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Approximating the flow-based domain for long-term market analysis in hydropower-dominated power systems

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Flow-based market clearing will be implemented in the Nordic system in 2024. Nordic hydropower, with its large reservoirs require long-term production planning. Therefore, using exogenous flow-based constraints, we aim at approximating the flow-based domain of a model with a detailed description.

First, we demonstrate that when using a detailed grid description, different aggregation schemes for power transfer distribution factors yield almost identical prices and reservoir handling.

Using a flat aggregation scheme as the reference, three cases with exogenous grid constraints are compared. The power transfer distribution factors are kept the same, but the capacities on the critical network elements are chosen to be the maximum, minimum and median of the observed values.

The results show that the case with median capacity can give a descent approximation of the prices obtained with detailed grid. The cases with minimum and maximum capacities can work as upper and lower bounds.

Keywords: Flow-Based Market Coupling, Capacity calculation, RAM, PTDF, Nordic region

ABBREVIATIONS

CNE	Critical Network Element
GSK	Generation Shift Key
PTDF	Power Transfer Distribution Factor
RAM	Remaining Available margin

INTRODUCTION

Flow-Based Market Coupling (FBMC) is the preferred capacity calculation methodology within the EU target model. It is currently scheduled to be implemented in the Nordic CCR in the beginning of 2024. This is expected to lead to a better utilization of the transmission grid by accounting for physical flow and bottlenecks more effectively during market clearing.

In the Core region, FBMC has already been introduced step by step [1]. However, in contrast to the Core region, which mainly consists of thermal and VRES power production, the Nordic region has a large share of hydropower. A good production strategy for large reservoir hydropower requires to plan 3-5 years ahead [2]. Due to the comparably longer planning horizon, including FBMC in production planning, price forecasting and market analyses might prove more difficult for market participants in the Nordic region.

For long-term planning of hydropower resources, which has geographically dispersed production sites, it is necessary to model the transmission grid as accurately as possible. The flow-based capacity domain is defined by two sets of parameters: Power Transfer Distribution Factors (PTDF) for each price area on each Critical Network Element (CNE), and the capacity on each CNE, which is called Remaining Available Margin (RAM). A thorough explanation of the method and parameters can be found in [3]. These parameters are dependent on both grid topology and the forecasted production and demand situation. The latter is changing hour by hour, and therefore difficult to determine a long time in advance. The parameters are also dependent on which Generation Shift Key (GSK) the TSOs choose for aggregating nodal PTDFs to area level PTDFs.

In this paper we try to answer the following research question: "How different will the results be when using exogenous grid constraints based on a detailed grid description, compared to using the detailed grid description itself". The goal is to examine the feasibility of using the limited grid information available to market participants in the Nordic region to perform good long-term market simulations.

The paper is structured as follows. First, we present the model setup and the Nordic dataset used in the analysis and explain the difference between using a detailed grid description and exogenously defined grid constraints. Then we demonstrate that when using a detailed grid description, the aggregation scheme (GSK) used has little to no impact on the system results in our example. Finally, we show that using exogenously defined grid constraints can work as an approximation of the detailed grid and discuss how the choice of capacities on the grid components (CNE) impacts the results.

DATASET AND MODEL SETUP

The long-term fundamental power market simulator FanSi, which is based on the method presented in [4] was used for analysing the cases in this paper.

FanSi can include physical grid constraints in two different ways. The first is to include a detailed grid model and iteratively add flow-based constraints to ensure that the market solution in the model does not cause overloads in the underlying grid [5]. The other is to provide exogenous grid constraints in the form of a PTDF-matrix and a set of RAM-values on each CNE. The PTDF matrix describes how power flow is distributed among CNEs in the grid, given a system dispatch, while RAM defines the capacity on the CNEs. For convenience we will refer to the option of using a detailed grid description as a detailed model, and the option of using exogenously defined grid constraints as the exogenous model. Figure 1 and Figure 2 show flowcharts of how the exogenous model and the detailed model handles FBMC constraints.

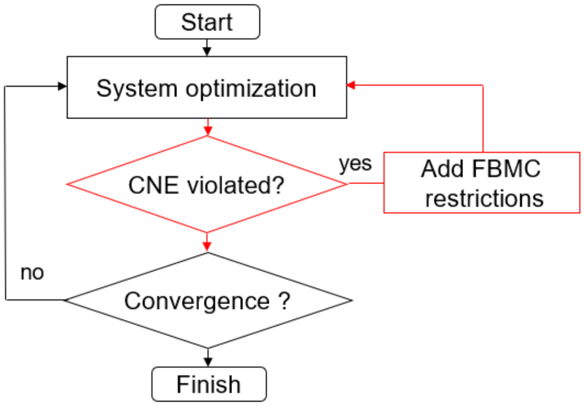

Figure 1 Flowchart exogenous model

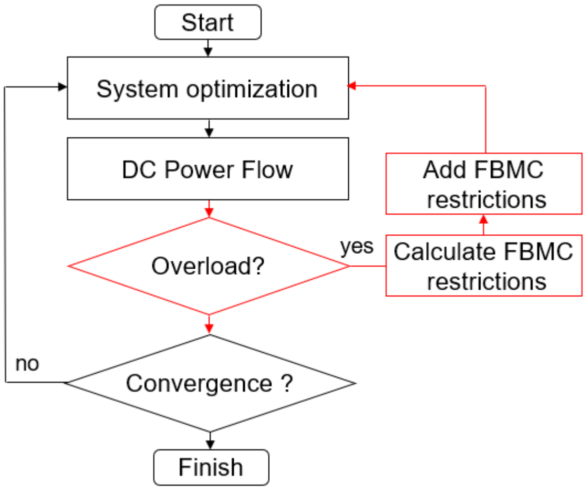

Figure 2 Flowchart detailed model

The dataset used for the analysis was developed in ongoing research projects[1] [6]. It represents a reference scenario for 2030 and covers the Nordic region with a high level of detail, while the remainder of Northern Europe is included in a lesser amount of detail, see Figure 3. The detailed grid description used was provided by the Norwegian regulatory authority, NVE [7]. Out of the 56 areas in the dataset, 17 are modeled with flow-based grid constraints, while the rest use a transport model (NTC) for the grid constraints. The areas modeled with flow-based constraints correspond to Norway and Sweden. The exogenous grid descriptions are derived from the detailed grid description.

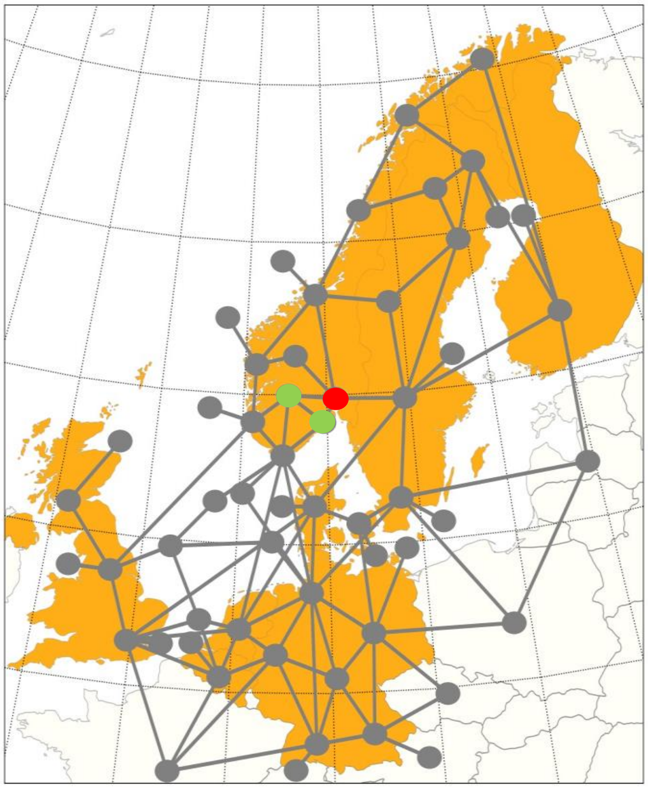

Figure 3 Map of model areas included in model. Areas in mainland Norway and Sweden is modeled with flow-based constraints.

DETAILED GRID VS. EXOGENOUS CONSTRAINTS

The main difference between the two ways of including flow-based constraints into a market simulator is that when including a detailed grid description, flow-based constraints are calculated endogenously given the system dispatch in each time step. Thus, the model can adjust for the difference between market flow and physical flow. In this context we refer to market flow as flow across grid elements when using aggregated area-PTDFs and physical flow as the flow across grid elements when using nodal PTDFs (or DC power flow). Since the area-PTDFs will not always be an accurate representation of the nodal PTDFs there will usually be a difference between physical and market flow. This difference is accounted for in the FBMC methodology by adjusting the available 'free margin' on the CNEs, RAM. In [3], this offset is

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[1] FME "HydroCen" NFR 257588 & IPN "New Environmental Constraints – consequences for the power system" NFR 309622

referred to as Fref' and described as 'the reference flow at zero net positions when using the computed PTDF'.

The result of performing this adjustment is that RAM on each CNE will vary from timestep to timestep due to change in system state. Additionally, when using a GSK that considers expected production and/or load, the PTDF matrix will also be constantly changing.

On the other hand, when using the exogenous model, the differences from timestep to timestep is much harder to account for. It is possible to define different constraints for each timestep but doing so in a sensible way requires assumptions in advance about how load and production will be distributed on a nodal level.

Comparison of GSK-strategies

Given that the topology of the grid does not change, the nodal PTDFs will remain constant. To find the area-PTDFs used in FBMC a GSK is applied. A GSK is an aggregation scheme that determines how each nodal PTDF is weighted within each area to arrive at the aggregated area-PTDF. Many different weighting strategies are possible, two examples are a flat strategy where the area-PTDF is the average of all the nodal PTDFs in the area or a production-based strategy where the area PTDF is a weighted average of the nodal PTDFs based on the expected production in that node for each timestep. The GSKs evaluated in our initial analysis is shown in Table 1.

Table 1 Compared GSKs

GSK	Description
0	Flat
1	Abs (Net export)
2	Abs (Production)
3	Abs (Load)
4	Abs (Production) + Abs (Load)

The results for the comparison of the different GSKs show that socio-economic welfare, prices, and reservoir-handling was almost identical for all weighting-strategies, as shown in Figure 4 and Figure 5. The reason is that even though the PTDFs are different, RAM will also be varying to correct for the difference between physical flow and market flow. The result being that the choice of GSK has no impact on the size of the flow-based capacity domain in our model setup.

Regardless, the choice of GSK is not irrelevant, as it determines how the flow-based domain is represented. This can be important if the output from the detailed grid model is used as an input to an exogenous model, as will likely be the case for the market participants in the Nordic region[2]. The difference between RAM-values for the different GSKs is shown for one line in Figure 6. Keep in mind that the PTDFs will also be different for each strategy, so that the resulting constraints end up being equivalent.

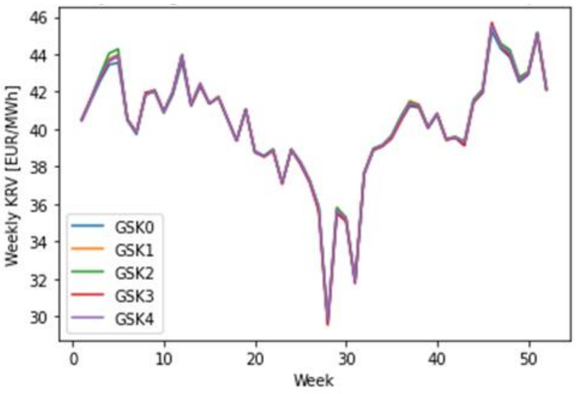

Figure 4 Weekly average price in Hallingdal

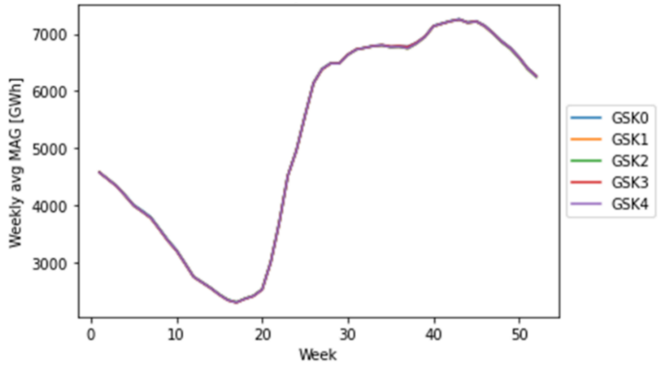

Figure 5 Reservoir level in Hallingdal over a year

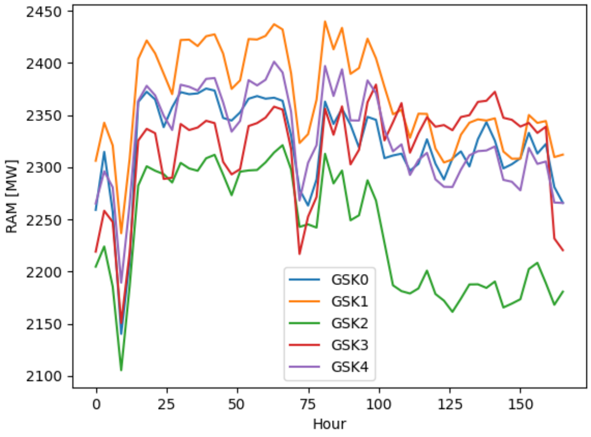

Figure 6 RAM on OSTLAND -> SOROST for each GSK

Comparison of different RAM choices

A. Motivation

The goal of the following analysis is to examine the viability of performing long-term market simulations based on the information available to the market participants in the Nordic

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[2] The flow-based domain including PTDFs and RAM on CNEs will be exogenously provided through a web platform.

region. Due to legal restrictions on information of critical infrastructure, various market participants in the Nordic region do not have access to a full detailed grid description. Currently, the intention is that by go-live of FBMC in the Nordics the published grid data will consist of one set of flow-based constraints for each hour of the day, published one day in advance, as is currently being done on [8] for an external parallel run. In the longer term, it is also planned to publish 3 sets of constraints for each day of the month at the beginning of the month, and 3 sets of constraints for each month of the year once a year [9].

Therefore, we will try to answer the question of how different the results will be when using exogenous grid constraints based on a detailed grid description, compared to using the detailed grid description itself. The grid parameters that need to be approximated for each CNE is RAM and the PTDFs from each area. The PTDF matrix can safely be kept constant from timestep to timestep. This follows from the previous section and is the case when using a flat GSK. This is convenient, as it will mean dealing with one varying value per CNE, instead of 12 (RAM and one PTDF for each market area). Here we will use the PTDF-matrix from a flat GSK, but in principle any set of PTDFs could be chosen and applied across all timesteps. RAM, on the other hand, would normally be varying to constantly adjust for the difference between market flow and physical flow. In our analysis we were not able to find obvious patterns in the variations on a weekly or seasonal level. This might however be possible with more effort. Since predicting the variations of RAM values in advance is a major challenge, this parameter will also be taken as constant across all time steps in our analysis.

Figure 7 shows the RAM values occurring on each of the lines bordering the model area Ostland (Oslo area in eastern Norway) for one simulated week with a flat GSK. In the figure the difference the maximum and minimum values are a few hundred MW. The highest variation across all CNEs is found between price areas SE2 and SE3, with a difference of more than 1000 MW between the maximum and the minimum values.

B. *Comparison minimum, maximum and median RAM with exogenous constraints*

For our analysis it is necessary to choose one RAM on each CNE. To understand how different selections of RAM-values might impact the results, we compare the results of the four cases in Table 2.

Table 2 Cases for comparison to assess impact of RAM

Case name	Description
GSK0	Detailed grid with flat GSK
Max ram	Exogenous PTDFs, maximum RAM
Min ram	Exogenous PTDFs, minimum RAM
Median ram	Exogenous PTDFs, median RAM

The PTDFs from the first case is used as exogenous PTDFs in the other cases. The RAM values in the cases with exogenous PTDFs are chosen to be the maximum, minimum and median of the observed RAM values in the reference case. The "min ram" and "max ram" cases can be thought of as representing a heavily constrained and a heavily relaxed grid.

When using a model with exogenous flow-based constraints it is impossible to know whether the achieved market solutions would cause any overloads in the full grid model. Therefore, when comparing the results of the exogenous model with the detailed model, the objective should be to get as similar results as possible. Alternatively, the objective could be to try to find lower and higher bounds for price, which would be the case for long-term price forecasting. Comparison of price in the model area 'Ostland' for each of the cases is shown in Figure 8.

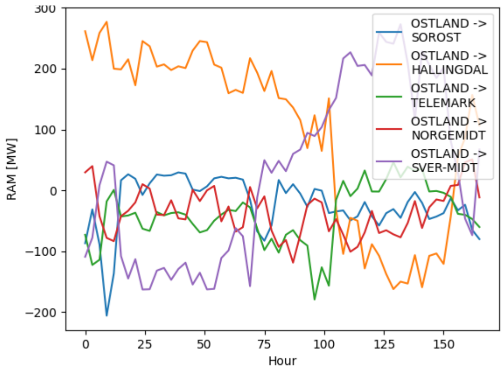

Figure 7 RAM on lines bordering OSTLAND, normalized around median

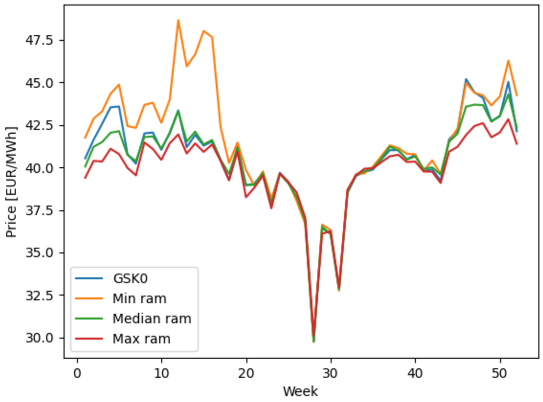

Figure 8 Price in OSTLAND

Figure 9 shows the same prices, but here the price in the reference case is subtracted from all the curves to highlight the differences. The latter figure shows that for Ostland minimum RAM gives an upper bound on price, maximum RAM gives a lower bound on price and median RAM gives the overall best match. This result will not generalize to other areas. Relaxed grid constraints lead to reduced price differences between the areas. Ostland usually has a net import of power, and therefore normally has a higher price than neighboring areas. Thus, relaxing the grid constraints for Ostland leads to lower prices, while for an exporting area it might lead to higher prices. For areas that swap frequently between net import and net export the direction of the price change will depend on the market situation, this is shown in Figure 10 for a model area in southern Norway.

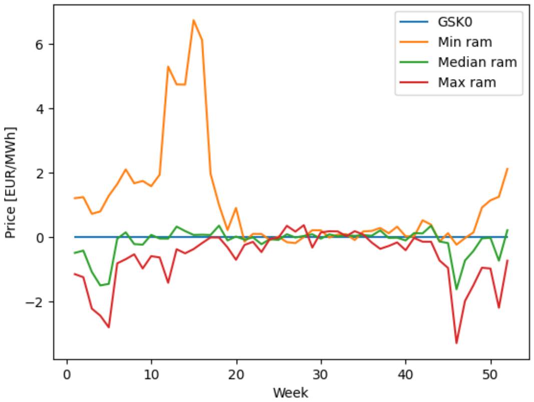

Figure 9 Price in OSTLAND, normalized around reference

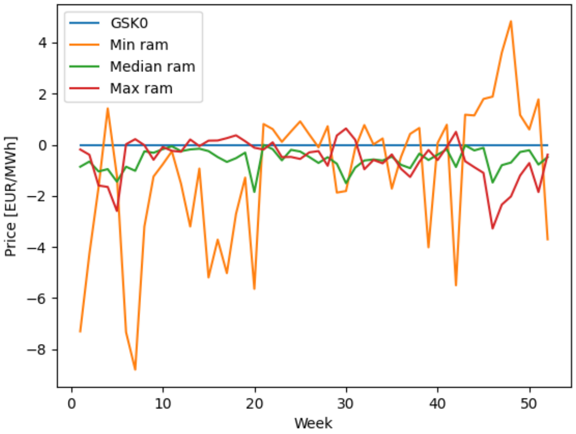

Figure 10 Price in SORLAND, normalized around reference

C. *Correlation of RAM*

Variations in RAM on certain grid components is highly correlated. The reason for varying RAM is due to the deviation between the detailed grid flow and the market flow. However, both the detailed and aggregated PTDF-matrices are still internally consistent. That means an increase of the net position in an area is going to result in an equal increase of flow out of the area, distributed across all the lines bordering the area. The only thing different for physical flow and market flow will be how the flow is distributed among the lines. Because of this, if market flow gives an overestimation of a flow on one line out of an area, the sum of the flow on the remaining lines will be correspondingly underestimated.

The correlation of flow deviations translates directly into correlation of RAM. Negatively correlated lines will never have their minimum RAM values at the same time. On the contrary it is likely that when one line is at a minimum, some of the correlated lines will be at a maximum and vice versa. In figure Figure 11, the lines from Ostland to Telemark and the lines from Ostland to Hallingdal are correlated. Even though the "Min ram" and "Max ram" cases can be useful, they are also unrealistic. The median ram case, on the other hand, might do a good job of preserving realistic relations between the lines. Another way to achieve realistic relations between the lines would be to use a snapshot of the RAM-values in one hour. In the appendix, a full matrix is included showing the correlations between RAM on each pair of lines.

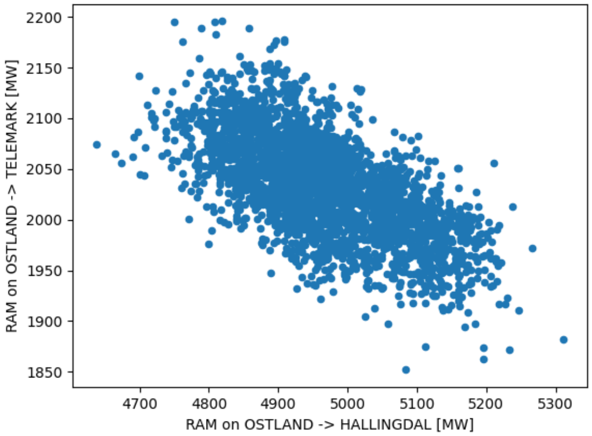

Figure 11 Correlation of RAM on two lines

CONCLUSION

Due to large amounts of hydropower with its multi-year reservoirs, the planning and forecasting horizon for Nordic market participants is rather long. With the introduction of FBMC in the Nordics, market actors face the challenge of accounting for, and forecasting, the flow-based domain a long time in advance. Because of legislation limiting access to a detailed grid description, it is necessary to make production plans and price forecasting based on the exogenously defined grid constraints published by the Nordic TSOs.

To assess the feasibility of doing so, in this paper we have first demonstrated that when using a detailed grid, the choice of GSK has limited impact on the results. The reason is that RAM will be varying to account for the different PTDFs. Next, we showed that the results of the model with detailed grid can be approximated by using a constant set of PTDFs and a single unchanging RAM value on each line. Even though the results are not a perfect match, artificially relaxed or strict grid constraints can be used to create upper and lower bounds.

While this paper shows that using exogenously defined grid constraints can give similar results to a model with detailed grid description, it would nevertheless be preferred for market participants to be able to use a detailed grid description themselves. In the cases we have compared, the underlying market assumptions are identical to the reference case. More deviations and forecast errors could decrease accuracy of the exogenous grid constraints. In addition, to analyze cases where the grid topology changes, it seems necessary to use a detailed grid description. Examples of this would be to find the effects of outages on lines, or to account for future grid improvements.

ACKNOWLEDGEMENTS

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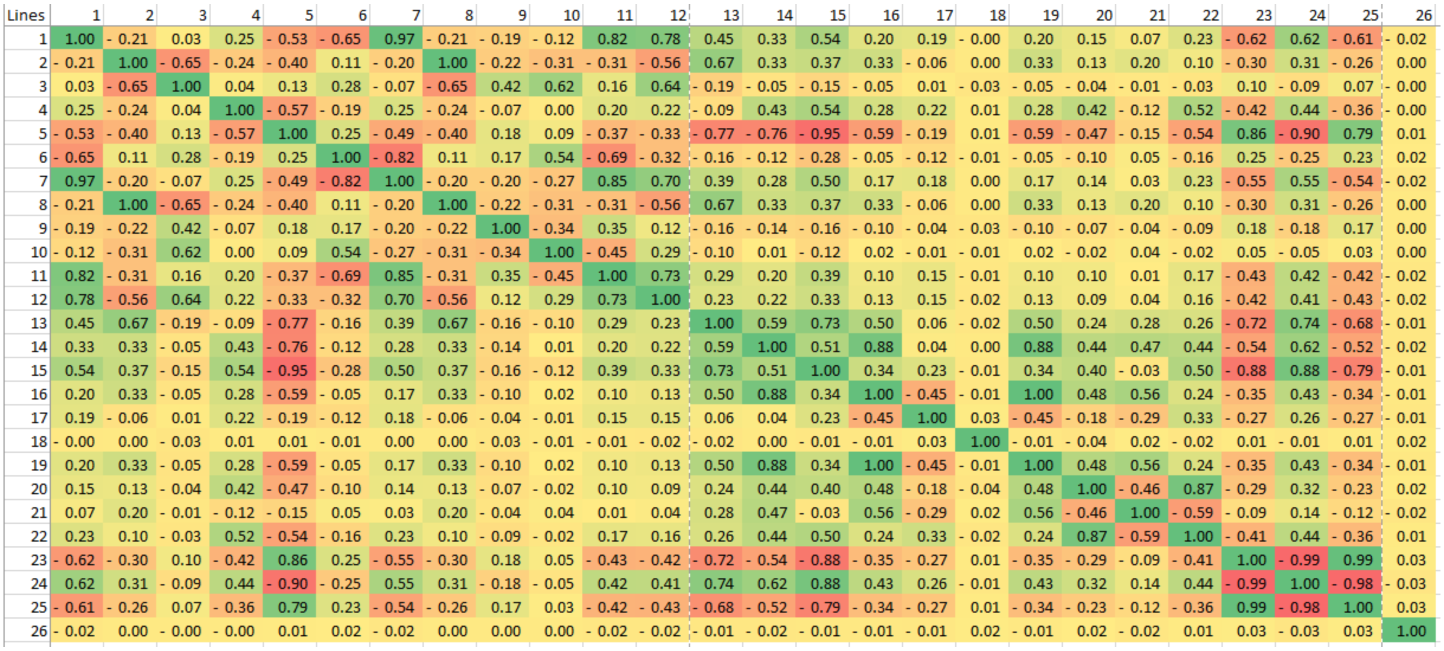
APPENDIX



Lines	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	1.00	- 0.21	0.03	0.25	- 0.53	- 0.65	0.97	- 0.21	- 0.19	- 0.12	0.82	0.78	0.45	0.33	0.54	0.20	0.19	- 0.00	0.20	0.15	0.07	0.23	- 0.62	0.62	- 0.61	- 0.02
2	- 0.21	1.00	- 0.65	- 0.24	- 0.40	0.11	- 0.20	1.00	- 0.22	- 0.31	- 0.31	- 0.56	0.67	0.33	0.37	0.33	- 0.06	0.00	0.33	0.13	0.20	0.10	- 0.30	0.31	- 0.26	0.00
3	0.03	- 0.65	1.00	0.04	0.13	0.28	- 0.07	- 0.65	0.42	0.62	0.16	0.64	- 0.19	- 0.05	- 0.15	- 0.05	0.01	- 0.03	- 0.05	- 0.04	- 0.01	- 0.03	0.10	- 0.09	0.07	- 0.00
4	0.25	- 0.24	0.04	1.00	- 0.57	- 0.19	0.25	- 0.24	- 0.07	0.00	0.20	0.22	- 0.09	0.43	0.54	0.28	0.22	0.01	0.28	0.42	- 0.12	0.52	- 0.42	0.44	- 0.36	- 0.00
5	- 0.53	- 0.40	0.13	- 0.57	1.00	0.25	- 0.49	- 0.40	0.18	0.09	- 0.37	- 0.33	- 0.77	- 0.76	- 0.95	- 0.59	- 0.19	0.01	- 0.59	- 0.47	- 0.15	- 0.54	0.86	- 0.90	0.79	0.01
6	- 0.65	0.11	0.28	- 0.19	0.25	1.00	- 0.82	0.11	0.17	0.54	- 0.69	- 0.32	- 0.16	- 0.12	- 0.28	- 0.05	- 0.12	- 0.01	- 0.05	- 0.10	0.05	- 0.16	0.25	- 0.25	0.23	0.02
7	0.97	- 0.20	- 0.07	0.25	- 0.49	- 0.82	1.00	- 0.20	- 0.20	- 0.27	0.85	0.70	0.39	0.28	0.50	0.17	0.18	0.00	0.17	0.14	0.03	0.23	- 0.55	0.55	- 0.54	- 0.02
8	- 0.21	1.00	- 0.65	- 0.24	- 0.40	0.11	- 0.20	1.00	- 0.22	- 0.31	- 0.31	- 0.56	0.67	0.33	0.37	0.33	- 0.06	0.00	0.33	0.13	0.20	0.10	- 0.30	0.31	- 0.26	0.00
9	- 0.19	- 0.22	0.42	- 0.07	0.18	0.17	- 0.20	- 0.22	1.00	- 0.34	0.35	0.12	- 0.16	- 0.14	- 0.16	- 0.10	- 0.04	- 0.03	- 0.10	- 0.07	- 0.04	- 0.09	0.18	- 0.18	0.17	0.00
10	- 0.12	- 0.31	0.62	0.00	0.09	0.54	- 0.27	- 0.31	- 0.34	1.00	- 0.45	0.29	- 0.10	0.01	- 0.12	0.02	- 0.01	- 0.01	0.02	- 0.02	0.04	- 0.02	0.05	- 0.05	0.03	0.00
11	0.82	- 0.31	0.16	0.20	- 0.37	- 0.69	0.85	- 0.31	0.35	- 0.45	1.00	0.73	0.29	0.20	0.39	0.10	0.15	- 0.01	0.10	0.10	0.01	0.17	- 0.43	0.42	- 0.42	- 0.02
12	0.78	- 0.56	0.64	0.22	- 0.33	- 0.32	0.70	- 0.56	0.12	0.29	0.73	1.00	0.23	0.22	0.33	0.13	0.15	- 0.02	0.13	0.09	0.04	0.16	- 0.42	0.41	- 0.43	- 0.02
13	0.45	0.67	- 0.19	- 0.09	- 0.77	- 0.16	0.39	0.67	- 0.16	- 0.10	0.29	0.23	1.00	0.59	0.73	0.50	0.06	- 0.02	0.50	0.24	0.28	0.26	- 0.72	0.74	- 0.68	- 0.01
14	0.33	0.33	- 0.05	0.43	- 0.76	- 0.12	0.28	0.33	- 0.14	0.01	0.20	0.22	0.59	1.00	0.51	0.88	0.04	0.00	0.88	0.44	0.47	0.44	- 0.54	0.62	- 0.52	- 0.02
15	0.54	0.37	- 0.15	0.54	- 0.95	- 0.28	0.50	0.37	- 0.16	- 0.12	0.39	0.33	0.73	0.51	1.00	0.34	0.23	- 0.01	0.34	0.40	- 0.03	0.50	- 0.88	0.88	- 0.79	- 0.01
16	0.20	0.33	- 0.05	0.28	- 0.59	- 0.05	0.17	0.33	- 0.10	0.02	0.10	0.13	0.50	0.88	0.34	1.00	- 0.45	- 0.01	1.00	0.48	0.56	0.24	- 0.35	0.43	- 0.34	- 0.01
17	0.19	- 0.06	0.01	0.22	- 0.19	- 0.12	0.18	- 0.06	- 0.04	- 0.01	0.15	0.15	0.06	0.04	0.23	- 0.45	1.00	0.03	- 0.45	- 0.18	- 0.29	0.33	- 0.27	0.26	- 0.27	- 0.01
18	- 0.00	0.00	- 0.03	0.01	0.01	- 0.01	0.00	0.00	- 0.03	- 0.01	- 0.01	- 0.02	- 0.02	0.00	- 0.01	- 0.01	0.03	1.00	- 0.01	- 0.04	0.02	- 0.02	0.01	- 0.01	0.01	0.02
19	0.20	0.33	- 0.05	0.28	- 0.59	- 0.05	0.17	0.33	- 0.10	0.02	0.10	0.13	0.50	0.88	0.34	1.00	- 0.45	- 0.01	1.00	0.48	0.56	0.24	- 0.35	0.43	- 0.34	- 0.01
20	0.15	0.13	- 0.04	0.42	- 0.47	- 0.10	0.14	0.13	- 0.07	- 0.02	0.10	0.09	0.24	0.44	0.40	0.48	- 0.18	- 0.04	0.48	1.00	- 0.46	0.87	- 0.29	0.32	- 0.23	0.02
21	0.07	0.20	- 0.01	- 0.12	- 0.15	0.05	0.03	0.20	- 0.04	0.04	0.01	0.04	0.28	0.47	- 0.03	0.56	- 0.29	0.02	0.56	- 0.46	1.00	- 0.59	- 0.09	0.14	- 0.12	- 0.02
22	0.23	0.10	- 0.03	0.52	- 0.54	- 0.16	0.23	0.10	- 0.09	- 0.02	0.17	0.16	0.26	0.44	0.50	0.24	0.33	- 0.02	0.24	0.87	- 0.59	1.00	- 0.41	0.44	- 0.36	0.01
23	- 0.62	- 0.30	0.10	- 0.42	0.86	0.25	- 0.55	- 0.30	0.18	0.05	- 0.43	- 0.42	- 0.72	- 0.54	- 0.88	- 0.35	- 0.27	0.01	- 0.35	- 0.29	- 0.09	- 0.41	1.00	- 0.99	0.99	0.03
24	0.62	0.31	- 0.09	0.44	- 0.90	- 0.25	0.55	0.31	- 0.18	- 0.05	0.42	0.41	0.74	0.62	0.88	0.43	0.26	- 0.01	0.43	0.32	0.14	0.44	- 0.99	1.00	- 0.98	- 0.03
25	- 0.61	- 0.26	0.07	- 0.36	0.79	0.23	- 0.54	- 0.26	0.17	0.03	- 0.42	- 0.43	- 0.68	- 0.52	- 0.79	- 0.34	- 0.27	0.01	- 0.34	- 0.23	- 0.12	- 0.36	0.99	- 0.98	1.00	0.03
26	- 0.02	0.00	- 0.00	- 0.00	0.01	0.02	- 0.02	0.00	0.00	0.00	- 0.02	- 0.02	- 0.01	- 0.02	- 0.01	- 0.01	- 0.01	0.02	- 0.01	0.02	- 0.02	0.01	0.03	- 0.03	0.03	1.00

Figure 12 Matrix showing correlations between all lines included