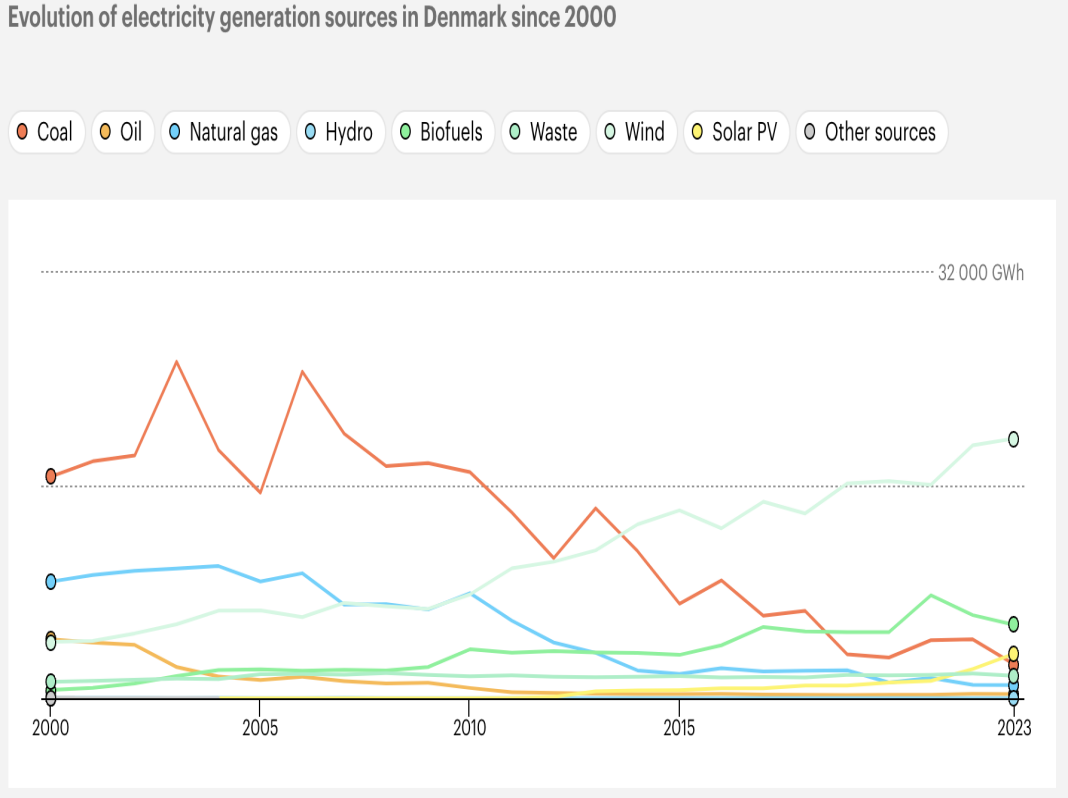
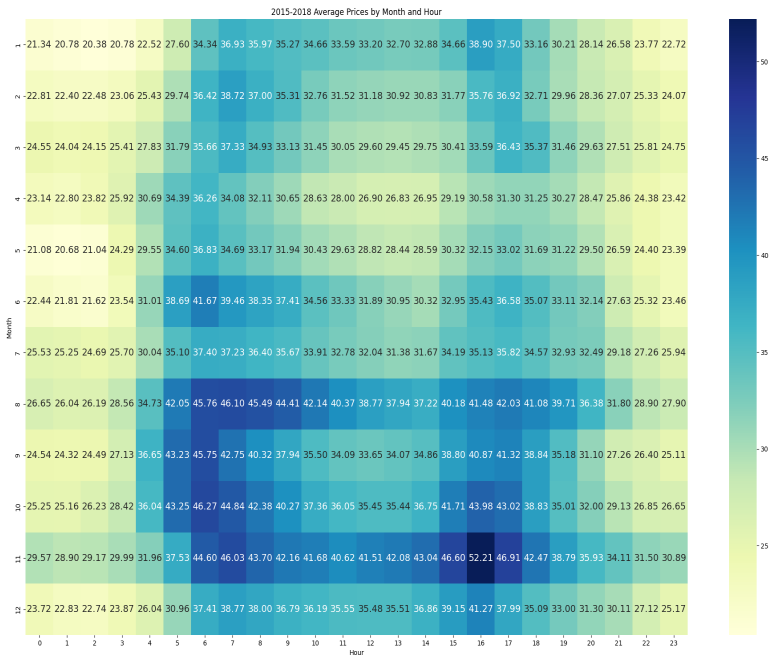
A View at the Denmark Electricity Market

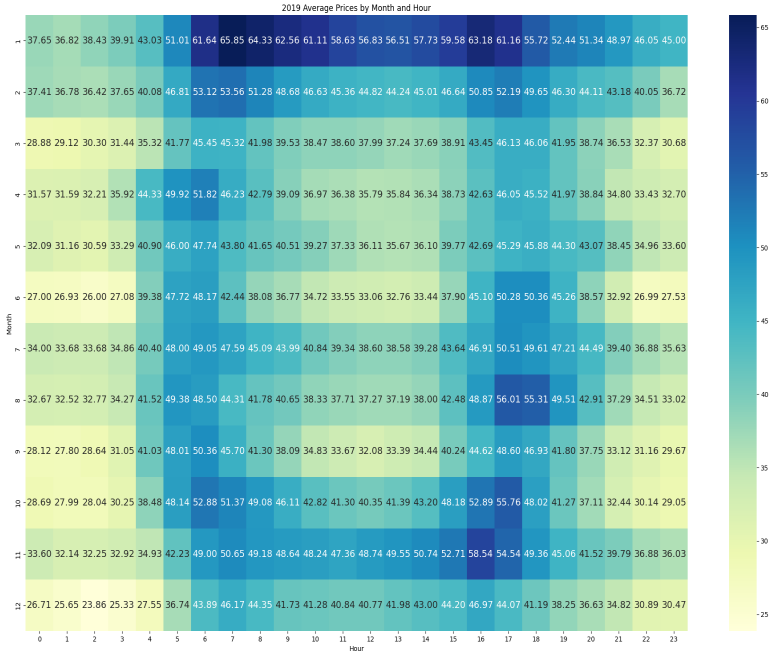


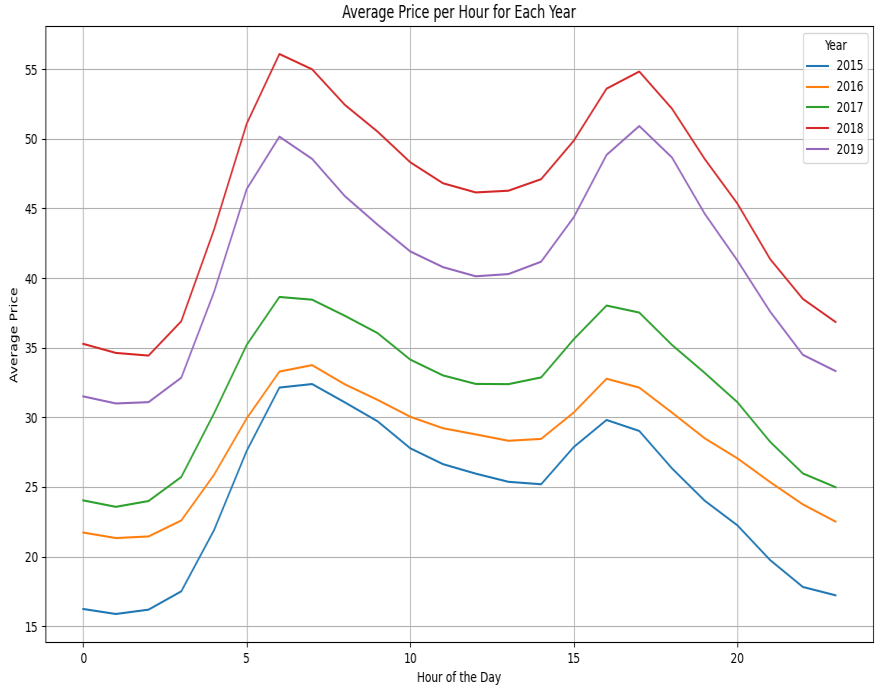
Project Overview

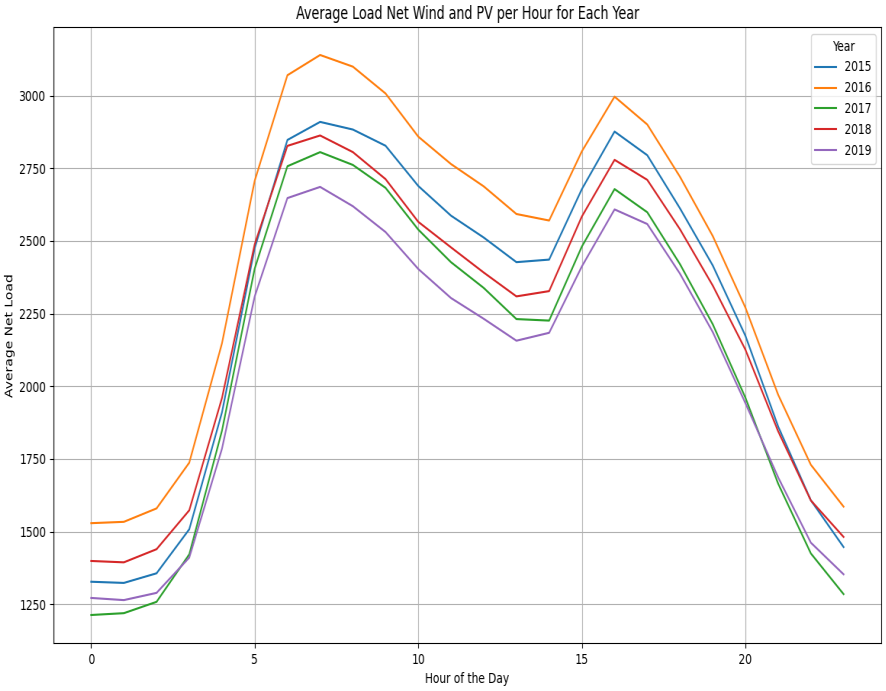
Over the past two decades, Denmark has seen a tremendous shift in their energy landscape. Since the year 2000, Denmark evolved from relying on coal for their electricity generation to relying primarily on wind, biofuels and solar energy. The high penetration of intermittent resources such as wind and solar present an opportunity for batteries and other forms of energy arbitrage. However, to perform a profitable arbitrage strategy, one must be able to reliably predict electrity prices. In this project, I use load, resource capacity, weather, and simualated capacity factor data to predict day ahead prices in DK1, a bidding zone in Denmark. This document presents the results and analysis of 3 XGBoost models as well as some vizualizations to gain a better understanding of the day ahead market in DK1.

Metric	2015-2018	2019
AVG Price	32.51	41.19
STDEV	14.40	11.94
Min	-53.62	-48.29
Max	144.33	109.45


2015-2018 Average Prices by Month and Hour
Month
Hour
1 21.34 20.78 20.38 20.78 22.52 27.60 34.34 36.93 35.97 35.27 34.66 33.59 33.20 32.70 32.88 34.66 38.90 37.50 33.16 30.21 28.14 26.58 23.77 22.72
2 22.81 22.40 22.48 23.06 25.43 29.74 36.42 38.72 37.00 35.31 32.76 31.52 31.18 30.92 30.83 31.77 35.76 36.92 32.71 29.96 28.36 27.07 25.33 24.07
3 24.55 24.04 24.15 25.41 27.83 31.79 35.66 37.33 34.93 33.13 31.45 30.05 29.60 29.45 29.75 30.41 33.59 36.43 35.37 31.46 29.63 27.51 25.81 24.75
4 23.14 22.80 23.82 25.92 30.69 34.39 36.26 34.08 32.11 30.65 28.63 28.00 26.90 26.83 26.95 29.19 30.58 31.30 31.25 30.27 28.47 25.86 24.38 23.42
5 21.08 20.68 21.04 24.29 29.55 34.60 36.83 34.69 33.17 31.94 30.43 29.63 28.82 28.44 28.59 30.32 32.15 33.02 31.69 31.22 29.50 26.59 24.40 23.39
6 22.44 21.81 21.62 23.54 31.01 38.69 41.67 39.46 38.35 37.41 34.56 33.33 31.89 30.95 30.32 32.95 35.43 36.58 35.07 33.11 32.14 27.63 25.32 23.46
7 25.53 25.25 24.69 25.70 30.04 35.10 37.40 37.23 36.40 35.67 33.91 32.78 32.04 31.38 31.67 34.19 35.13 35.82 34.57 32.93 32.49 29.18 27.26 25.94
8 26.65 26.04 26.19 28.56 34.73 42.05 45.76 46.10 45.49 44.41 42.14 40.37 38.77 37.94 37.22 40.18 41.48 42.03 41.08 39.71 36.38 31.80 28.90 27.90
9 24.54 24.32 24.49 27.13 36.65 43.23 45.75 42.75 40.32 37.94 35.50 34.09 33.65 34.07 34.86 38.80 40.87 41.32 38.84 35.18 31.10 27.26 26.40 25.11
10 25.25 25.16 26.23 28.42 36.04 43.25 46.27 44.84 42.38 40.27 37.36 36.05 35.45 35.44 36.75 41.71 43.98 43.02 38.83 35.01 32.00 29.13 26.85 26.65
11 29.57 28.90 29.17 29.99 31.96 37.53 44.60 46.03 43.70 42.16 41.68 40.62 41.51 42.08 43.04 46.60 52.21 46.91 42.47 38.79 35.93 34.11 31.50 30.89
12 23.72 22.83 22.74 23.87 26.04 30.96 37.41 38.77 38.00 36.79 36.19 35.55 35.48 35.51 36.86 39.15 41.27 37.99 35.09 33.00 31.30 30.11 27.12 25.17
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
25 30 35 40 45 50

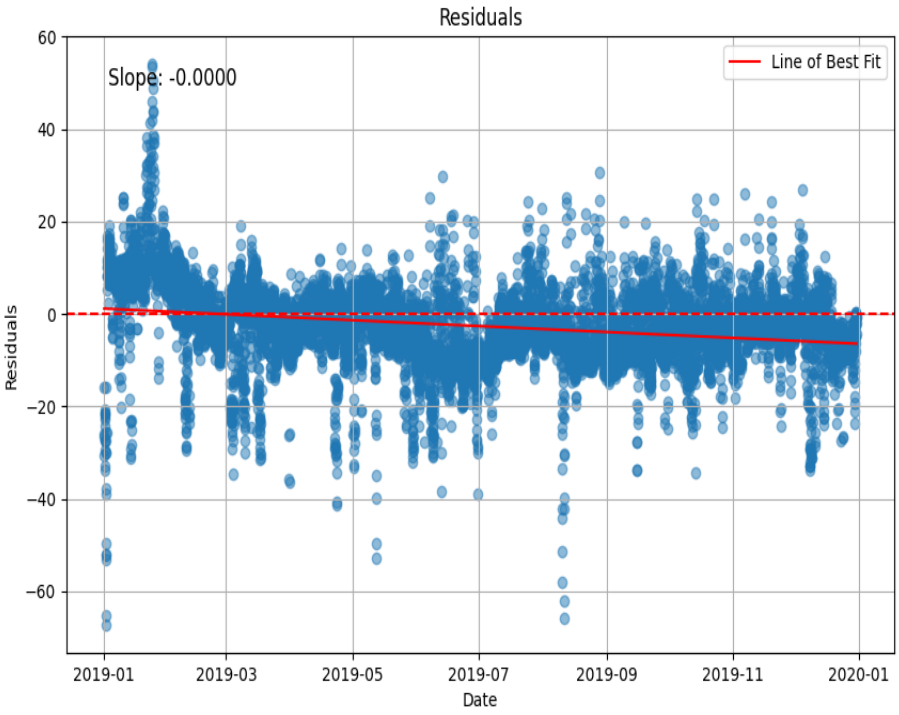

2019 Average Prices by Month and Hour
Month
Hour
1 37.65 36.82 38.43 39.91 43.03 51.01 61.64 65.85 64.33 62.56 61.11 58.63 56.83 56.51 57.73 59.58 63.18 61.16 55.72 52.44 51.34 48.97 46.05 45.00
2 37.41 36.78 36.42 37.65 40.08 46.81 53.12 53.56 51.28 48.68 46.63 45.36 44.82 44.24 45.01 46.64 50.85 52.19 49.65 46.30 44.11 43.18 40.05 36.72
3 28.88 29.12 30.30 31.44 35.32 41.77 45.45 45.32 41.98 39.53 38.47 38.60 37.99 37.24 37.69 38.91 43.45 46.13 46.06 41.95 38.74 36.53 32.37 30.68
4 31.57 31.59 32.21 35.92 44.33 49.92 51.82 46.23 42.79 39.09 36.97 36.38 35.79 35.84 36.34 38.73 42.63 46.05 45.52 41.97 38.84 34.80 33.43 32.70
5 32.09 31.16 30.59 33.29 40.90 46.00 47.74 43.80 41.65 40.51 39.27 37.33 36.11 35.67 36.10 39.77 42.69 45.29 45.88 44.30 43.07 38.45 34.96 33.60
6 27.00 26.93 26.00 27.08 39.38 47.72 48.17 42.44 38.08 36.77 34.72 33.55 33.06 32.76 33.44 37.90 45.10 50.28 50.36 45.26 38.57 32.92 26.99 27.53
7 34.00 33.68 33.68 34.86 40.40 48.00 49.05 47.59 45.09 43.99 40.84 39.34 38.60 38.58 39.28 43.64 46.91 50.51 49.61 47.21 44.49 39.40 36.88 35.63
8 32.67 32.52 32.77 34.27 41.52 49.38 48.50 44.31 41.78 40.65 38.33 37.71 37.27 37.19 38.00 42.48 48.87 56.01 55.31 49.51 42.91 37.29 34.51 33.02
9 28.12 27.80 28.64 31.05 41.03 48.01 50.36 45.70 41.30 38.09 34.83 33.67 32.08 33.39 34.44 40.24 44.62 48.60 46.93 41.80 37.75 33.12 31.16 29.67
10 28.69 27.99 28.04 30.25 38.48 48.14 52.88 51.37 49.08 46.11 42.82 41.30 40.35 41.39 43.20 48.18 52.89 55.76 48.02 41.27 37.11 32.44 30.14 29.05
11 33.60 32.14 32.25 32.92 34.93 42.23 49.00 50.65 49.18 48.64 48.24 47.36 48.74 49.55 50.74 52.71 58.54 54.54 49.36 45.06 41.52 39.79 36.88 36.03
12 26.71 25.65 23.86 25.33 27.55 36.74 43.89 46.17 44.35 41.73 41.28 40.84 40.77 41.98 43.00 44.20 46.97 44.07 41.19 38.25 36.63 34.82 30.89 30.47
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
25 30 35 40 45 50 55 60 65

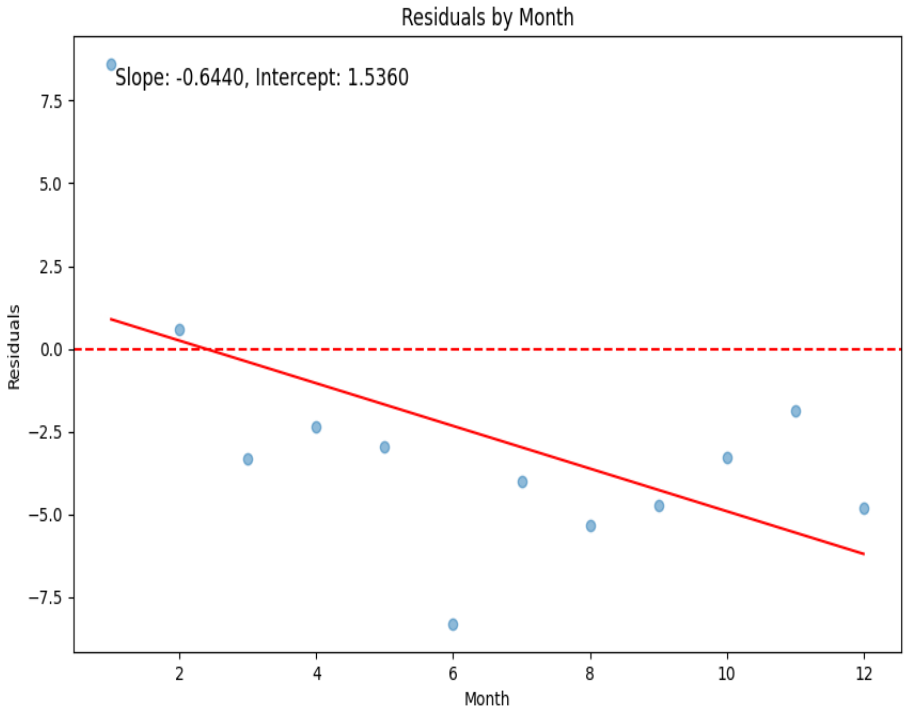

Average Price per Hour for Each Year
Year
2015
2016
2017
2018
2019
Average Price
Hour of the Day
55
50
45
40
35
30
25
20
15
0
5
10
15
20

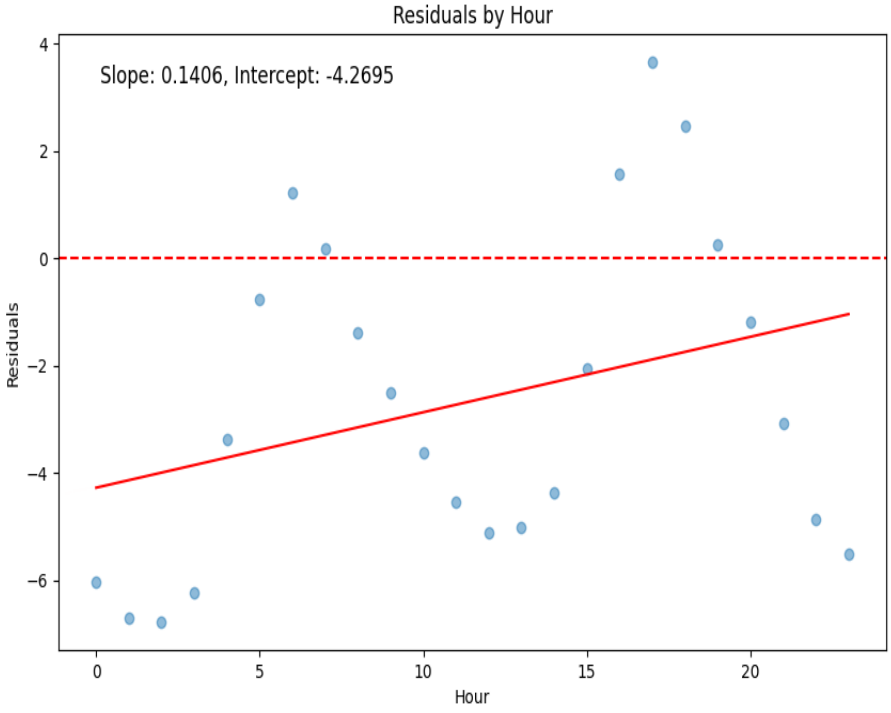

Average Load Net Wind and PV per Hour for Each Year
Year
2015
2016
2017
2018
2019
Average Net Load
Hour of the Day
3000
2750
2500
2250
2000
1750
1500
1250
0
5
10
15
20

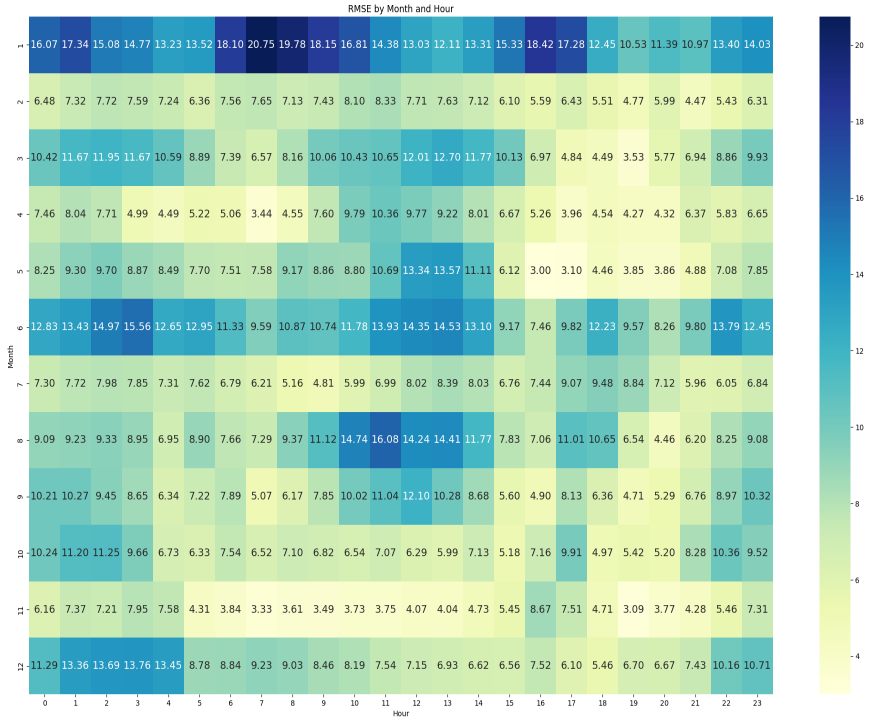
Performance Metrics: All variables

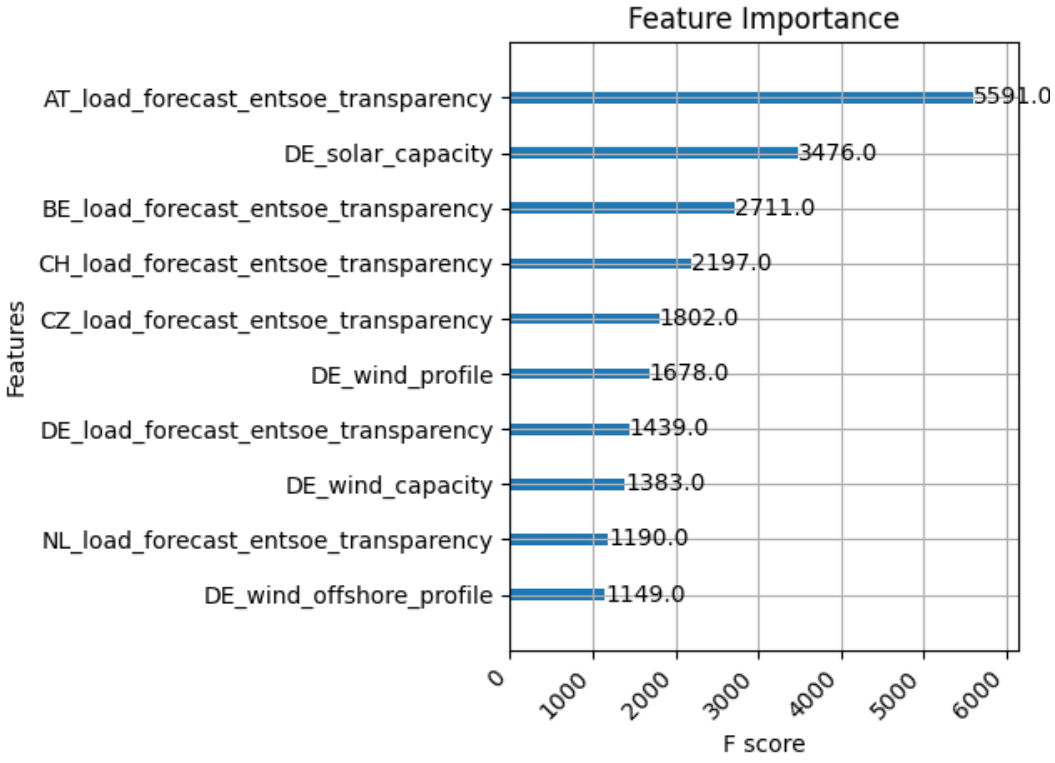
Metric	Model Performance
MAE	6.865
RMSE	86.060
R2	0.5028
Train R2	0.8184
Features	268




Residuals by Month
Slope: -0.6440, Intercept: 1.5360
Residuals
Month
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
2
4
6
8
10
12

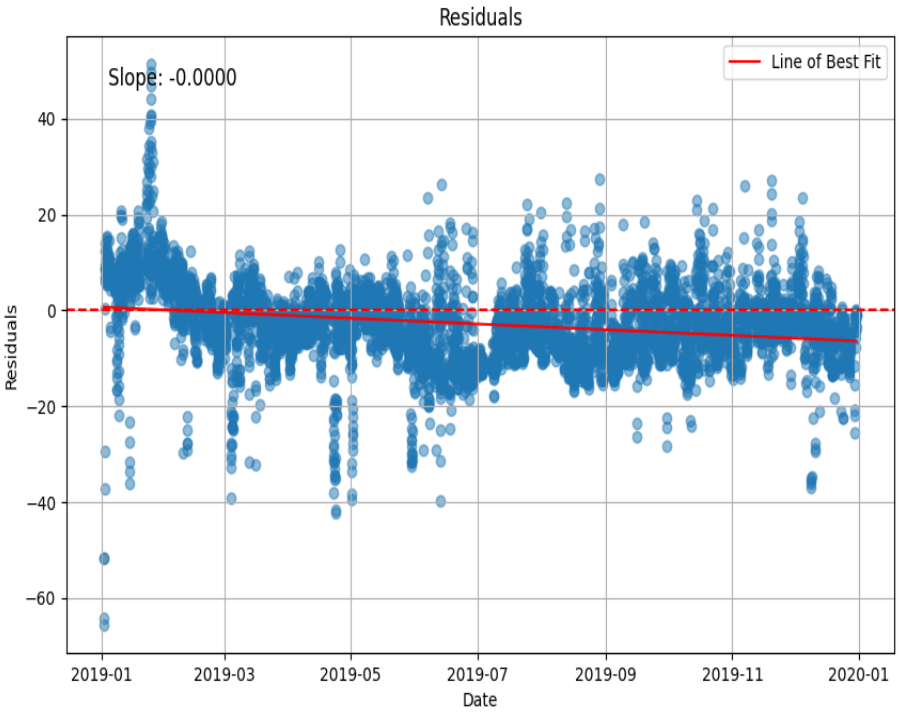

Residuals by Hour
Slope: 0.1406, Intercept: -4.2695
Residuals
Hour
4
2
0
−2
−4
−6
0
5
10
15
20

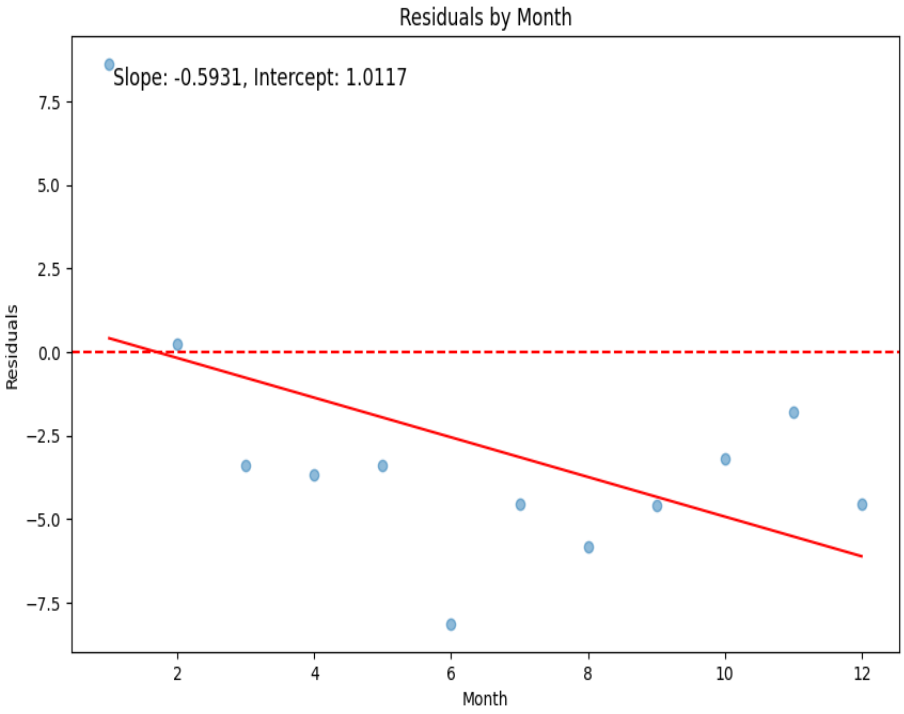

RMSE by Month and Hour
Month
Hour
1 16.07 17.34 15.08 14.77 13.23 13.52 18.10 20.75 19.78 18.15 16.81 14.38 13.03 12.11 13.31 15.33 18.42 17.28 12.45 10.53 11.39 10.97 13.40 14.03
2 6.48 7.32 7.72 7.59 7.24 6.36 7.56 7.65 7.13 7.43 8.10 8.33 7.71 7.63 7.12 6.10 5.59 6.43 5.51 4.77 5.99 4.47 5.43 6.31
3 10.42 11.67 11.95 11.67 10.59 8.89 7.39 6.57 8.16 10.06 10.43 10.65 12.01 12.70 11.77 10.13 6.97 4.84 4.49 3.53 5.77 6.94 8.86 9.93
4 7.46 8.04 7.71 4.99 4.49 5.22 5.06 3.44 4.55 7.60 9.79 10.36 9.77 9.22 8.01 6.67 5.26 3.96 4.54 4.27 4.32 6.37 5.83 6.65
5 8.25 9.30 9.70 8.87 8.49 7.70 7.51 7.58 9.17 8.86 8.80 10.69 13.34 13.57 11.11 6.12 3.00 3.10 4.46 3.85 3.86 4.88 7.08 7.85
6 12.83 13.43 14.97 15.56 12.65 12.95 11.33 9.59 10.87 10.74 11.78 13.93 14.35 14.53 13.10 9.17 7.46 9.82 12.23 9.57 8.26 9.80 13.79 12.45
7 7.30 7.72 7.98 7.85 7.31 7.62 6.79 6.21 5.16 4.81 5.99 6.99 8.02 8.39 8.03 6.76 7.44 9.07 9.48 8.84 7.12 5.96 6.05 6.84
8 9.09 9.23 9.33 8.95 6.95 8.90 7.66 7.29 9.37 11.12 14.74 16.08 14.24 14.41 11.77 7.83 7.06 11.01 10.65 6.54 4.46 6.20 8.25 9.08
9 10.21 10.27 9.45 8.65 6.34 7.22 7.89 5.07 6.17 7.85 10.02 11.04 12.10 10.28 8.68 5.60 4.90 8.13 6.36 4.71 5.29 6.76 8.97 10.32
10 10.24 11.20 11.25 9.66 6.73 6.33 7.54 6.52 7.10 6.82 6.54 7.07 6.29 5.99 7.13 5.18 7.16 9.91 4.97 5.42 5.20 8.28 10.36 9.52
11 6.16 7.37 7.21 7.95 7.58 4.31 3.84 3.33 3.61 3.49 3.73 3.75 4.07 4.04 4.73 5.45 8.67 7.51 4.71 3.09 3.77 4.28 5.46 7.31
12 11.29 13.36 13.69 13.76 13.45 8.78 8.84 9.23 9.03 8.46 8.19 7.54 7.15 6.93 6.62 6.56 7.52 6.10 5.46 6.70 6.67 7.43 10.16 10.71
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
20 18 16 14 12 10 8 6 4

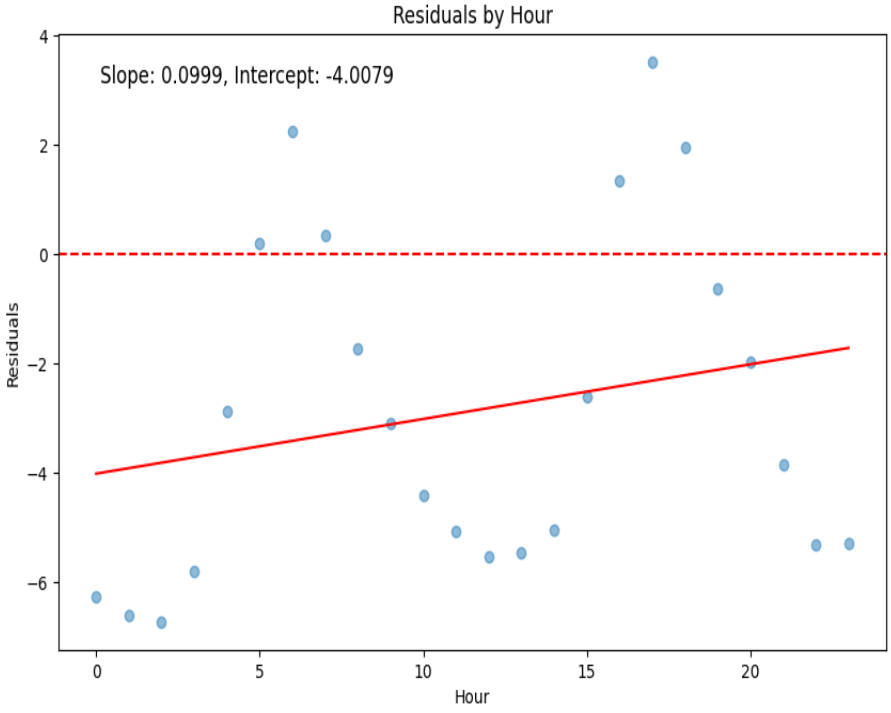

Feature Importance
Features
AT_load_forecast_entsoe_transparency
DE_solar_capacity
BE_load_forecast_entsoe_transparency
CH_load_forecast_entsoe_transparency
CZ_load_forecast_entsoe_transparency
DE_wind_profile
DE_load_forecast_entsoe_transparency
DE_wind_capacity
NL_load_forecast_entsoe_transparency
DE_wind_offshore_profile
5591.0
3476.0
2711.0
2197.0
1802.0
1678.0
1439.0
1383.0
1190.0
1149.0
0
1000
2000
3000
4000
5000
6000
F score

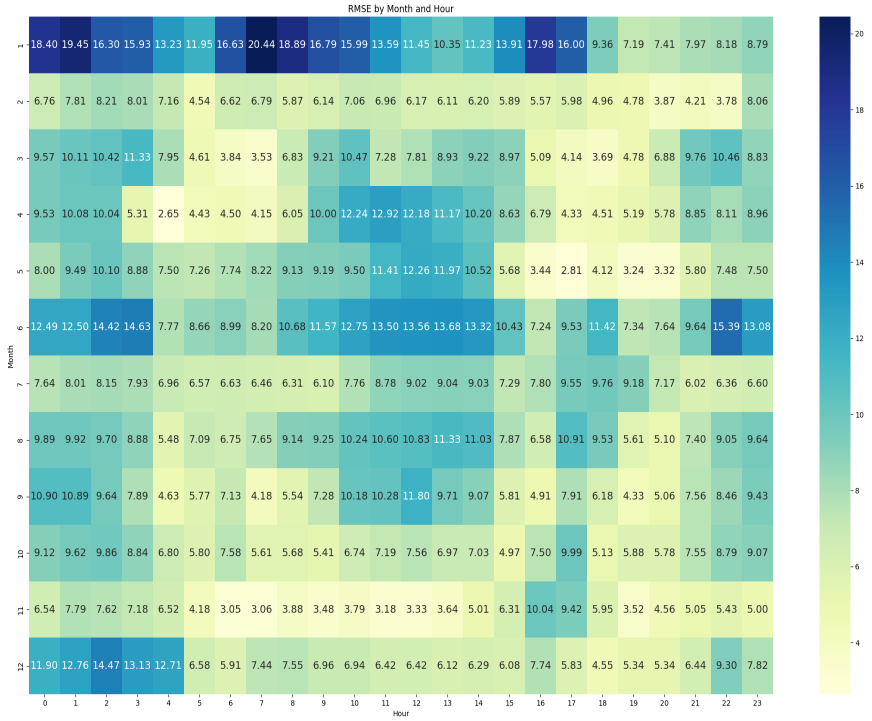
Performance Metrics: All variables + NG Prices

Metric	Model Performance
MAE	6.719
RMSE	78.336
R2	0.4504
Train R2	0.7988
Features	269




Residuals by Month
Slope: -0.5931, Intercept: 1.0117
Residuals
Month
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
2
4
6
8
10
12


Residuals by Hour
Slope: 0.0999, Intercept: -4.0079
Residuals
Hour
4
2
0
−2
−4
−6
0
5
10
15
20


RMSE by Month and Hour
Month
Hour
1 18.40 19.45 16.30 15.93 13.23 11.95 16.63 20.44 18.89 16.79 15.99 13.59 11.45 10.35 11.23 13.91 17.98 16.00 9.36 7.19 7.41 7.97 8.18 8.79
2 6.76 7.81 8.21 8.01 7.16 4.54 6.62 6.79 5.87 6.14 7.06 6.96 6.17 6.11 6.20 5.89 5.57 5.98 4.96 4.78 3.87 4.21 3.78 8.06
3 9.57 10.11 10.42 11.33 7.95 4.61 3.84 3.53 6.83 9.21 10.47 7.28 7.81 8.93 9.22 8.97 5.09 4.14 3.69 4.78 6.88 9.76 10.46 8.83
4 9.53 10.08 10.04 5.31 2.65 4.43 4.50 4.15 6.05 10.00 12.24 12.92 12.18 11.17 10.20 8.63 6.79 4.33 4.51 5.19 5.78 8.85 8.11 8.96
5 8.00 9.49 10.10 8.88 7.50 7.26 7.74 8.22 9.13 9.19 9.50 11.41 12.26 11.97 10.52 5.68 3.44 2.81 4.12 3.24 3.32 5.80 7.48 7.50
6 12.49 12.50 14.42 14.63 7.77 8.66 8.99 8.20 10.68 11.57 12.75 13.50 13.56 13.68 13.32 10.43 7.24 9.53 11.42 7.34 7.64 9.64 15.39 13.08
7 7.64 8.01 8.15 7.93 6.96 6.57 6.63 6.46 6.31 6.10 7.76 8.78 9.02 9.04 9.03 7.29 7.80 9.55 9.76 9.18 7.17 6.02 6.36 6.60
8 9.89 9.92 9.70 8.88 5.48 7.09 6.75 7.65 9.14 9.25 10.24 10.60 10.83 11.33 11.03 7.87 6.58 10.91 9.53 5.61 5.10 7.40 9.05 9.64
9 10.90 10.89 9.64 7.89 4.63 5.77 7.13 4.18 5.54 7.28 10.18 10.28 11.80 9.71 9.07 5.81 4.91 7.91 6.18 4.33 5.06 7.56 8.46 9.43
10 9.12 9.62 9.86 8.84 6.80 5.80 7.58 5.61 5.68 5.41 6.74 7.19 7.56 6.97 7.03 4.97 7.50 9.99 5.13 5.88 5.78 7.55 8.79 9.07
11 6.54 7.79 7.62 7.18 6.52 4.18 3.05 3.06 3.88 3.48 3.79 3.18 3.33 3.64 5.01 6.31 10.04 9.42 5.95 3.52 4.56 5.05 5.43 5.00
12 11.90 12.76 14.47 13.13 12.71 6.58 5.91 7.44 7.55 6.96 6.94 6.42 6.42 6.12 6.29 6.08 7.74 5.83 4.55 5.34 5.34 6.44 9.30 7.82
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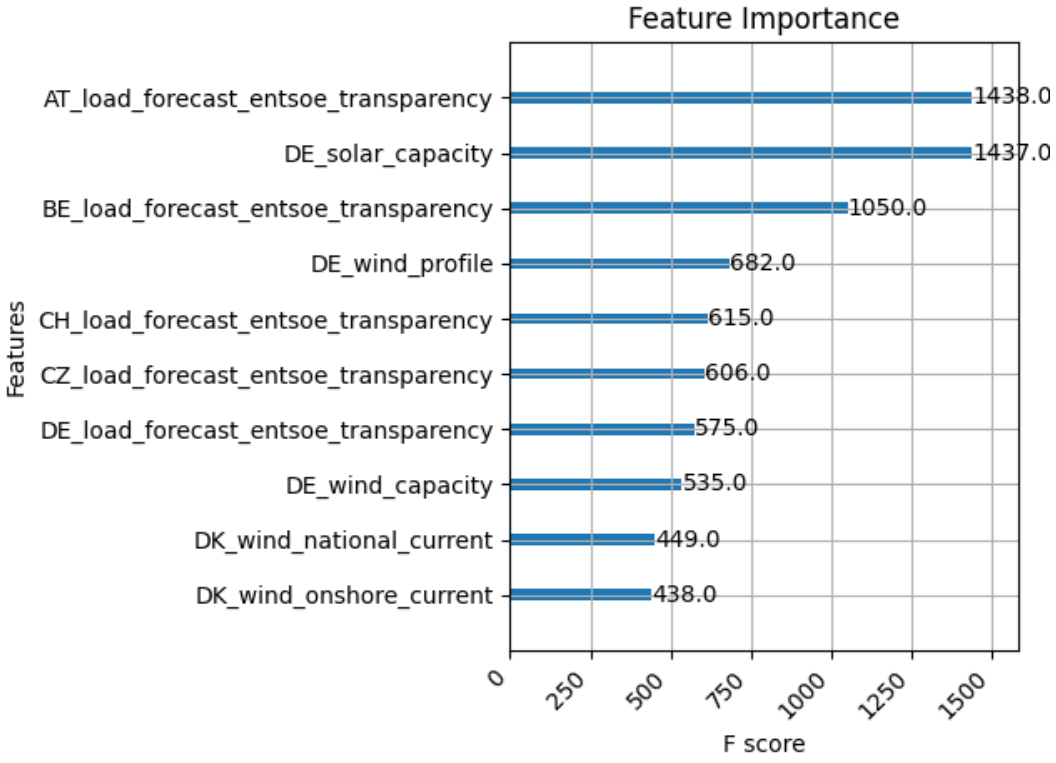
20 18 16 14 12 10 8 6 4


Feature Importance
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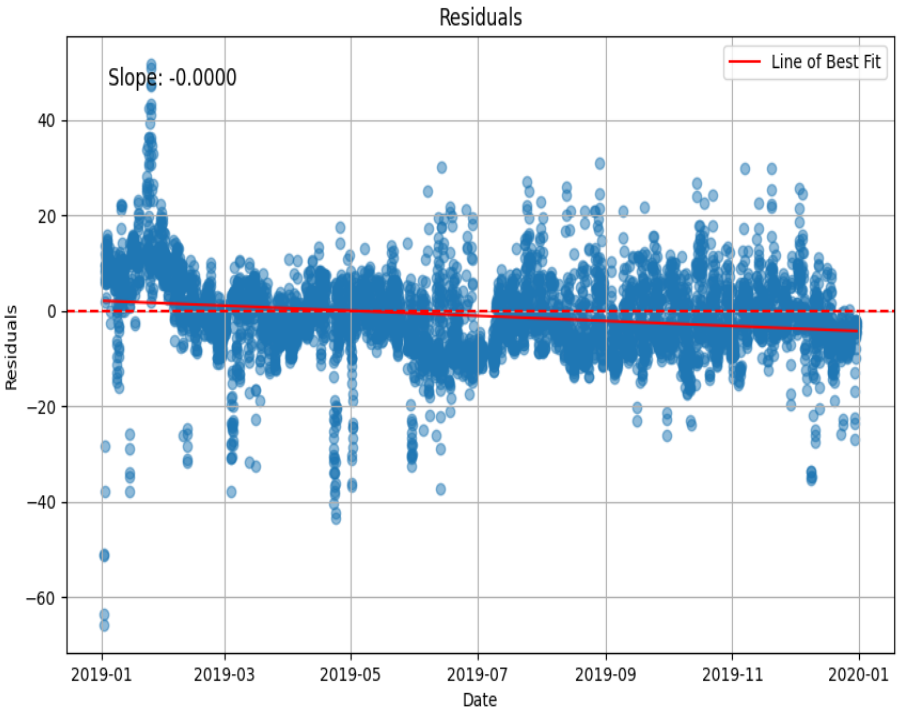
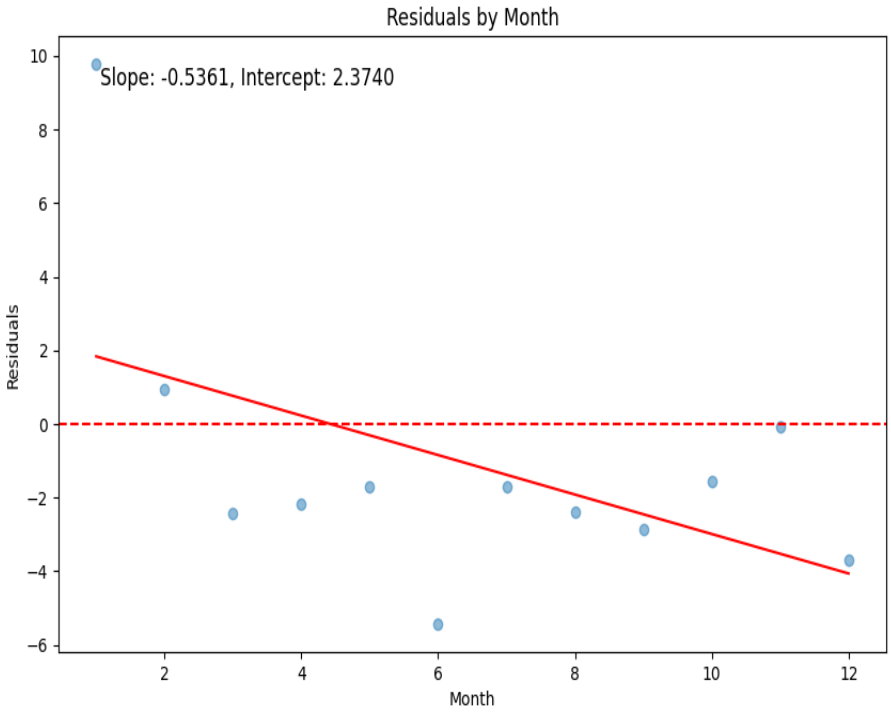
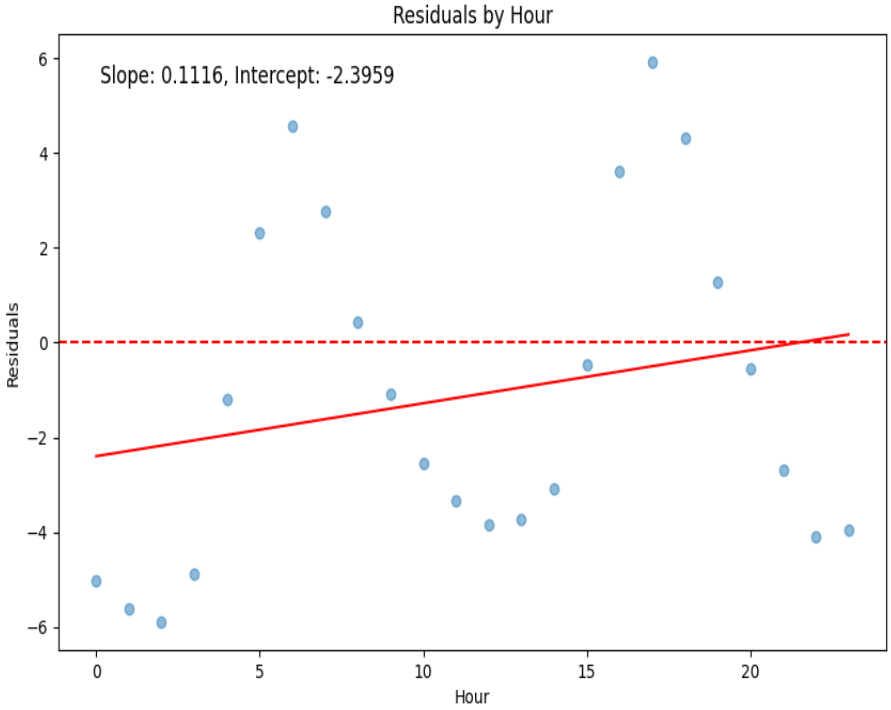
DE_solar_capacity 1437.0
BE_load_forecast_entsoe_transparency 1050.0
DE_wind_profile 682.0
CH_load_forecast_entsoe_transparency 615.0
CZ_load_forecast_entsoe_transparency 606.0
DE_load_forecast_entsoe_transparency 575.0
DE_wind_capacity 535.0
DK_wind_national_current 449.0
DK_wind_onshore_current 438.0
0 250 500 750 1000 1250 1500
F score

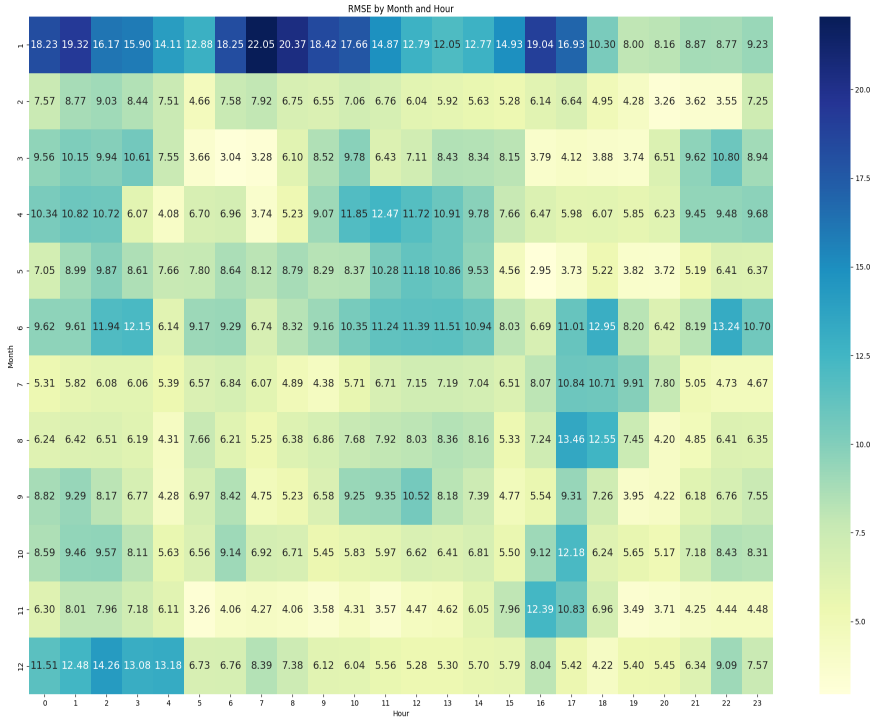
Performance Metrics: Important Features Model

Metric	Model Performance
MAE	6.296
RMSE	73.521
R2	0.4842
Train R2	0.7318
Features	48




Residuals by Month
Slope: -0.5361, Intercept: 2.3740
Residuals
Month
10
8
6
4
2
0
−2
−4
−6
2
4
6
8
10
12


Residuals by Hour
Slope: 0.1116, Intercept: -2.3959
Residuals
Hour
6
4
2
0
−2
−4
−6
0
5
10
15
20


RMSE by Month and Hour
Month
Hour
1 18.23 19.32 16.17 15.90 14.11 12.88 18.25 22.05 20.37 18.42 17.66 14.87 12.79 12.05 12.77 14.93 19.04 16.93 10.30 8.00 8.16 8.87 8.77 9.23
2 7.57 8.77 9.03 8.44 7.51 4.66 7.58 7.92 6.75 6.55 7.06 6.76 6.04 5.92 5.63 5.28 6.14 6.64 4.95 4.28 3.26 3.62 3.55 7.25
3 9.56 10.15 9.94 10.61 7.55 3.66 3.04 3.28 6.10 8.52 9.78 6.43 7.11 8.43 8.34 8.15 3.79 4.12 3.88 3.74 6.51 9.62 10.80 8.94
4 10.34 10.82 10.72 6.07 4.08 6.70 6.96 3.74 5.23 9.07 11.85 12.47 11.72 10.91 9.78 7.66 6.47 5.98 6.07 5.85 6.23 9.45 9.48 9.68
5 7.05 8.99 9.87 8.61 7.66 7.80 8.64 8.12 8.79 8.29 8.37 10.28 11.18 10.86 9.53 4.56 2.95 3.73 5.22 3.82 3.72 5.19 6.41 6.37
6 9.62 9.61 11.94 12.15 6.14 9.17 9.29 6.74 8.32 9.16 10.35 11.24 11.39 11.51 10.94 8.03 6.69 11.01 12.95 8.20 6.42 8.19 13.24 10.70
7 5.31 5.82 6.08 6.06 5.39 6.57 6.84 6.07 4.89 4.38 5.71 6.71 7.15 7.19 7.04 6.51 8.07 10.84 10.71 9.91 7.80 5.05 4.73 4.67
8 6.24 6.42 6.51 6.19 4.31 7.66 6.21 5.25 6.38 6.86 7.68 7.92 8.03 8.36 8.16 5.33 7.24 13.46 12.55 7.45 4.20 4.85 6.41 6.35
9 8.82 9.29 8.17 6.77 4.28 6.97 8.42 4.75 5.23 6.58 9.25 9.35 10.52 8.18 7.39 4.77 5.54 9.31 7.26 3.95 4.22 6.18 6.76 7.55
10 8.59 9.46 9.57 8.11 5.63 6.56 9.14 6.92 6.71 5.45 5.83 5.97 6.62 6.41 6.81 5.50 9.12 12.18 6.24 5.65 5.17 7.18 8.43 8.31
11 6.30 8.01 7.96 7.18 6.11 3.26 4.06 4.27 4.06 3.58 4.31 3.57 4.47 4.62 6.05 7.96 12.39 10.83 6.96 3.49 3.71 4.25 4.44 4.48
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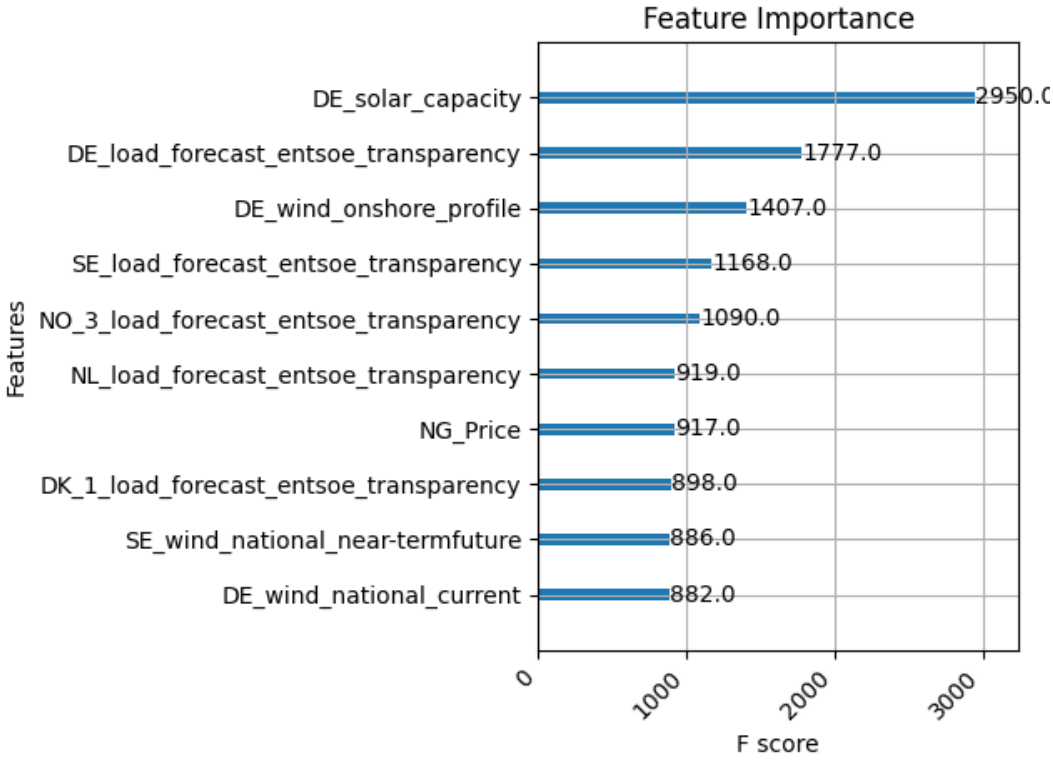
Feature Importance
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F score