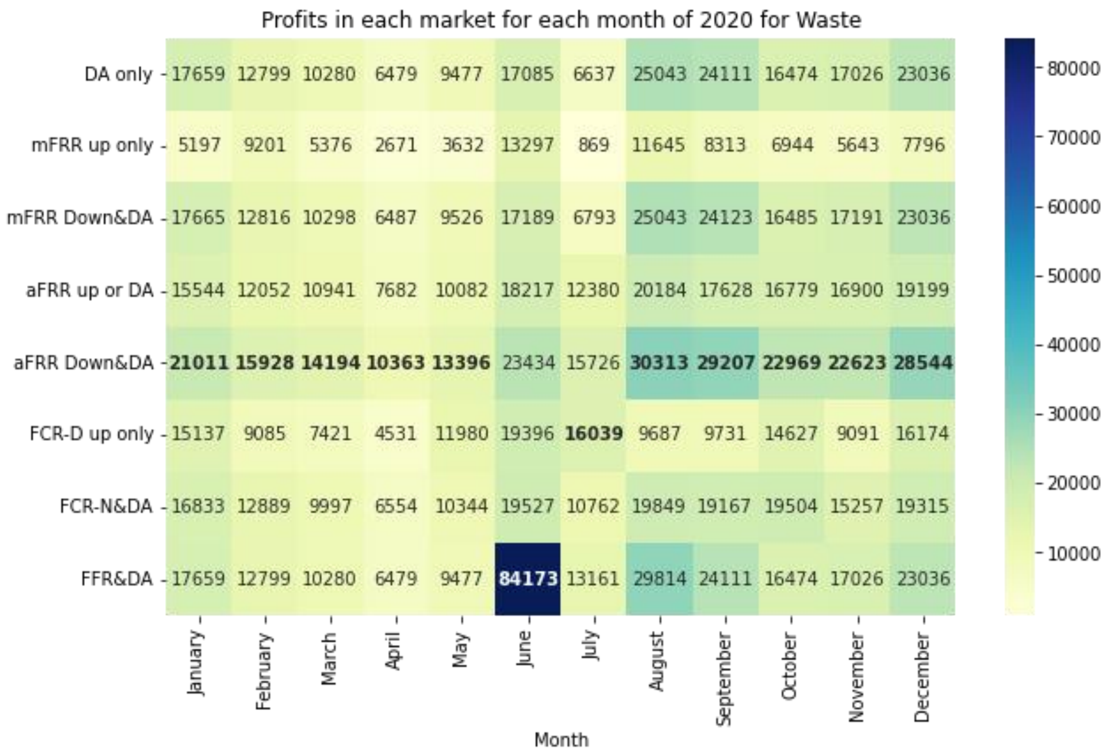

Figure 10: Monthly profits from each market in 2020 for waste.

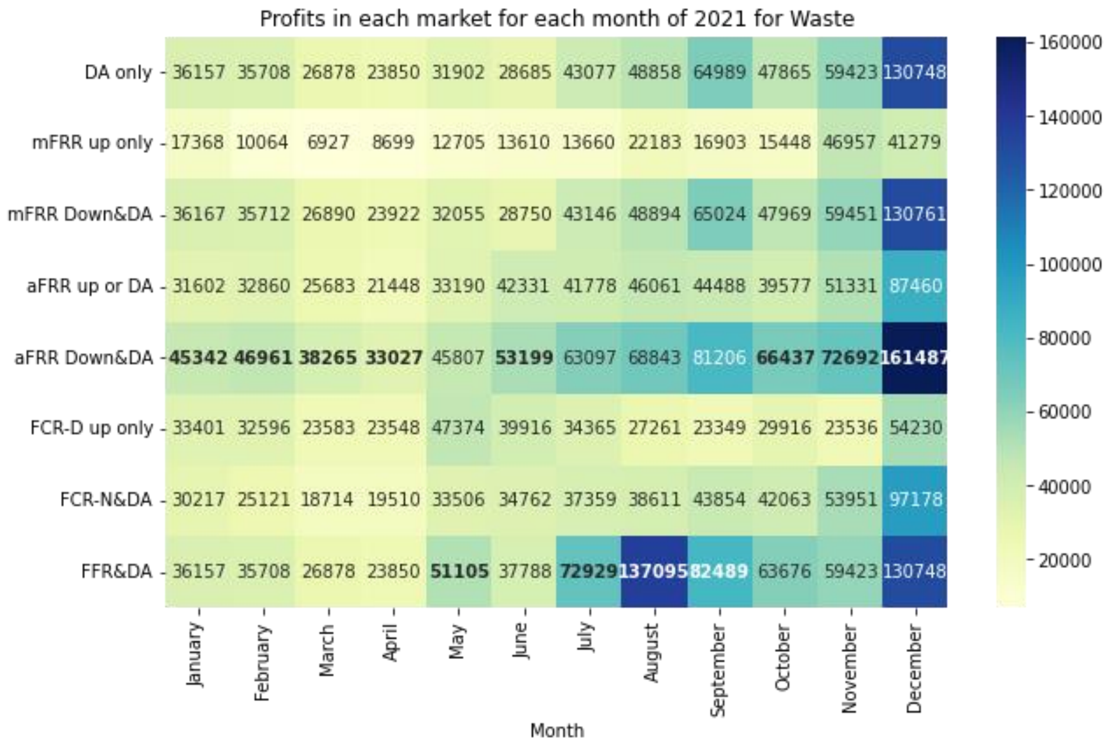

Figure 11: Monthly profits from each market in 2021 for waste.

Total yearly profits for the different markets for 2020 and 2021 are shown in Figure 12. The trends are similar in 2020 and 2021. The top three markets are FFR, aFRR down and mFRR down.

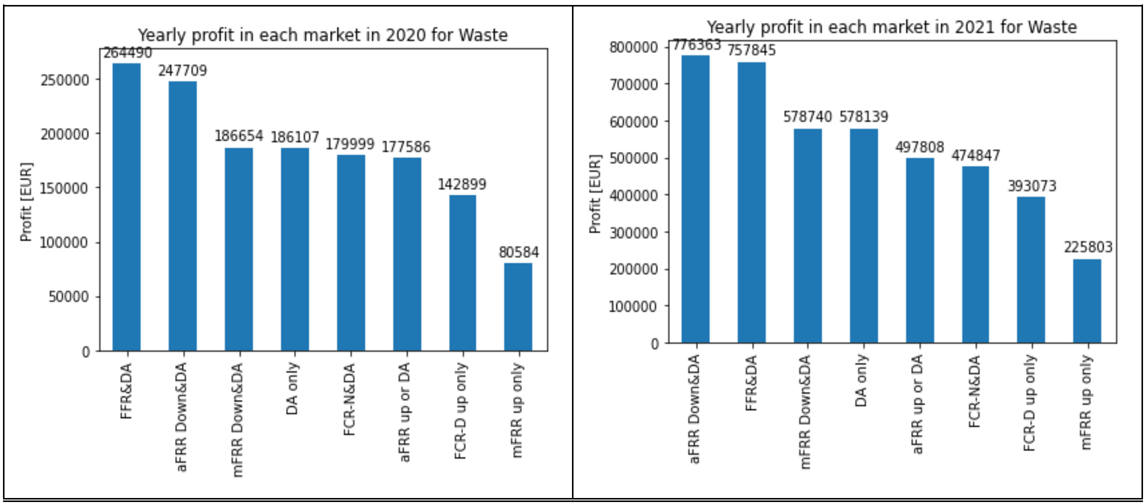

Figure 12: Annual profits for 1 MWh of capacity participating in different markets for 2020 and 2021 for waste. Note that the scale on the y-axes is different in the two figures.

5.3 Fuel: Recycled wood

Similarly, the analysis is done for recycled wood with price 10 EUR/MWh. The marginal cost is then 11.11 EUR/MWh.

From Figure 13, it can be seen that the number of hours for non-zero profit is higher than wood chips and less than waste. This is reasonable since the fuel price (marginal cost) is in between waste and wood chips. Looking at the monthly profits in Figure 14 and Figure 15, the results are also in between those of waste and wood chips.

The yearly profit analysis in Figure 16 shows that the FFR and down-regulating markets are again the market with highest profits. Interestingly, in 2020, both the aFRR up market and the FCR-D up market had highest profits than the day-ahead market, which never happened for the other two fuels.

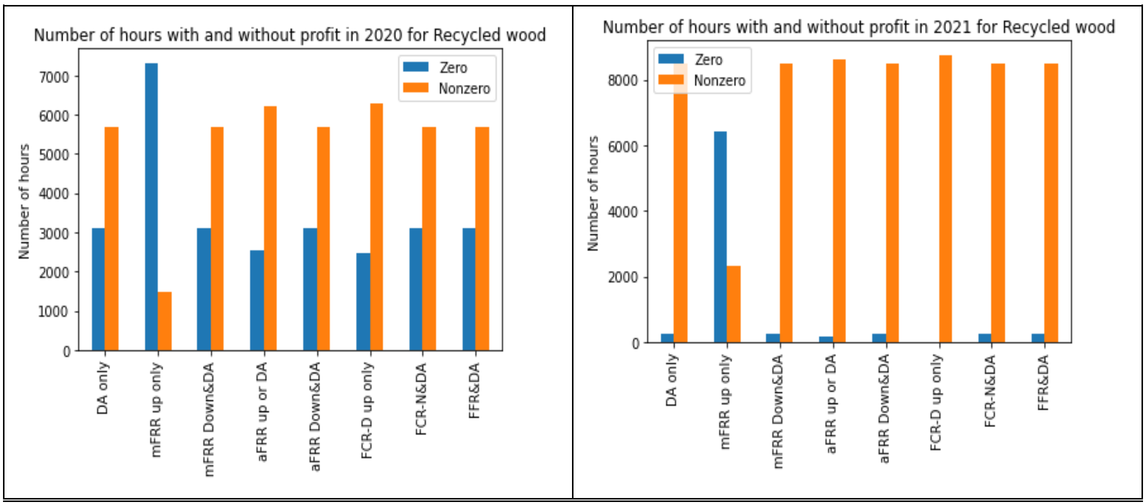

Figure 13: Number of hours with and without profits in each market for recycled wood for 2020 and 2021.

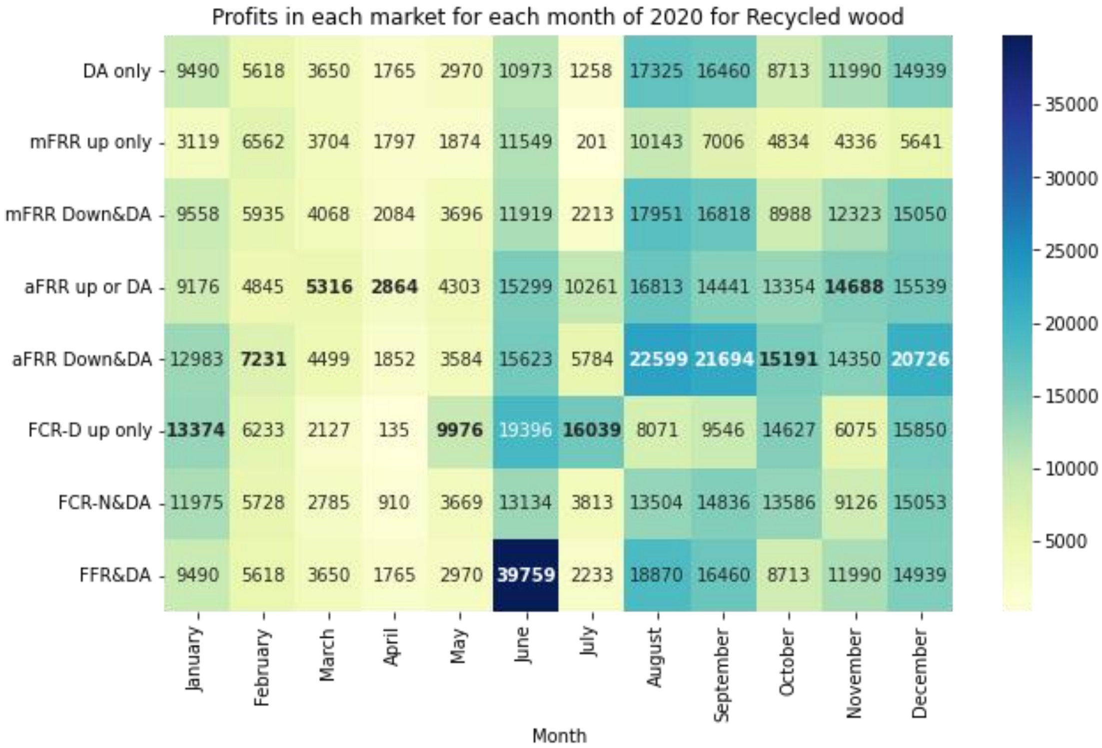

Figure 14: Monthly profits from each market in 2020 for recycled wood.

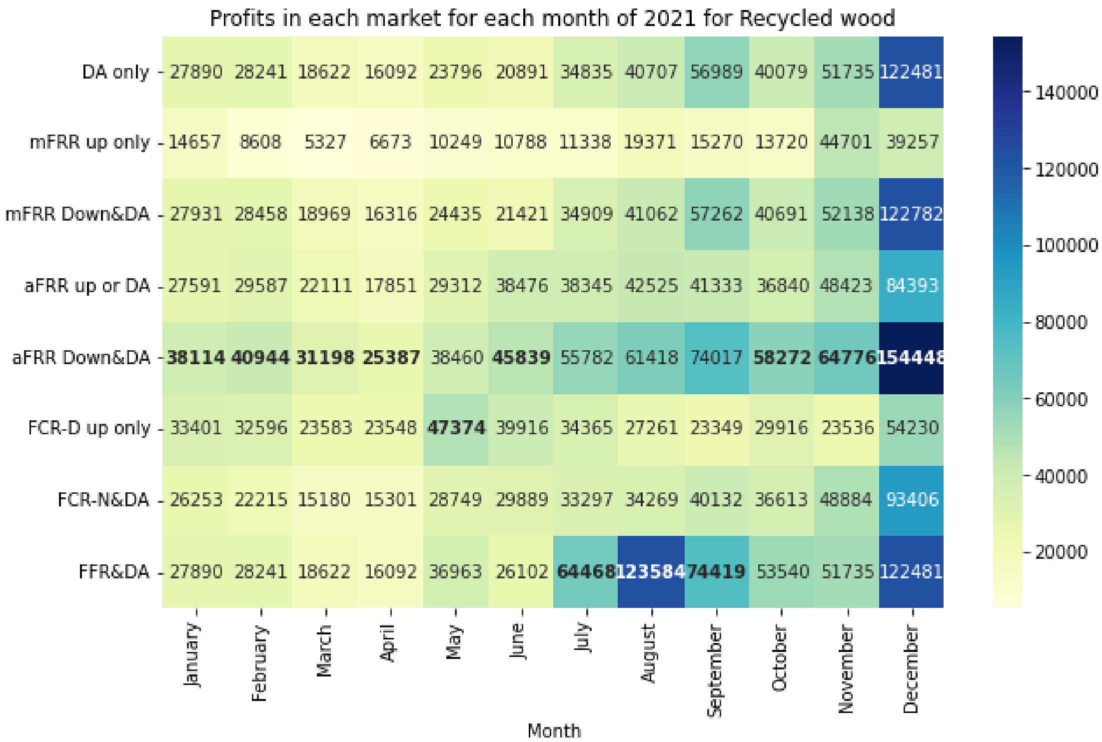

Figure 15: Monthly profits from each market in 2021 for recycled wood.

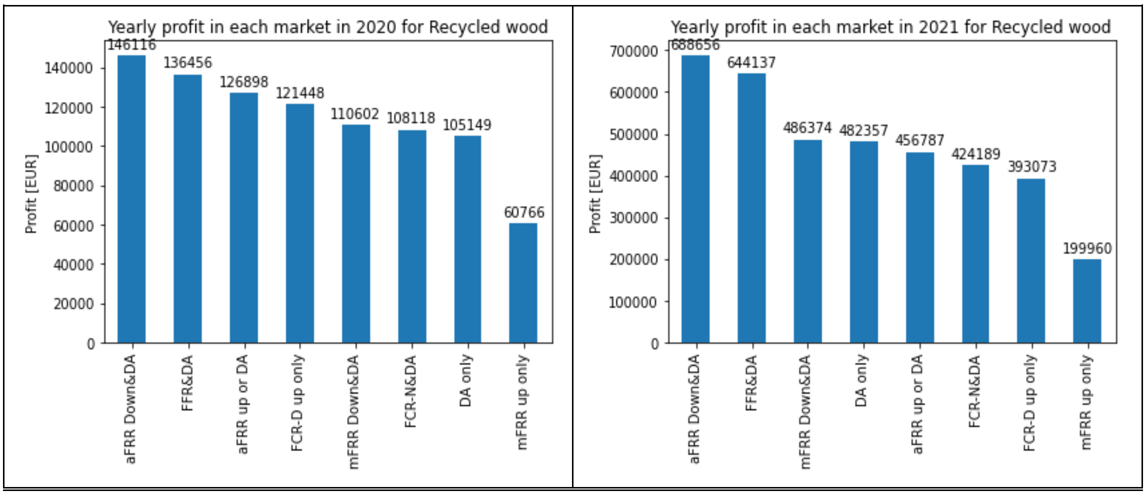

Figure 16: Total profits for 1 MWh of capacity participating in different markets for 2020 and 2021 for recycled wood.

5.4 Fuel: Wood pellets

The last analysed fuel is wood pellets with fuel price 30 EUR/MWh and marginal cost 33.33 EUR/MWh.

It can be expected that the number of hours with zero profits increases due to high fuel price in comparison with other fuels and this is confirmed in Figure 17.

Looking at the monthly and yearly profits in Figure 18, Figure 19 and Figure 20, the trends are similar to the ones for wood chips, but with lower profits due to the higher marginal cost. An interesting fact is that FCR-D up is the most profitable market in January 2020 but has very limited profitability the rest of that year. Also, the mFRR up market is the most profitable one in 2020, which is unique for this fuel. This can be explained by the relatively high marginal cost combined with 2020 prices lower than in 2021, which means that a unit based on this fuel enters other markets less often. In particular, it will enter the DA market less often, which limits its participation in mFRR down, aFRR down, FCR-N and FFR that all require being accepted on the DA market.

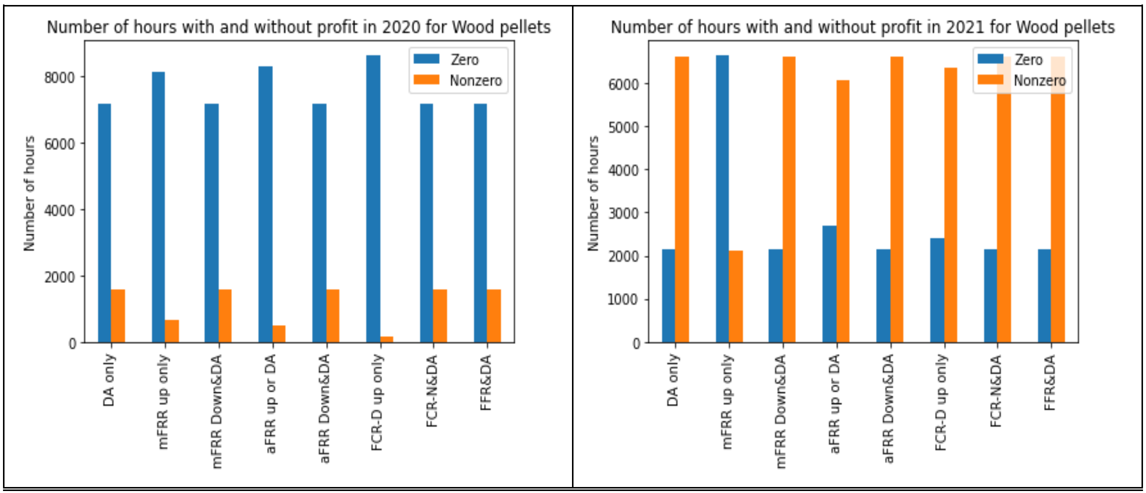

Figure 17: Number of hours with and without profits in each market for wood pellets.

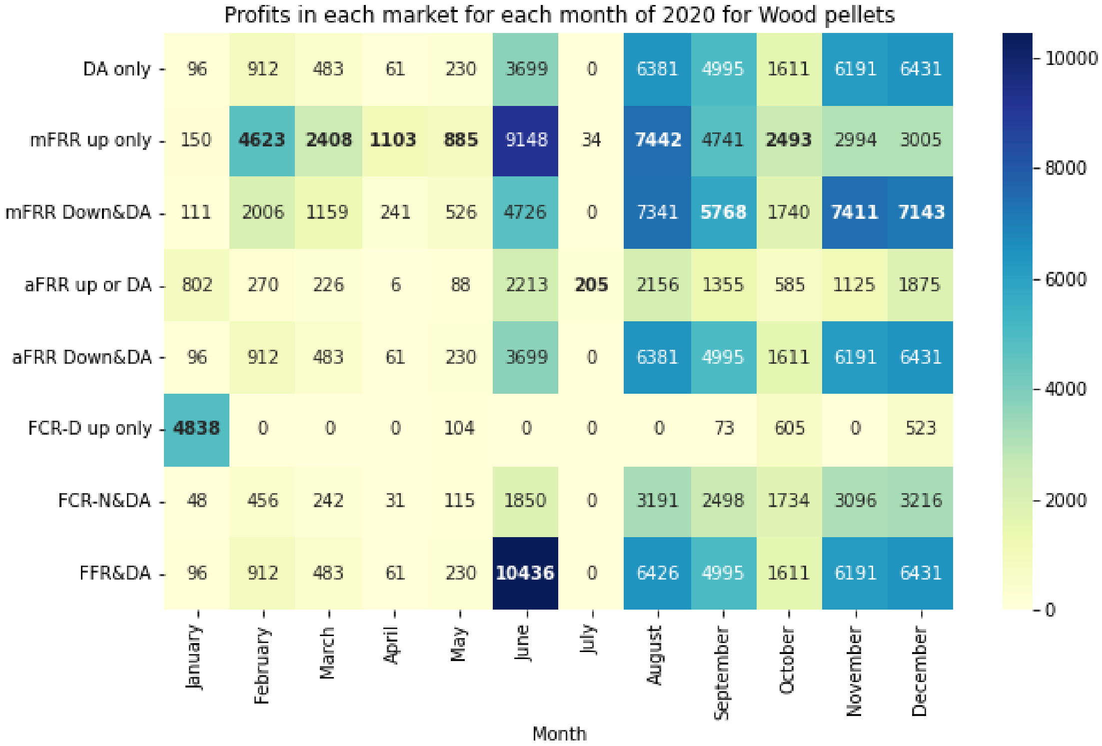

Figure 18: Monthly profits from each market in 2020 for recycled wood pellets.

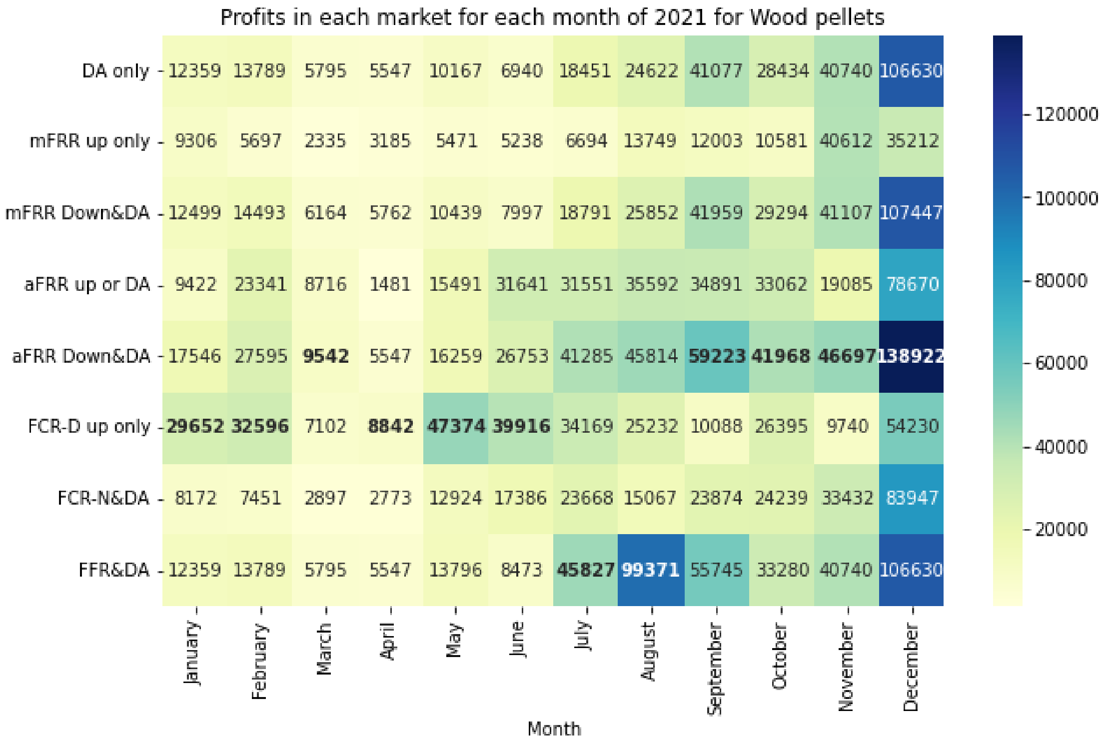

Figure 19: Monthly profits from each market in 2021 for recycled wood pellets.

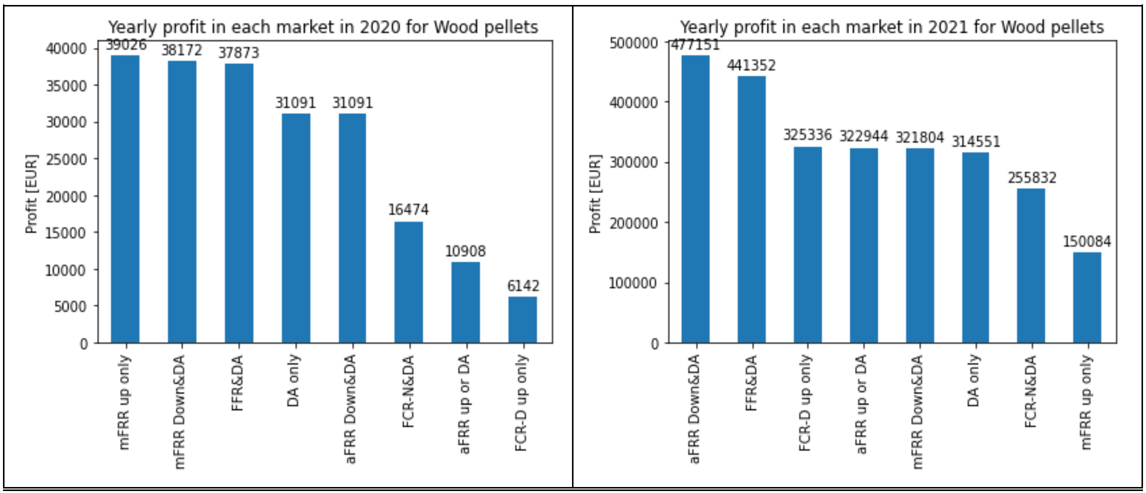

Figure 20: Total profits for 1 MWh of capacity participating in different markets for 2020 for recycled wood pellets.

5.5 Summary of the profit calculations

Figure 22 and Figure 22 represent the annual profit earned for each fuel on each market for 2020 and 2021, respectively grouped by fuel (Figure 21) and market (Figure 22). The level of profit decreases by increasing the fuel price (see Table 4).

The most profitable market differs for each fuel. For waste and recycled wood, the most profitable markets are always FFR or aFRR down for both years. For wood chips, the mFRR down and FFR markets are the most profitable ones in 2020. For wood pellets, the mFFR up and mFRR down are the most profitable ones in 2020. In 2021, aFRR down is the most profitable market for all fuels, closely followed by FFR. The level of profit for some markets also can decrease significantly for an expensive fuel, i.e., for wood pellets in 2020 for the FCR-D market.

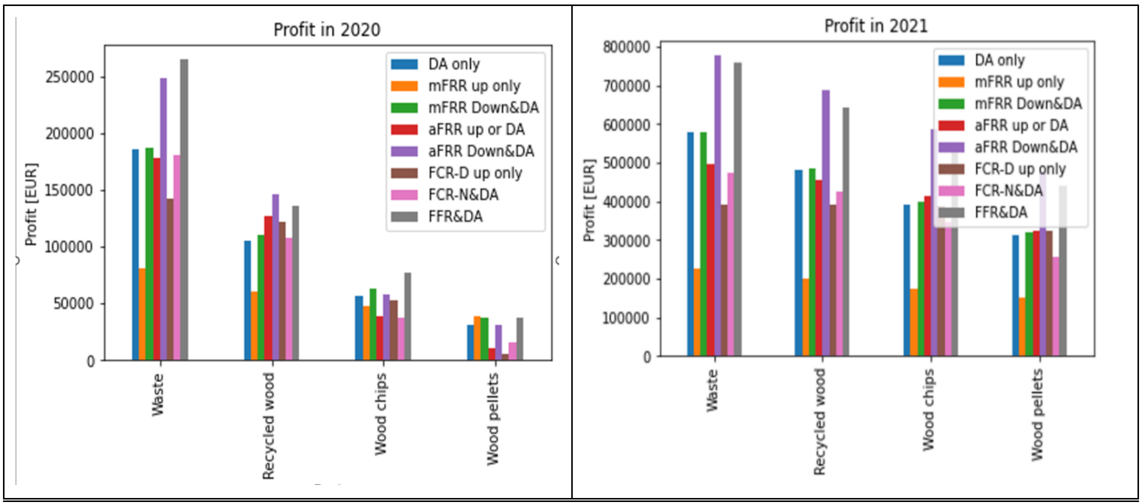

Figure 21: Comparison of the yearly profits for the 4 different fuels for each market in 2020 and 2021.

The sensitivities of the profits to the fuel prices are different in 2020 and 2021. As seen from Figure 22. In 2020, a waste-based unit (cheapest fuel at 0 EUR/MWh) would have gotten much more profit than the second cheapest fuel (recycled wood at 10 EUR/MWh). However, the difference was not as big in 2021. This is due to the much higher prices in 2021, which enables units using recycled wood to get accepted bids almost as often as the waste-based units.

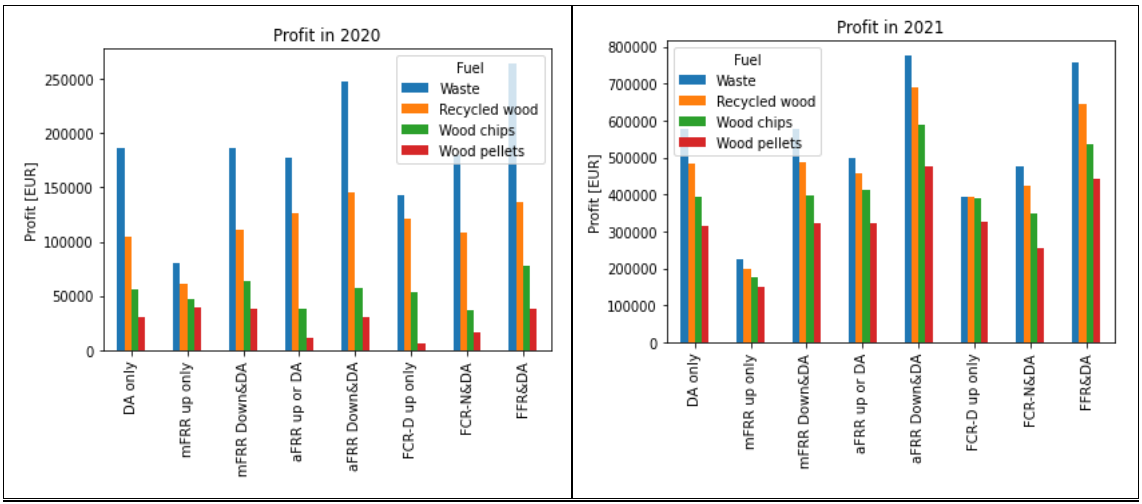

Figure 22: Comparison of the yearly profits in the different markets for 2020 and 2021 and the four analysed fuels.

6 Conclusion

In this deliverable, the historical prices on day-ahead and ancillary service markets are analysed for 2020 and 2021. It is shown that it is not enough to compare procurement prices to compare different markets. Instead, the three components of the operational profits should be considered: capacity compensation, energy compensation and production costs. First, the markets have different designs regarding capacity and energy compensations. Second, they have different characteristics when it comes to activation, which impacts production costs and energy compensation. Third, a unit can in some cases participate in several markets at the same time (for example day-ahead and down-regulation). These differences are not captured accurately if only procurement prices are considered.

A methodology to compute historical profits based on the estimation of the three components on the different markets is proposed. It is applied to a hypothetical 1 MWh of capacity from a hypothetical CHP plant using different fuels and participating in the day-ahead and different ancillary service markets. Profits are computed for the different markets.

Four fuels for CHP plant with different prices have been selected for analysis: waste, recycled wood, wood chips and wood pellets. Profits are, as expected, highly dependent on fuel prices for two reasons: (1) higher fuel prices lead to higher bid prices and, therefore, lower likelihood of being accepted; (2) higher fuel prices entail higher production costs.

Generally, the FFR market and aFRR down markets are the most profitable markets. The exception is mFRR up which was the most profitable market in 2020 for wood pellets and mFRR down, also for 2020, which was the most profitable market for both wood chips and wood pellets.

The profit evaluation performed in this deliverable provides some insights into the profitability of the different ancillary service markets. It does not consider, however, technical limitations such as minimum and maximum production levels, and ramp rates. It does not consider either the strong coupling with the heating system when district heating units deliver ancillary services. Nor does it consider how thermal storage could increase the capacity made available to ancillary service markets. These aspects will be considered in future work.

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