Karlsruhe Institute of Technology

Evaluating the benefit of grid-based weather information in energy forecasting

Bachelors's Thesis of

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I declare that I have developed and written the enclosed thesis completely by myself, and have not used sources or means without declaration in the text.

PLACE, DATE

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(Marcel Herm)

Abstract

As the share of electricity from regenerative sources is growing constantly, the weather becomes an increasingly important factor in the analysis of electricity markets. Hence, this thesis uses local weather data to predict electricity spot prices. More precisely, we include wind speed and temperature from individual German weather stations into time series and statistical learning models. However, as the available weather information is vast and renewable power is not generated everywhere, we use random forests and Bayesian structural time series to perform a feature selection. Overall, we manage to improve our forecasting accuracy of the EPEX electricity prices by up to 7.69 % in terms of root mean squared error and up to 8.19 % in terms of mean absolute error.

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1. Introduction

According to Li et al. (2009), especially temperature and perceived temperature have a great impact on energy demand. Consequently, several authors combine forecasting energy time series using weather data. They mostly either focus on forecasting photovoltaic (PV) electricity generation as in Bofinger and Heilscher (2014) and Sperati et al. (2016) or on electricity generation from wind as in Davò et al. (2016) and Alessandrini et al. (2015).

It is notable, that works using station-based data often try to do some sort of geographic interpolation to be able to obtain values for every possible position. Considering this thesis, there is no such problem, as the used grid-based data already provides such distributed values. Thus, when using grid-based data, the step of interpolation can be omitted, and therefore, less effort is required. Some works also regard only forecasting for specific locations or accumulated values for bigger areas. With grid-based data, more general predictions can be made regarding the target location, as there is no binding to a certain locality.

Another interesting point is, that the works that forecast weather related time series all used grid-based data, though some of them also used station-based data to refine their forecasts. Among the papers that aimed for forecasting power or similar often only station-based data is used which leads to the assumption that less effort has been made in these fields, as it is still more complex to acquire grid-based data. However, there remains the possibility that station-based data is more suitable, even though this means a trade-off in terms of flexibility. Of course it is also possible that this has to do with the fact, that there is no grid-based power data available as this may harm privacy issues.

2. Related Work

This chapter gives an overview of related work in the field of energy forecasting considering grid-based data. After describing the general approach of search, there are some sources presented ordered by degree of relation to this thesis.

In order to find relevant literature, arXiv[1],Google Scholar[2] and BASE[3] are used.
In the process of search, the following criteria are applied to identify relevant literature:

- The title of the paper suggests that the authors work with geographic or grid-based data

- The title of the paper implies that the subject of the paper is being situated in the field of energy networks

- The title of the paper suggests that the authors aim at forecasting values

- The abstract or introduction of the paper suggests that the authors work with geographic or grid-based data

- The abstract or introduction of the paper suggests that the authors aim at forecasting or rather how forecasting is done

Subsequently, there will be two papers outlined which provide useful information for related research. After that, the papers that meet above criteria are outlined and explained regarding the used type of data, the forecast time series, applied forecasting methods and the forecast horizon.

There were some papers containing valuable information such as Kamińska-Chuchmala (2014), in particular due to its subject of forecasting internet traffic load and the high correlation between internet traffic load and electricity load, as can be read in Morley et al.

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[1]https://arxiv.org/
[2]https://scholar.google.de/
[3]https://www.base-search.net/

(2018). They apply Ordinary Kriging (OK) to spatially interpolate station-based data. Due to the great similarity between these fields, it is has great potential for related subjects and also influenced this work e. g. concerning further research. Furthermore it underlines the benefit of grid-based data by illustrating the necessary effort of processing station-based data. Another suitable example utilizing station-based data is Fairley et al. (2017) which investigates marine energy generation and critically discusses implications for electricity supply. This combines localization issues and the electricity network. Unfortunately, the aim here is not to forecast, but only to examine the problem.

The first group of related work utilizes grid-based, station-based or both types of data to forecast various, not necessarily electricity generation related, time series. In the first paper elaborated by Ludwig et al. (2015), the use of station-based weather data from Deutscher Wetterdienst (DWD) for electricity price forecasting in Germany is investigated. The price history is obtained from European Power Exchange (EPEX SPOT). The work does not consider Neural Networks (NN), but rather compares Least Absolute Shrinkage Selection Operation (LASSO) and Random Forests (RF) in addition to Autoregressive-Moving Average (ARMA) and Autoregressive-Moving Average with Exogenous Inputs (ARMAX) models. A desirable side effect from RF is the output of the variable importance which is useful in order to filter variables by order of their relevance. As this work has a focus on short-term forecasts, the forecast time series here is the electricity price for the next day, thus having a forecast horizon of 24 hours. Another example of this group is Salcedo-Sanz et al. (2018), where grid-based weather data is used to forecast solar radiation in Australia. The evaluated methods are combinations of Coral Reefs Optimization (CRO), Extreme Learning Machine (ELM), Grouping Genetic Algorithm (GGA), Multivariate Adaptive Regression Splines (MARS), Support Vector Regression (SVR) for a forecast horizon of 24 hours. Similarly, Diagne et al. (2013) utilizes grid-based weather data for solar radiation forecasting. Different data sources are compared, specifically European Centre of Medium-Range Weather Forecasts (ECMWF), Fifth-generation Mesoscale Model (MM5) and Weather Research and Forecasting Model (WRF). The paper focuses on Autoregressive (AR) methods including ARMA, Autoregressive Integrated Moving Average (ARIMA) and Coupled Autoregressive and Dynamical System (CARDS), NN and Wavelet Neural Networks (WNN) considering short time ranges from 5 min up to 6h.

The second group of related work forecast electricity generation, but in contrast to the first group, make use of station-based data. E. g. Aguiar et al. (2016) utilize both, grid-based and station-based weather data to improve Global Horizontal Solar Irradiance (GHI) forecasts

on Gran Canaria Island. GHI is similar to solar radiation that is forecast in the previous paper. In order to obtain the desired results, NN are applied. As the authors consider intra-day forecasting, the forecast horizon is limited to a range from 1 up to 6 hours in this case. Bofinger and Heilscher (2014) acquire data only from local weather stations to forecast solar power generation. The data is then refined with grid-based data from ECMWF by applying Model Output Statistics (MOS) and Inverse Distance Weighting (IDW), spatially interpolated and then simulated for Germany in order to predict a temporal range of 24-120 hours. In a work, that has been published by Haben et al. (2018), station-based weather data is applied to forecast low voltage load in the United Kingdom. They implement Kernel Density Estimation (KDE), Simple Seasonal Linear Regression (SSLR), Autoregressive model using an average weekly profile (ARWD), Autoregressive model using an average weekly profile including annual seasonality (ARWDY) and Holt-Winters-Taylor Exponential Smoothing Method (HWT-ESM) and compare them for forecast horizons of up to 4 days. Alessandrini et al. (2015) utilize non-gridded wind and power data from a wind farm in northern Sicily in Italy, with which they forecast generated wind power. Here, a novel approach, an Analog Ensemble (AnEn), which originally is used for meteorological ensemble forecasts, is applied to the data to retain a probabilistic prediction for the next 0-132 hours.

The last group of related work forecasts electricity generation with grid-based data. An application of grid-based data from ECMWF is proposed in Sperati et al. (2016) for solar power prediction in Italy. They implement a Probability Density Function (PDF) combined with NN, Variance Deficit (VD), Ensemble Model Output Statistics (EMOS) and Persistence Ensemble (PE). The time series forecast includes a range of 0-72 hours. Similar to this thesis, De Felice et al. (2015) use grid-based data from ECMWF to forecast the electricity demand, though for Italy. Linear Regression (LR) and a Support Vector Machines (SVM) are applied. Given that power prediction is a rather complex problem, the non-linear SVM performs better than a simple LR. The last, and therefore most relevant paper presented, is Davò et al. (2016) who utilize grid-based wind speed data generated by applying the Regional Atmospheric Modelling System (RAMS) with boundary conditions from ECMWF. Furthermore, they acquire grid-based data of solar radiation energy per square meter as one of the two forecast time series is the solar irradiance. The data is coming from National Oceanic and Atmospheric Administration - Earth System Research Laboratory (NOAA/ESRL) and was provided for an online competition hosted by Kaggle[4]. Reference

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[4]https://www.kaggle.com/

power data is obtained from Terna[5] as the other predicted time series is the wind power produced over Sicily. A Principal Component Analysis (PCA) is employed, as grid-based data is even more prone to the curse of dimensionality because of the two additional dimensions. In terms of forecasting, they apply NN and an AnEn. The forecast horizon has a range of 0 to 72 hours and the output is a prediction of both, wind power and solar radiation.

Comparing the works above to this thesis, it is notable that none of them focuses on evaluating the benefit of grid-based data to forecast energy time series. Table 2.1 provides an overview about the mentioned related works regarding the type of the used weather data, used methods, the place of origin of the data, the forecast horizon and the forecast time series.

[5]https://www.terna.it/

paper	type of weather data	methods	location	forecast horizon	forecast time series
Ludwig et al. (2015)	station-based	ARMA,ARMAX,LASSO,RF	Germany	24h	energy prices
Salcedo-Sanz et al. (2018)	grid-based	ELM,CRO,MARS, MLR,SVR,GGA	Australia	24h	solar radiation
Diagne et al. (2013)	grid-based	ARMA,ARIMA,CARDS, NN,WNN	-	5 min-6h	solar radiation
Aguiar et al. (2016)	mixed	NN	Gran Canaria Island	1-6h	solar radiation
Bofinger and Heilscher (2014)	mixed	MOS,IDW	Germany	24-120h	solar power
Haben et al. (2018)	station-based	KDE,SSLR,ARWD, ARWDY,HWT-ESM	United Kingdom	up to 4 days	low voltage electricity load
Alessandrini et al. (2015)	station-based	AnEn	Sicily	0-132h	wind power
Sperati et al. (2016)	grid-based	PDF,NN,VD,EMOS,PE	Italy	0-72h	solar power
De Felice et al. (2015)	grid-based	LR,SVM	Italy	1-2 months	electricity demand
Davò et al. (2016)	grid-based	PCA,AnEn,NN	Sicily	0-72h	wind power,solar radiation
This thesis	grid-based	LR,ARMA,ARMAX,PCA	Germany	1-24h	electricity load

Table 2.1. List of related works regarding the type of the used weather data, used methods, place of origin of the data, forecast horizon and forecast time series.

3. Methodology

In this chapter, the used forecasting methods are explained further and why they were used, but also other methodological aspects of this thesis will be outlined.

3.1. Data acquisition

In order to acquire the needed weather data, ECMWF's Python-API is used for automated data acquisition. The API has been extended by some functionality recently and allows to download the data with different extensions. The chosen extension is .nc, because Python's xarray library allows performant access to these files.

3.2. Forecasting methods

For time series forecasting, often used methods are e. g. ARMA models as mentioned in **Hyndman2018**, but also NN, where it is common to reduce the number of input variables in order to speed up computation, which is desirable for the huge amount of grid-based data that grows quadratically with size. There are also some papers that use regression models other than ARMA such as LR, MLR or SVM.

Aguiar et al. (2016) applies NN to do intra-day solar radiation forecasting with a forecasting horizon of 1-6 hours on Gran Canaria and, as in this thesis, grid-based data from ECMWF is used.

3.2.1. ARMA

One of the most frequently used methods for forecasting in time series forecasting is ARMA, which is a combination of AR and Moving Average (MA) terms. ARIMA is quite similar to this, but involves an additional differentiation term to consider the trend of past

data. The formal description of an ARMA is given as follows:

$$y_t = c + \epsilon_t + \sum_{i=1}^{p} a_i y_{t-i} + \sum_{j=1}^{q} b_j \epsilon_{t-j} \qquad (3.1)$$

With c as a constant, ϵ_t as noise terms with respect to time t, p as size of the AR part, q as size of the MA part, a and b for the AR and MA coefficients respectively and y_t as the predicted value.

3.2.2. ARMAX

Another similar method is ARMAX, which includes an additional term for exogenous variables. This term can be used to include relations to external factors that do not depend on the endogenous data. The formal description is given by:

$$y_t = c + \epsilon_t + \sum_{i=1}^{p} a_i y_{t-i} + \sum_{j=1}^{q} b_j \epsilon_{t-j} + \sum_{k=1}^{n} c_k x_k \qquad (3.2)$$

Which almost equals to Equation (3.1) for the ARMA. There is an additional term for n included exogenous variables x with c as the respective coefficients.

3.2.2.1. only calendar variables as exogenous inputs

3.2.2.2. additional weather variables as exogenous inputs

3.3. Feature Selection

3.3.1. Principal Component Analysis

3.4. Forecast Evaluation

3.4.1. Root Mean Squared Error

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (a_i - p_i)^2} \qquad (3.3)$$

With n for the size, a for the actual values and p for predicted values.

3.4.2. Mean Absolute Percentage Error

$$MAPE = \frac{1}{n} \times 100 \sum_{i=1}^{n} \left| \frac{a_i - p_i}{a_i} \right| \tag{3.4}$$

With n for the size, a for the actual values and p for predicted values.

4. Evaluation

This chapter provides information about the input data acquired from different sources, the methods that were used to forecast electricity load and other statistical methods and also evaluates them regarding performance and the quality of the output.

4.1. Data

4.1.1. ECMWF

The data used in this thesis originates from ECMWF, which is a research institute that produces global numerical weather predictions and other data.
It is time series based and for each timestamp there is a 2-dimensional array referred to by longitude and latitude respectively.

It must be mentioned that, as the data used has been reanalysed, so the expected error is likely to be smaller than if working with real-time data.

As data parameters there are also longitude and latitude, where the longitude is chosen to be from 5.5 to 15.5 and the latitude from 47 to 55.5. As the resolution of the used grid is at 0.25°, this results in a total of 1435 grid points per timestamp. As the range of the data from ECMWF extends from 2015/1/1 to 2019/3/31(TODO update), there is a total of 1551 days with each 12 timestamps due to the 2 hours frequency and thus 18612 timestamps. Considering that there is a value for each point in the grid and every timestamp, there are 26708220 values for each variable.

Plotting the data on a map results in a result as can be seen in **??** and Figure 4.1. In this case the temperature measured at 2 meters is visualized.
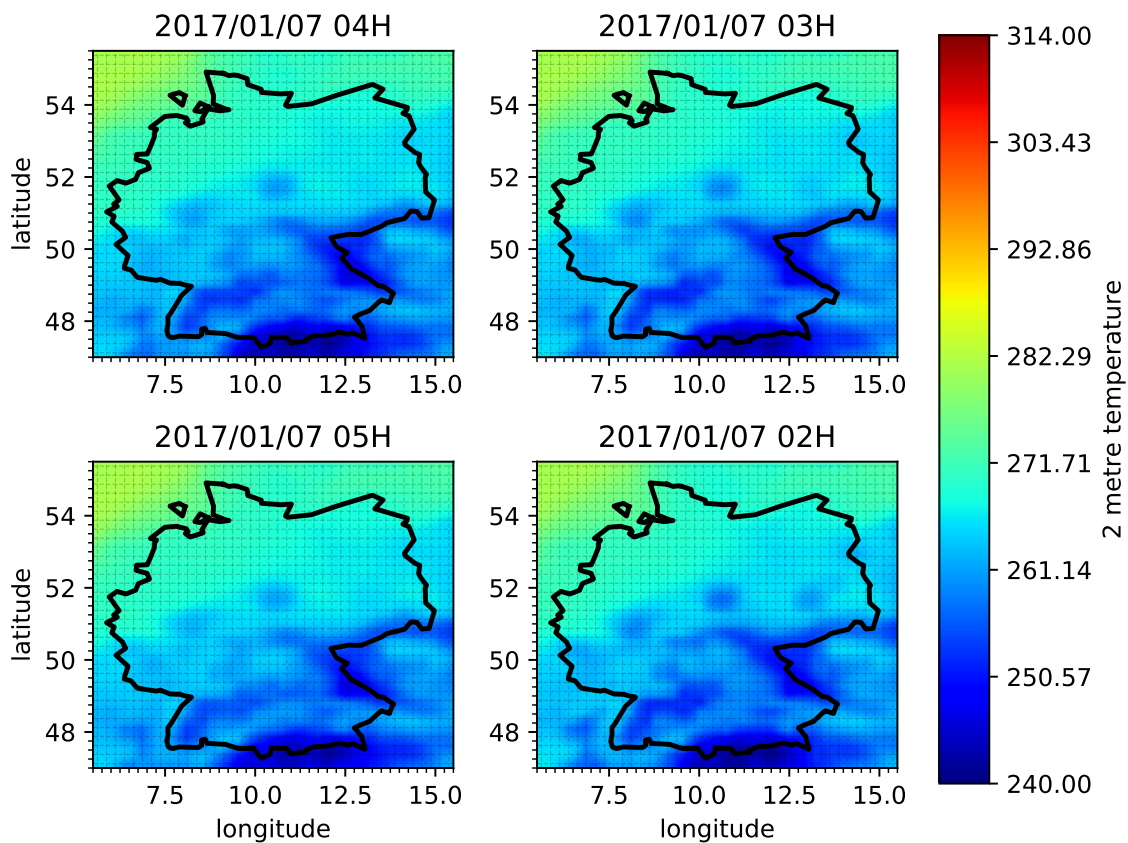
Figure 4.1. Map showing 4 times with highest temperature variance in Germany, where top left is highest, top right second highest, bottom left third highest and bottom right fourth highest variance (TODO put this in text).

In order to reduce complexity, a shapefile of the NUTS dataset was used. The shapefile contains all countries in the EU. The shape of Germany was filtered from this data and each point in the dataset is checked whether it is within Germany or not. The result can be seen in Section 4.1.1. The filtered map first is saved in a numpy.ndarray and then applied on the data to mask unwanted data visualized in Section 4.1.1.

The initial dataset contains a set of variables listed in Table 4.1 where also the units, min and max are shown for each variable respectively.

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[1]https://ec.europa.eu/eurostat/de/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts

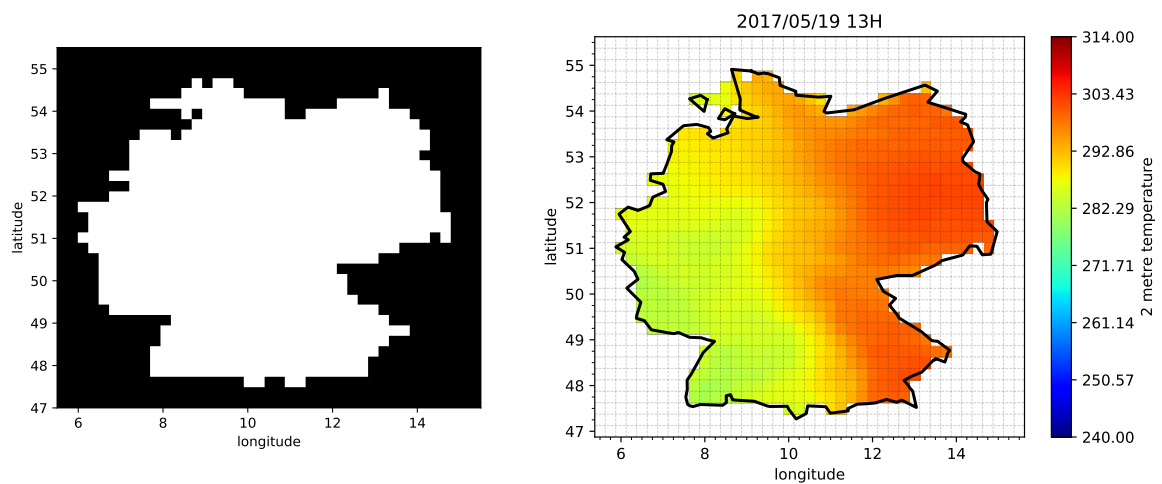[2]https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets

Figure 4.2. 2D boolean numpy.ndarray (left) used to filter grid squares that are within germany. It was created by using a shapefile of Germany from Eurostat[1]and checking for each point of the grid whether it is within the shape. When applied to the weather data, only relevant data within Germany is obtained (right).

variable name	units	min	max
10 metre U wind component	$m\ s^{-1}$	-18.56	21.92
10 metre V wind component	$m\ s^{-1}$	-21.51	20.00
2 metre temperature	K	240.97	313.26
Leaf area index, high vegetation	$m^2\ m^{-2}$	0.00	4.90
Leaf area index, low vegetation	$m^2\ m^{-2}$	0.00	3.84
Low cloud cover	$(0 - 1)$	0.00	1.00
Soil temperature level 1	K	257.91	313.64
Surface latent heat flux	$J\ m^{-2}$	-2203977.00	359411.00
Surface net thermal radiation	$J\ m^{-2}$	-663417.00	142945.02
Surface sensible heat flux	$J\ m^{-2}$	-1703159.00	801354.00
Total cloud cover	$(0 - 1)$	0.00	1.00
Total column rain water	$kg\ m^{-2}$	0.00	2.73
Total sky direct solar radiation at surface	$J\ m^{-2}$	-0.12	3088320.00

Table 4.1. List of exogenous weather variables used to forecast the load including min, max values from ECMWF[2].

4.1.2. Load data

Besides weather data used to refine the forecasting results, also historic load data was needed. Therefore data has been retained from Open Power System Data[3]. Figure A.1 shows the distribution of loads over time with one point per day at 12 am UTC time. The color shows the mean temperature measured at 2 meters.

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[3]https://data.open-power-system-data.org/time_series/

4.1.3. Population

For further improvement and in order to figure out important point in the grid, population data for Germany has been selected from Eurostat[4].

4.2. Programming part

4.2.1. Programming Language

For the programming part, Python 3.6+ has been chosen, as there is a variety of libraries to process all used file formats and because it tends to be a time saving language, also for visualization.

4.2.2. Documentation

In regard to coding styles, especially when it comes to docstrings, the numpy conventions were used. The three major points for this were first, that it is a popular and often used style, then it is also a visually oriented style which means, that it is easy to read and last it is supported by several (TODO check which, sphinx?!) autodoc tools that create a HTML based documentation from existing source code with docstrings.

4.3. Preparation

4.4. Results

4.4.1. ARMA

Describe the results you have obtained using your methods described above. Again use proper visualization methods.

4.4.2. Experiment 1

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[4]`https://ec.europa.eu/eurostat/data/database`
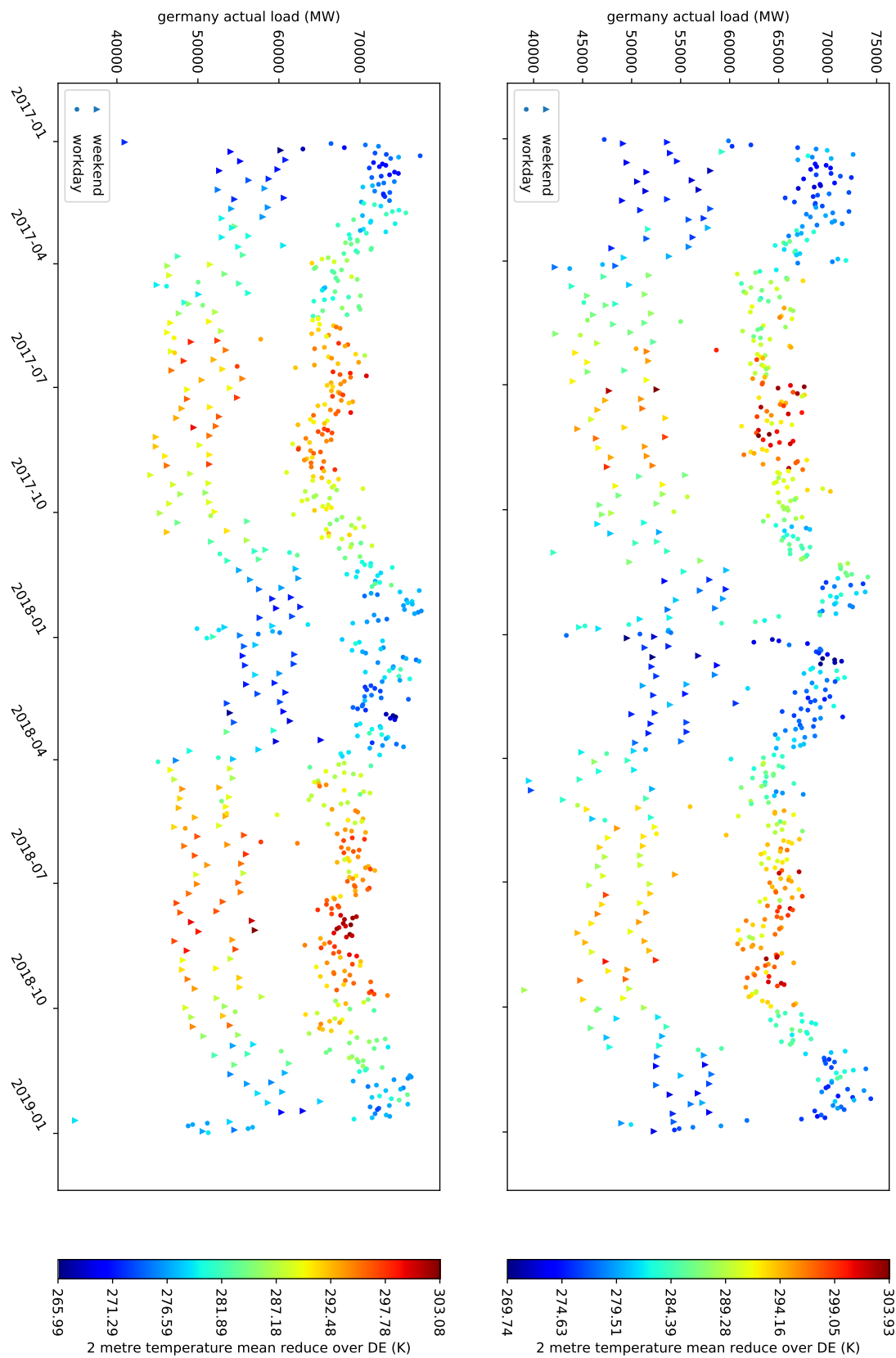
4.4.3. Experiment 2

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Figure 4.3. Load curve with mean of 2 meter measured temperature in Germany as color from 2015/1/1 to 2018/12/31 with one single point per day at 12 AM UTC time respectively.
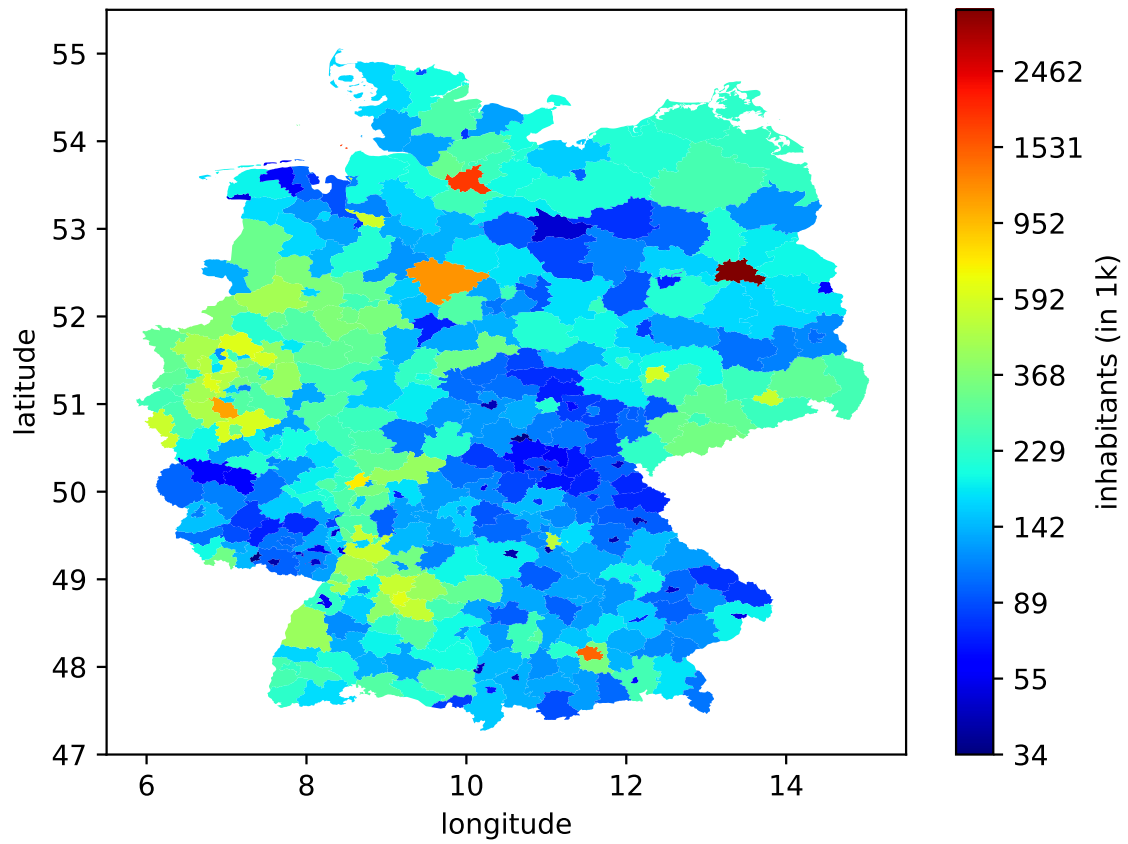
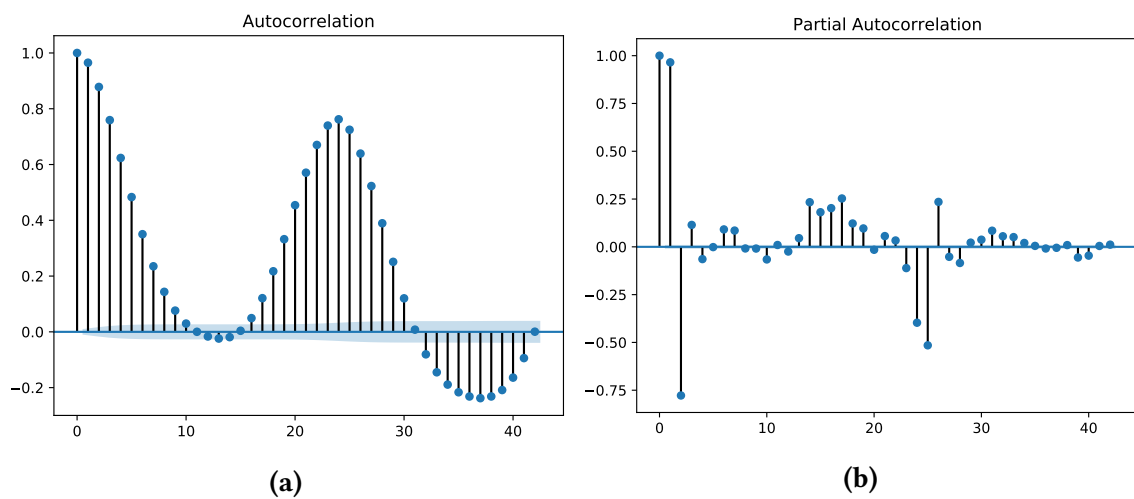**Figure 4.4.** Population of Germany for each region respectively using a log scale for better distinction.

Figure 4.5. Autocorrelation (a) and Partial Autocorrelation (b) plots used to select the order of ARMA and ARMAX models.
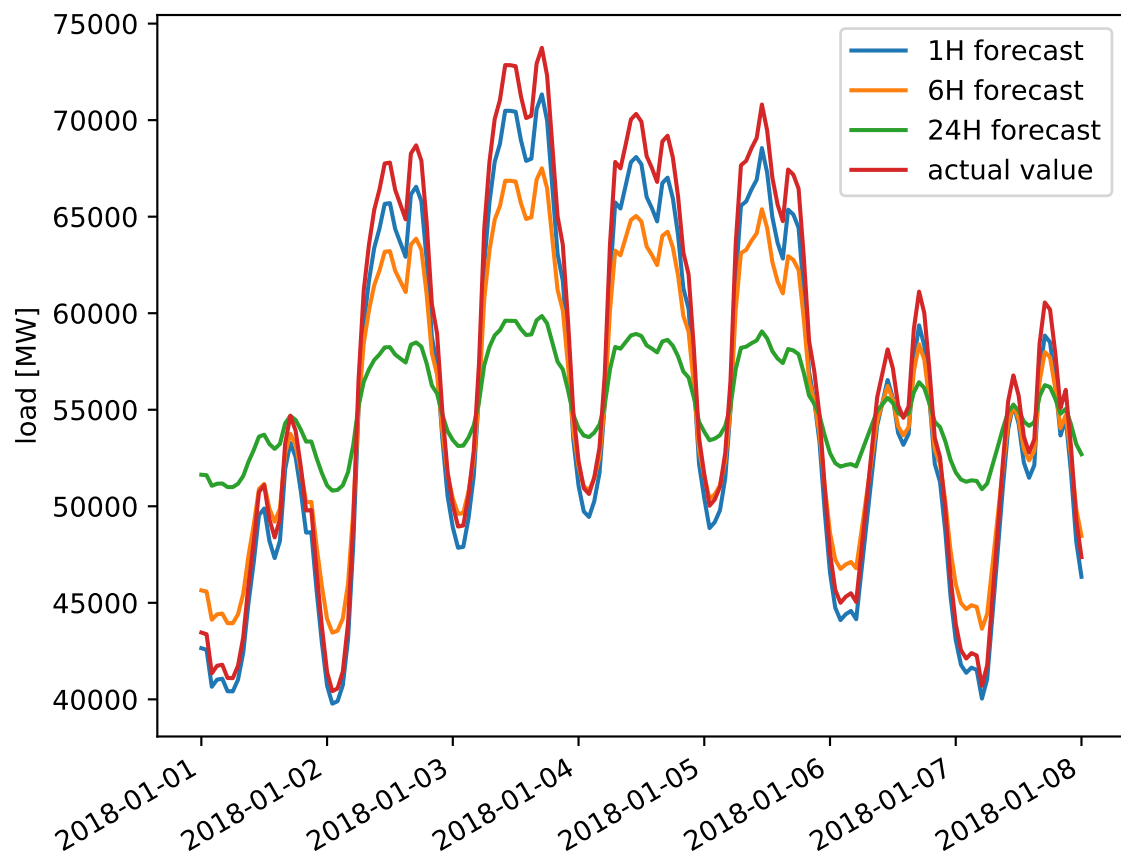
Figure 4.6. An example forecast for an ARMA(1,1) using load data from 2015/1/1 to 2018/5/1 forecasting one week for each step 1, 6 and 24 hours respectively.

5. Discussion

This chapter is supposed to discuss your results. Point out what your results mean. What are the limitations of your approach, managerial implications or future impact? Explain the broader picture but be critical with your methods.

6. Conclusion

It needs to be clarified, that in contrast to most of the presented works, this thesis uses reanalysed data from ECMWF as weather predictions which means, that the forecasts might behave differently from forecasts in other works as what here is assumed to be a weather forecast is more accurate than usually. This also means that results from this thesis may not exactly match results using the same procedure with real-time data.

Terms and abbreviations

AnEn Analog Ensemble. 5–7

AR Autoregressive. 4, 9, 10

ARIMA Autoregressive Integrated Moving Average. 4, 7, 9

ARMA Autoregressive-Moving Average. v, 4, 7, 9, 10, 19

ARMAX Autoregressive-Moving Average with Exogenous Inputs. v, 4, 7, 10, 19

ARWD Autoregressive model using an average weekly profile. 5, 7

ARWDY Autoregressive model using an average weekly profile including annual seasonality. 5, 7

CARDS Coupled Autoregressive and Dynamical System. 4, 7

CRO Coral Reefs Optimization. 4, 7

DWD Deutscher Wetterdienst. 4

ECMWF European Centre of Medium-Range Weather Forecasts. vii, 4, 5, 9, 13, 15, 23

ELM Extreme Learning Machine. 4, 7

EMOS Ensemble Model Output Statistics. 5, 7

EPEX SPOT European Power Exchange. 4

GGA Grouping Genetic Algorithm. 4, 7

GHI Global Horizontal Solar Irradiance. 4, 5

HWT-ESM Holt-Winters-Taylor Exponential Smoothing Method. 5, 7

IDW Inverse Distance Weighting. 5, 7

KDE Kernel Density Estimation. 5, 7

LASSO Least Absolute Shrinkage Selection Operation. 4, 7

LR Linear Regression. 5, 7, 9

MA Moving Average. 9, 10

MARS Multivariate Adaptive Regression Splines. 4, 7

MLR Multiple Linear Regression. 7, 9

MM5 Fifth-generation Mesoscale Model. 4

MOS Model Output Statistics. 5, 7

NN Neural Networks. 4–7, 9

NOAA/ESRL National Oceanic and Atmospheric Administration - Earth System Research
Laboratory. 5

NUTS Nomenclature des Unités territoriales statistiques. 14

OK Ordinary Kriging. 4

PCA Principal Component Analysis. 6, 7

PDF Probability Density Function. 5, 7

PE Persistence Ensemble. 5, 7

PV photovoltaic. 1

RAMS Regional Atmospheric Modelling System. 5

RF Random Forests. 4, 7

SSLR Simple Seasonal Linear Regression. 5, 7

SVM Support Vector Machines. 5, 7, 9

SVR Support Vector Regression. 4, 7

VD Variance Deficit. 5, 7

WNN Wavelet Neural Networks. 4, 7

WRF Weather Research and Forecasting Model. 4

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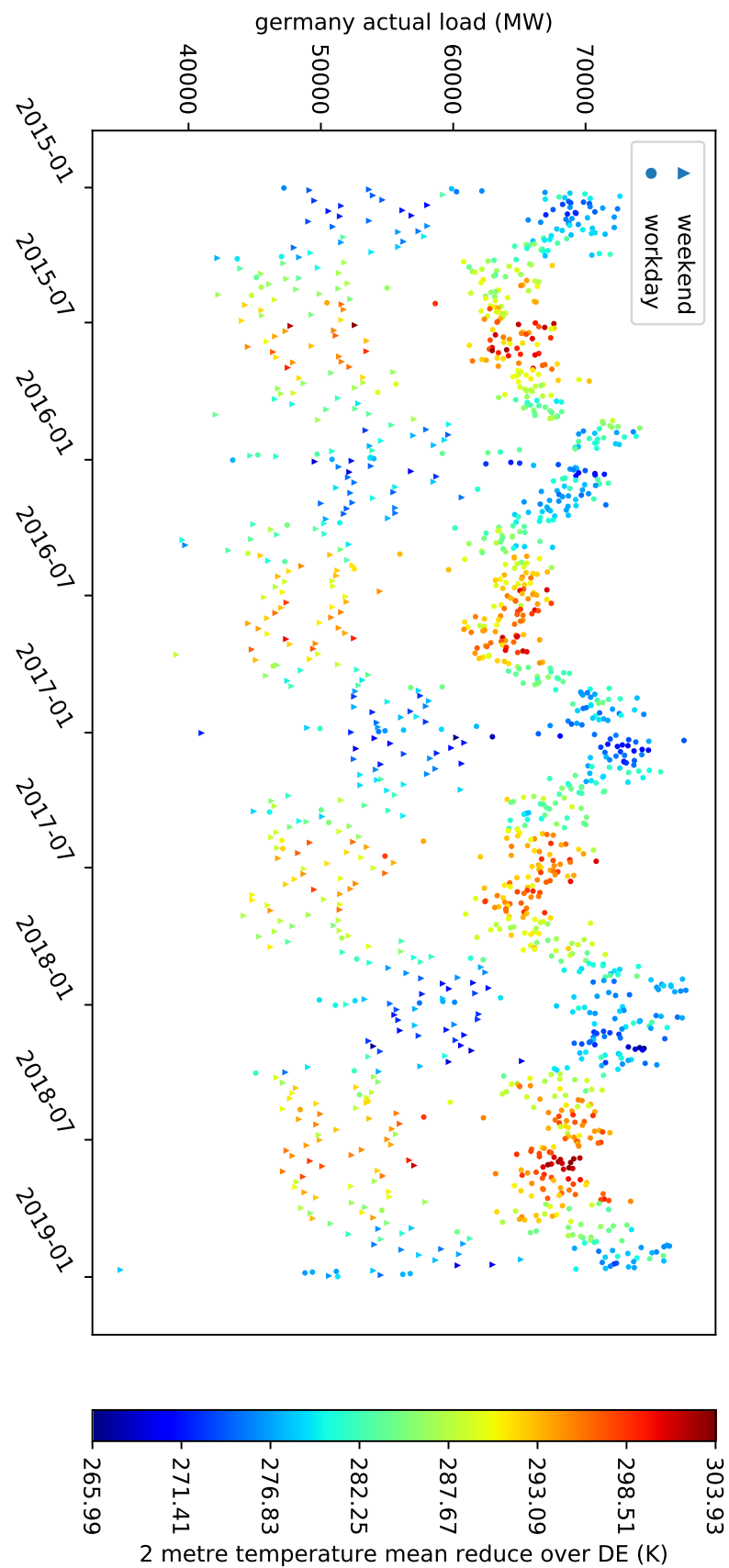
A. Appendix

A.1. Evaluation

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Figure A.1. Load curve with mean of 2 meter height measured temperature in germany as color from 2015/1/1 to 2018/12/31 with one single point per day at 12am utc time respectively.