Short-term Forecasting Documentation

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Welcome to the short-term-forecasting wiki!

Short-term forecasting of electricity generation, demand and prices using machine learning.

This work is part of Nithiya Streethran's research as Early-Stage Researcher (ESR) 9 of the ENSYSTRA - ENergy SYStems in TRAnsition Innovative Training Network. ENSYSTRA is funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No: 765515.

Background

The transition towards a future low-carbon economy is driven globally by the Paris Agreement [Pari15], which recognises the need for sustainable development worldwide to counter the threats of climate change. The European Union (EU) is committed to reduce greenhouse gas (GHG) emissions by 2050 to 80-90 % below 1990 levels [Ener12]. As the energy industry is responsible for the highest share of anthropogenic GHG emissions, importance is placed on how changes in energy systems can help achieve these GHG emission reduction targets [Ener12].

A number of opportunities exist for the decarbonisation of the energy industry. The International Renewable Energy Agency (IRENA), in their renewable energy roadmap study, has identified renewable energy as having the highest potential in reducing energy-related carbon dioxide (CO_2) emissions globally, which is closely followed by energy efficiency and electrification with renewable energy [Glob18]. In a 2018 political agreement, the EU member states agreed upon a target of at least 32 % of the demand being met with renewables by 2030, through national targets of the individual member states [ReneND]. The electricity demand in the transport sector is also expected to increase due to expected petrol and diesel engine bans and subsequently the electrification of road transport [Worl17].

The energy system is also transitioning towards a decentralised system with more consumer participation and new forms of flexibilities, including sector coupling, demand-side management (DSM), energy conversion and storage, cross-border interconnection and curtailment. This allows demand patterns to shift to better suit the generation patterns in systems with high penetration of variable renewable energy (VRE) resources, such as solar and wind [Lund17], [Towa18]. However, this requires cooperation involving many actors with various responsibilities and dependencies that interact within this energy system, and opens up the opportunity to perform interdisciplinary research work in the area of energy system analysis.

The ENSYSTRA - ENergy SYStems in TRAnsition Innovative Training Network has been established to address the challenges of the energy transition with interdisciplinary collaboration and regional cooperation involving academia, government and industry [AbouND]. ENSYSTRA is centred on the North Sea region and focusses on performing interdisciplinary modelling work involving technology, economics, social science and humanities, and combining various modelling approaches in different levels and resolutions. ENSYSTRA aims to keep an open science approach, which will allow the resulting models to be subject to full scientific scrutiny.

Energy systems models, which are tools used to project the future energy supply of a country or region [Herb12], is the centre of ENSYSTRA. The figure below explains the energy systems modelling process using a system analysis approach [Kroo15]. This process starts with creating a model of the actual energy system by simplifying and conceptualising the present system. This conceptualised system with all assumptions is then mathematically solved to produce numerical results. These results can then be interpreted and conclusions can be drawn regarding the future energy system. Such conclusions form the evidence-base for decision makers, resulting in policy implications or operational strategies that help achieve these climate targets.

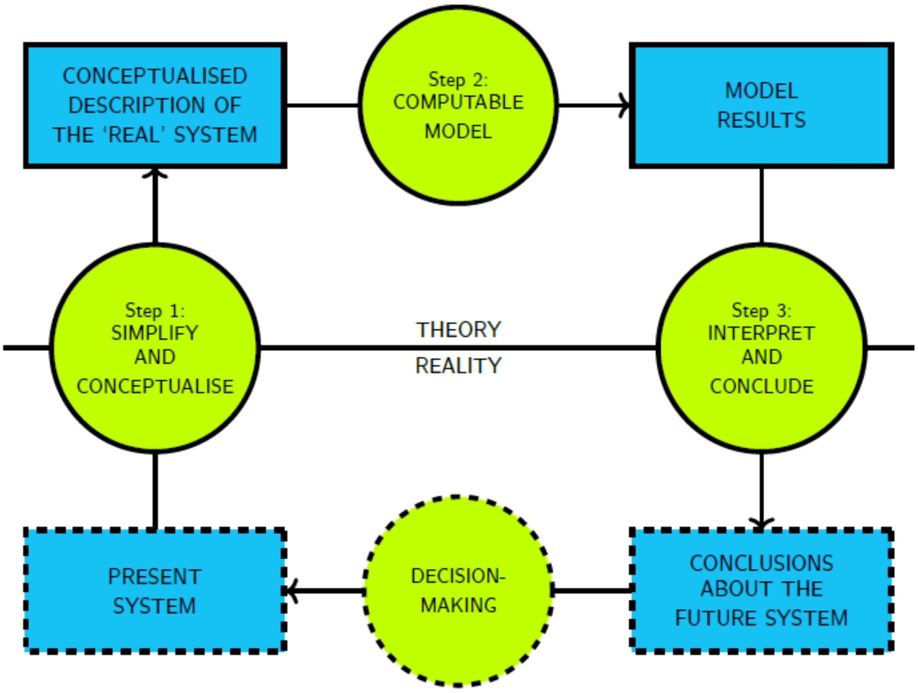

Figure 1: The system analysis approach applied on the energy system modelling process, adapted from Krook-Riekkola 2015 [Kroo15].

There are 15 early-stage researchers (ESRs) across four work packages (WPs) in ENSYSTRA, as shown in the figure below. The research project entitled "Development of a real-time optimisation solution for dispatchable energy supply units" is conducted by ESR 9, who is enrolled as a PhD student at University of Stavanger (UiS) in Norway. This project is within WP 2 (technology prospects and development pathways), which focusses on technological options for the energy transition, mainly in terms of techno-economic performance over time. For this research project, the technology focus is on the digitalisation of the electricity sector. As the electricity system transitions into smart systems, the system will have an increasing amount of sensors and controllers that continuously record measurements of the system [Lund17]. Advancements in these technologies mean that data that is fast, heterogeneous and high in volume from the electricity system will be generated. Data with these characteristics must be managed and analysed effectively to gain insights on the electricity system, which can then be converted to strategies that optimise the system [Mana12]. This project will specifically investigate how artificial intelligence (AI) can play a role in the transition to a low-carbon electricity system by utilising high resolution data of the system. The next section will investigate this, as well as explain what is meant by "real-time" and "dispatchable" in the context of electricity systems in this project.

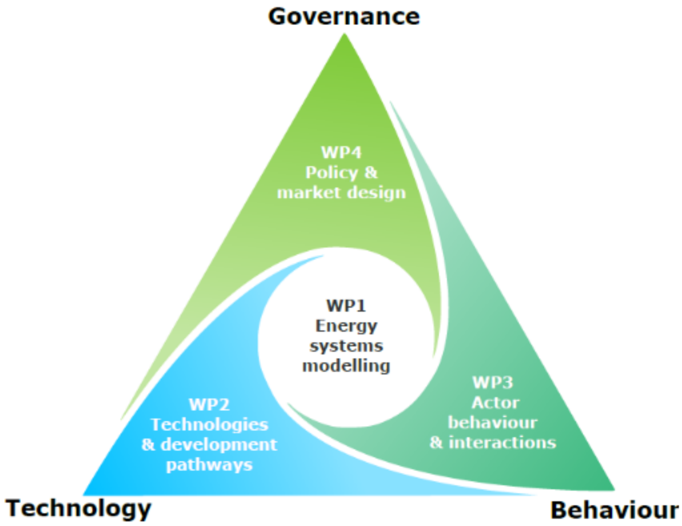

Figure 2: Interactions between the four WPs of the ENSYSTRA project. Source: ENSYSTRA [AbouND].

Problem definition

Electricity system

The electricity system can be seen as having two components; the physical grid consisting of generators and transmission and distribution systems, and the electricity market consisting of a number of actors [Erba16].

Electricity systems exist in different resolutions and levels of uncertainty. The figure below represents the different scales of electricity systems, mainly in terms of temporal resolution, but also uncertainty and spatial resolution [Glis18], [Pfen14]. Temporally, "real-time" is referred to as the time of dispatch. It can be observed that the operational planning scale has high spatial and temporal resolution, and relatively low uncertainty. Operational planning includes dispatch planning and plant scheduling (i.e., unit commitment), which ranges from a few minutes to a week before dispatch. Maintenance planning can take a few weeks to years, as it involves upgrade and maintenance work which may require shut-down of units or assets, in turn affecting the availability of generation units and grid infrastructure. Adequacy assessments, which takes years, involve assessing the existing generation and storage capacities and planning for new installations based on demand projections, to ensure this demand will be met in the future. Finally, grid investment decisions, including planning transmission and distribution grid networks, cross-border and regional interconnections and grid capacity expansions, take many years to decades and have very high uncertainty as a result.

Generation technologies

The table below shows the characteristics of the main energy generation technologies, including their costs. These generation sources have different variabilities, fuel types, flexibilities, costs and carbon emissions. According to the EU reference scenario 2016 [EnerND], wind and solar energy resources, which are

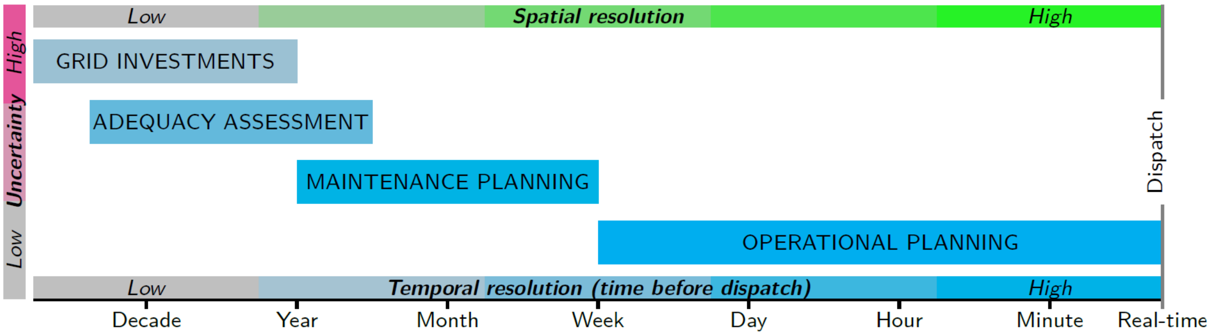

Figure 3: The various scales of electricity systems in terms of their approximate temporal resolution, as well as spatial resolution and uncertainty, adapted from Glismann 2018 and Pfenninger, et al. 2014 [Glis18], [Pfen14].

VRE resources, are expected to generate a total of 35 % of EU's electricity by 2050, which is a significant increase (23 %) from 2015 levels. Conversely, generation from nuclear and solids, which are not variable and provide base load generation, are expected to decrease significantly. Unlike conventional generators, VRE are intermittent as they are dependent on atmospheric conditions, such as wind speed and cloud cover, and they vary both spatially (i.e., location-dependent) and temporally [Josk11]. Therefore, VRE generation cannot be controlled to meet the demand patterns and needs of the energy system [Josk11], which is a challenge to electricity and energy system operators in general. The costs listed in this table are derived based on National Renewable Energy Laboratory (NREL)'s NREL-SEAC 2008 Data Set [Tidb10]. VRE generation technologies have high capital expenditure (CAPEX) compared to conventional fossil-powered and biomass generation. Conversely, the operational expenditure (OPEX), which includes fuel and fixed operational and maintenance (O&M) costs, is low for VRE generation technologies, as they have no fuel costs unlike conventional generators.

Table 1: Characteristics of the main energy generation technologies, adapted from Erbach 2016 [Erba16] and Tidball, et al. 2010 [Tidb10].

Type[f1]	Variable	Fuel type	Flexibility	Low carbon	CAPEX	OPEX	LCOE[f2]
Coal	no	fossil	medium	no	low	high	very low
Natural gas	no	fossil	high	no	very low	very high	low
Biomass	no	renewable	medium	yes[f3]	low	very high	very high
Nuclear	no	nuclear	low	zero-emission	medium	medium	medium
Hydro	no	renewable	very high	zero-emission			
Solar	yes	renewable	very low	zero-emission	very high	very low	very high
Wind	yes	renewable	very low	zero-emission			
Onshore wind					high	very low	very low
Offshore wind					very high	low	high
Geothermal	no	renewable	high	zero-emission	high	medium	high

[f1] *Costs for natural gas, biomass, solar and geothermal are that of advanced combustion turbine, biomass gasification plant, utility-scale photovoltaic and hydrothermal plant respectively*

[f2] *LCOE - levelised cost of electricity*

[f3] *regrowth of biomass compensates emissions*

Electricity market

The actors in the electricity market include generators, retailers, large and small consumers, transmission system operators (TSOs), distribution network operators (DNOs), balance responsible parties (BRPs), aggregators, regulators, and market operators [Erba16], [PinsND], [TheC15].

There are two types of electricity markets; the retail market and the wholesale market [Erba16]. The retail market involves the retailers buying electricity from generators and selling it to consumers. The wholesale market involves generators, retailers and (large) consumers, who buy and sell electricity. Energy-only transactions in the wholesale market have different temporal resolutions [PinsND], [TheC15] and take place before dispatch, shown in green in the figure below. Balancing markets, shown in pink in the figure below, which involve both energy and services, operate both before and after dispatch [TheC15]. The energy-only markets are operated by the market operator or power exchanges, while the balancing market is operated by the system operator. The day-ahead and intra-day markets can be considered short-term electricity markets, as the former takes place 24 hours in advance of dispatch, while the latter takes place continuously after the day-ahead market, up to minutes before dispatch [Over16].

The figure below is a typical supply and demand curve with merit order ranking [Pins18]. In an electricity

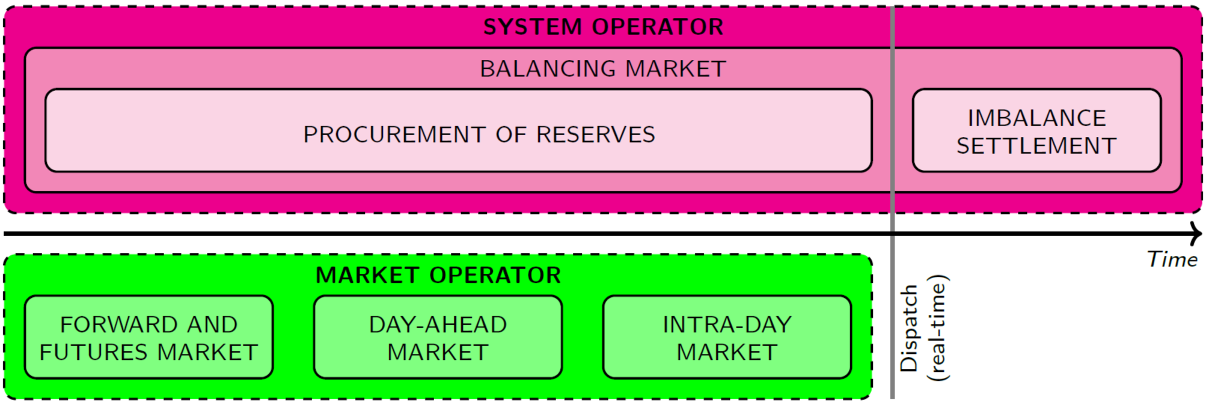

Figure 4: The various electricity markets in terms of operator and temporal resolution, before and after dispatch, adapted from KU Leuven Energy Institute 2015 and Pinson 2018 [PinsND], [TheC15].

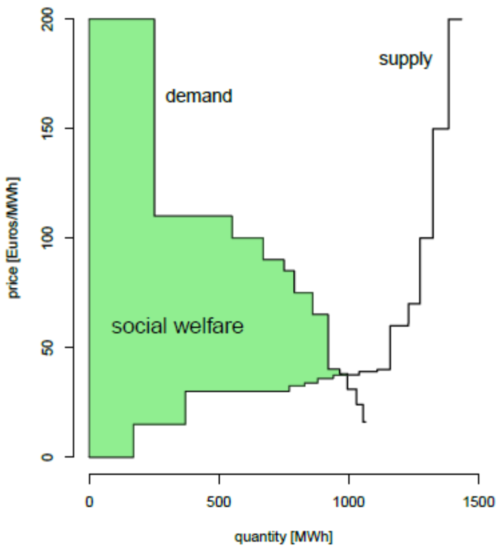

Figure 5: Merit order ranking of supply and demand bids in an electricity market auction, illustrating the equilibrium point and maximisation of the social welfare. Source: Pinson 2018 [Pins18].

nature. Increased investments and utilisation of renewables is important to ensure cheaper electricity for consumers and enable the transition to a low-carbon electricity system.

Objectives

The main research objective of this project is:

> *To develop an open-source, machine learning-based electricity market model for the North Sea region which will help electricity generators, retailers, large consumers, BRPs and system operators in short-term electricity markets (i.e., day-ahead and intra-day markets) to develop operational and bidding strategies that maximise their revenue under uncertainty of VRE generation. The model will consist of a forecaster based on machine learning, which will use high resolution time series weather forecasts for the upcoming period, and recent historical measurements of electricity generation, demand and market prices, to forecast the latter three quantities for the upcoming period. These forecasts will serve as inputs to an optimiser, which maximises social welfare in the electricity market and produces a list of offers, which will be translated into operational strategies.*

Based on the main research objective, the following research questions have been derived:

- What methods and resources are needed to process and store the large volume of high resolution data required for this model?

- What type of machine learning algorithms are suited for the time series forecasting of electricity prices, demand and generation?
- What optimisation methods are suitable for maximising the social welfare problem in the electricity market, and what are the constraints to this optimisation problem?
- What methods can be used to analyse the inputs and outputs of the model and translate them into operational strategies relevant to the market participant?
- How can this model be standardised and published so that it is available for use openly by any participant in the electricity market, as well as other interested parties, such as policymakers?
- How can this high resolution electricity market operational model be integrated with the overall North Sea energy systems model to provide insights on long-term planning and investments in the energy sector?

Regions

Territories in the North Sea region

As per the definition provided by the European MSP Platform [NortND] and the CPMR North Sea Commission [Memb15], the North Sea region consists of eight countries: Belgium, Denmark, France, Germany, Netherlands, Norway, Sweden and United Kingdom.

The nomenclature of territorial units for statistics (NUTS) classifies territorial units in Europe in different levels [NUTSND]:

- NUTS 0: country-level
- NUTS 1: major socio-economic regions
- NUTS 2: basic regions for the application of regional policies
- NUTS 3: small regions for specific diagnoses

As explained in the problem definition section, short-term operational planning and systems with a high penetration of VRE must be described using data of high temporal and spatial resolutions. Therefore, NUTS 3 territories will be used as a standard in this project for aggregating short-term forecasting data.

This Jupyter notebook lists the NUTS territories in the North Sea region at all four NUTS levels. France is the only North Sea country with overseas territories included in the NUTS data (RUP FR - RÉGIONS ULTRAPÉRIPHÉRIQUES FRANÇAISES), so these were removed accordingly.

Performing the forecasting task at NUTS 3 level would be straightforward if it does not include the electricity market. Since the electricity market is considered in this project, it is important to look at how the bidding zones overlap with NUTS 3 territories.

Bidding zones in the North Sea region

A bidding zone is the largest geographical area within which market participants are able to exchange energy without capacity allocation [Bidd14]. According to [Bidd14], there are three types of bidding zones:

1. national borders (e.g., France or the Netherlands) - majority of bidding zones in Europe
2. larger than national borders (e.g., Austria, Germany and Luxembourg or the Single Electricity Market for the island of Ireland)
3. smaller zones within individual countries (e.g., Italy, Norway or Sweden)

The bidding zones in European electricity markets are illustrated in the map below [Tren17].

The power exchanges (market operators) that operate in the North Sea region are EPEX SPOT (Belgium, France, Germany, Netherlands, United Kingdom) and Nord Pool (Denmark, Norway, Sweden, United Kingdom) [Over16], [SeeMND], [EPEXND]. The day-ahead market takes place generally as an hourly auction 24 hours prior to dispatch [Over16]. The intra-day market has continuous trading and will operate until two hours and up to five minutes before dispatch [Over16].

Both Nord Pool and EPEX SPOT are part of the Price Coupling of Regions (PCR) project which aims to develop a single price coupling solution for the calculation of day-ahead electricity prices in Europe, taking into account day-ahead network capacities [PCR&17].

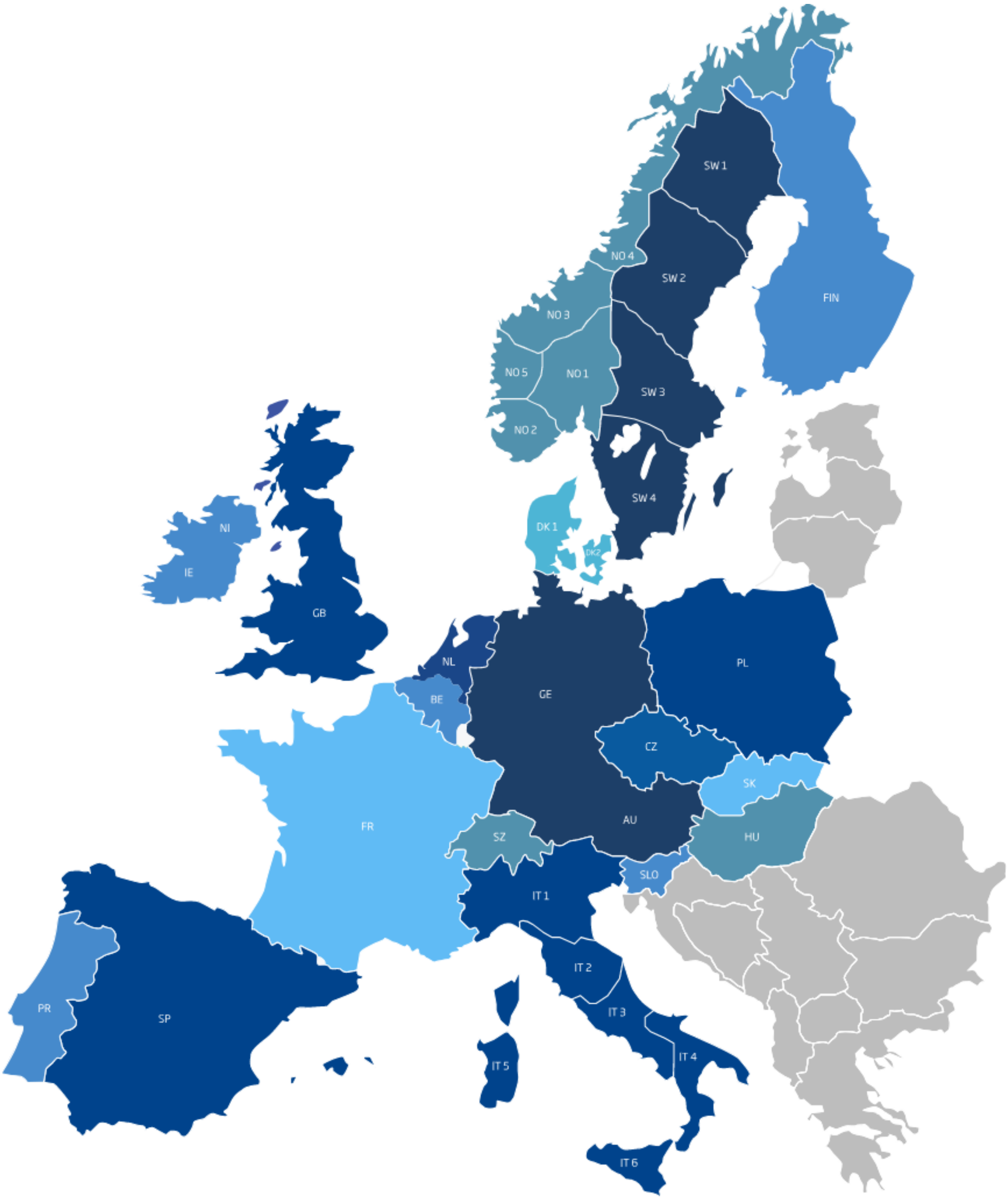

Figure 6: Bidding zones in European electricity markets. Source: Polskie Sieci Elektroenergetyczne [Tren17].

The table below lists all bidding zones in the North Sea region by country and market operator.

Table 2: Bidding zones and market operators in the North Sea region.

Country	Markets	Zones
Belgium (BE)	EPEX SPOT	BE
Germany (DE / GE)	EPEX SPOT	DE-AT-LU[f4]
Denmark (DK)	Nord Pool	DK1, DK2
France (FR)	EPEX SPOT	FR
Netherlands (NL)	EPEX SPOT	NL
Norway (NO)	Nord Pool	NO1, NO2, NO3, NO4, NO5
Sweden (SE / SW)	Nord Pool	SE1, SE2, SE3, SE4
United Kingdom (UK)	EPEX SPOT, Nord Pool	GB, I-SEM[f4]

[f4] *Austria (AT / AU); Luxembourg (LU); Great Britain (GB); Irish single electricity market (I-SEM), which includes Republic of Ireland (IE) and UK's Northern Ireland (NI).*

Mapping bidding zones to NUTS 3 territories is straightforward for Belgium, Germany, France and Netherlands (bidding zone type 1 or 2) – all NUTS 3 territories in these countries have the same bidding

Table 4: TSOs and cross-border interconnections in the North Sea region. Data: European Network of Transmission System Operators for Electricity [ENTSND], [RegiND].

Ctry.[f5]	**TSOs**	**Cross-border interconnection**[f5],[f6]	**Bidding zones**[f5],[f6]
BE	Elia System Operator	FR, LU, NL, UK	BE
DK	Energinet	DE, NO, SE	DK1, DK2
DE	TransnetBW, TenneT TSO, Amprion, 50Hertz Transmission	AT, CH, CZ, DK, FR, LU, NL, PL, SE	CZ+DE+SK, DE-AT-LU, DE-LU
FR	Réseau de Transport d'Electricité	BE, CH, DE, ES, IT, UK	FR
NL	TenneT TSO	BE, DE, NO, UK	NL
NO	Statnett	DK, FI, NL, SE	NO1, NO2, NO3, NO4, NO5
SE	Svenska Kraftnät	DK, FI, DE, LT, NO, PL	SE1, SE2, SE3, SE4
UK	National Grid Electricity Transmission, System Operator for Northern Ireland, Scottish Hydro Electric Transmission, ScottishPower Transmission	BE, FR, IE, NL	GB, IE (SEM)

[f5] *Ctry. - Country; AT - Austria; BE - Belgium; CH - Switzerland; CZ - Czech Republic; DE - Germany; DK - Denmark; ES - Spain; FI - Finland; FR - France; GB - Great Britain; IE - Ireland; IT - Italy; LT - Lithuania; LU - Luxembourg; NL - Netherlands; NO - Norway; PL - Poland; SE - Sweden; SK - Slovakia; UK - United Kingdom; SEM - Single electricity market.*

[f6] *These countries are not part of the North Sea region: AT, CH, CZ, ES, FI, IE, IT, LT, LU, PL.*

Data

Data folder navigation

- ENTSO-E
  - generation and load data for each bidding zone in the North Sea region, grouped by country
- Meteo - meteorological data, grouped by country
- Market - market data for the North Sea region
- NUTS - territorial units
- output - output or modified data from this project

Met data

Deutscher Wetterdienst

- CDC (Climate Data Center) portal
- CDC OpenData
- Terms of use for data on the CDC ftp server
- Data set descriptions
  - Hourly station observations of air temperature at 2 m above ground in °C for Germany
  - Hourly station observations of relative humidity in % for Germany
  - Hourly station observations of precipitation amount in mm for Germany
  - Hourly station observations of form of precipitation (WR code) for Germany
  - Hourly station observations of index whether precipitation has fallen for Germany
  - Hourly mean of station observations of wind speed ca. 10 m above ground in m/s for Germany
  - Hourly mean of station observations of wind direction at ca. 10 m above ground in degree for Germany
  - Hourly station observations of air pressure at station level in hpa for Germany
  - Hourly station observations of air pressure at mean sea level in hpa for Germany
  - Hourly station observations of cloud coverage in eighths for Germany
- Hourly wind data

Royal Netherlands Meteorological Institute

Met Office

Norwegian Meteorological Institute

Swedish Meteorological and Hydrological Institute

Danish Meteorological Institute

Météo-France

The Royal Meteorological Institute of Belgium

Generation and demand data

ENTSO-E Transparency Platform

- GENERAL TERMS AND CONDITIONS FOR THE USE OF THE ENTSO-E TRANSPARENCY PLATFORM
- LIST OF DATA AVAILABLE FOR FREE RE-USE
- Downloaded data:
  - Actual Generation per Production Type
  - Total Load - Day Ahead / Actual

Market data

Nord Pool

- Membership list - Nord Pool
- Terms and conditions for use

EPEX Spot

- EPEX SPOT Exchange Members

Other data

NUTS (Nomenclature of territorial units for statistics)

Methodology

Modelling framework

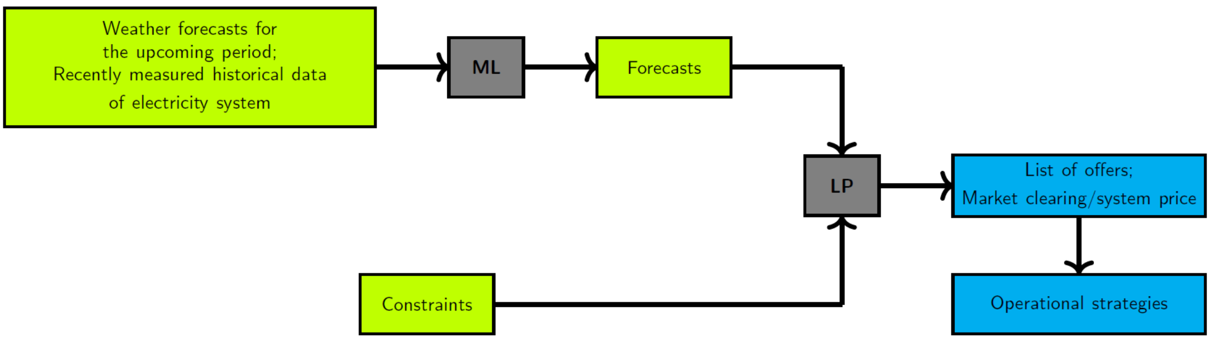

Figure 7: Modelling framework. License: CC BY-SA 4.0.

Data management

Time series forecasting

Market optimisation

Translating inputs and outputs into operational strategies

Standardisation and publication of model

Integrating operational time scales with long-term energy systems models

Glossary

Abbreviations

- AI - artificial intelligence
- BRP - balance responsible party
- CAPEX - capital expenditure
- CO_2 - carbon dioxide
- COMPETES - COmprehensive Market Power in Electricity Transmission and Energy Simulator
- DC - direct current
- DNO - distribution network operator
- DSM - demand-side management
- EMMA - The European Electricity Market Model
- ENSYSTRA - ENergy SYStems in TRAnsition
- ENTSO-E - European Network of Transmission Systems Operators for Electricity
- ESR - early-stage researcher
- ETSAP - Energy Technology Systems Analysis Program
- EU - European Union
- GAMS - General Algebraic Modeling System
- GHG - greenhouse gas
- IEA - International Energy Agency
- IRENA - International Renewable Energy Agency
- IRiE - Integrated Regulating power market in Europe
- JRC-IDEES - Joint Research Centre Integrated Database of the European Energy System
- MARKAL - MARKet ALlocation
- NREL - National Renewable Energy Laboratory
- NUTS - Nomenclature of territorial units for statistics
- O&M - operation and maintenance
- openmod - Open Energy Modelling Initiative
- OPEX - operational expenditure
- PCR - Price Coupling of Regions
- PhD - Doctor of Philosophy
- renpass - Renewable Energy Pathways Simulation System
- stELMOD - Stochastic Electricity Market Model
- TIMES - The Integrated MARKAL-EFOM System
- TSO - transmission system operator
- UiS - University of Stavanger
- VRE - variable renewable energy
- WP - work package

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