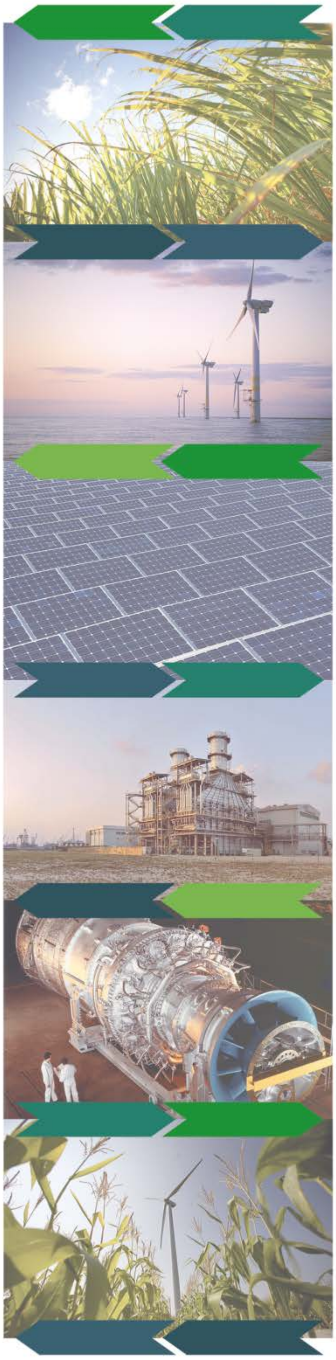
NAVIGATING THE ROADMAP FOR CLEAN, SECURE AND EFFICIENT ENERGY INNOVATION



Documentation and Guidelines to use the EMPIRE Model

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A report compiled within the H2020 project SET-Nav

www.set-nav.eu

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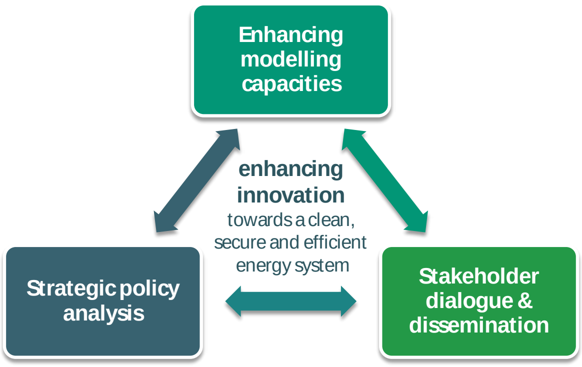
About the project

SET-Nav aims for supporting strategic decision making in Europe's energy sector, enhancing innovation towards a clean, secure and efficient energy system. Our research will enable the European Commission, national governments and regulators to facilitate the development of optimal technology portfolios by market actors. We will comprehensively address critical uncertainties facing technology developers and investors, and derive appropriate policy and market responses. Our findings will support the further development of the SET-Plan and its implementation by continuous stakeholder engagement.

These contributions of the SET-Nav project rest on three pillars: modelling, policy and pathway analysis, and dissemination. The call for proposals sets out a wide range of objectives and analytical challenges that can only be met by developing a broad and technically-advanced modelling portfolio. Advancing this portfolio is our first pillar. The EU's energy, innovation and climate challenges define the direction of a future EU energy system, but the specific technology pathways are policy sensitive and need careful comparative evaluation. This is our second pillar. Ensuring our research is policy-relevant while meeting the needs of diverse actors with their particular perspectives requires continuous engagement with stakeholder community. This is our third pillar.



Who are we?

The project is coordinated by Technische Universität Wien (TU Wien) and being implemented by a multinational consortium of European organisations, with partners from Austria, Germany, Norway, Greece, France, Switzerland, the United Kingdom, France, Hungary, Spain and Belgium.

The project partners come from both the research and the industrial sectors. They represent the wide range of expertise necessary for the implementation of the project: policy research, energy technology, systems modelling, and simulation.

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Table of Contents

1 Introduction

The EMPIRE Model is a stochastic linear programming model to analyze developments of the European power market. It was created as part of C. Skar's doctoral thesis and has been used to analyze decarbonization of the European power system focusing on the supply side of the power market. The purpose of the model is to support long-term capacity expansion of the power system under short-term operational uncertainty with a special focus of representing variable RES, namely wind, solar and hydro power. Energy demand, as well as investment options for energy supply technologies, their related costs and operational characteristics, are exogenous input data in the model. The output supports decisions regarding technology choices, investment volume and investment timing with requirements of ensuring a reliable energy system at minimum cost. The model output also supports short-term operational decisions of energy system components under uncertainty. The model is subject to operational uncertainty, so the stochastic scenarios represent different operational realizations of these data. The following input is uncertain in EMPIRE: (1) Availability of variable generation (wind and solar), (2) availability of hydro reservoirs and (3) electricity demand.

This Documentation is containing three sections.

Firstly, it will explain where to download and run the EMPIRE Model. It will describe the licensing and how to contribute working on EMPIRE. Furthermore, it will give a short overview about the mathematical formulation and the preprocessed calculations.

Secondly, the Documentation will give a detailed explanation about the input data. This contains information about the input structure, as well as different kinds of data. The input data can be provided as Excel files, or as .tab files, which is also further explained in this chapter.

Lastly, you will find a description of where the output data is stored and what kind results EMPIRE produces. It also shows possibilities to visualize and how to interpret them.

2 The EMPIRE Model

This section provides information about everything that's needed to run and edit the EMPIRE model. It shows where its stored and what additional software is needed. You will also find a license overview and an overview on the mathematical description.

2.1 Git-Repository

EMPIRE consists of two main programming scripts:

(1) generation script that transforms input data from Excel-Files to .tab-files
(2) an abstract model script to build, solve and generate results

Both scripts can be downloaded from the Git repository called EMPIRE-Pyomo: https://github.com/stianbacke/OpenEMPIRE.

In this repository the Data handler folder contains the Excel workbooks that are used to store and modify data.

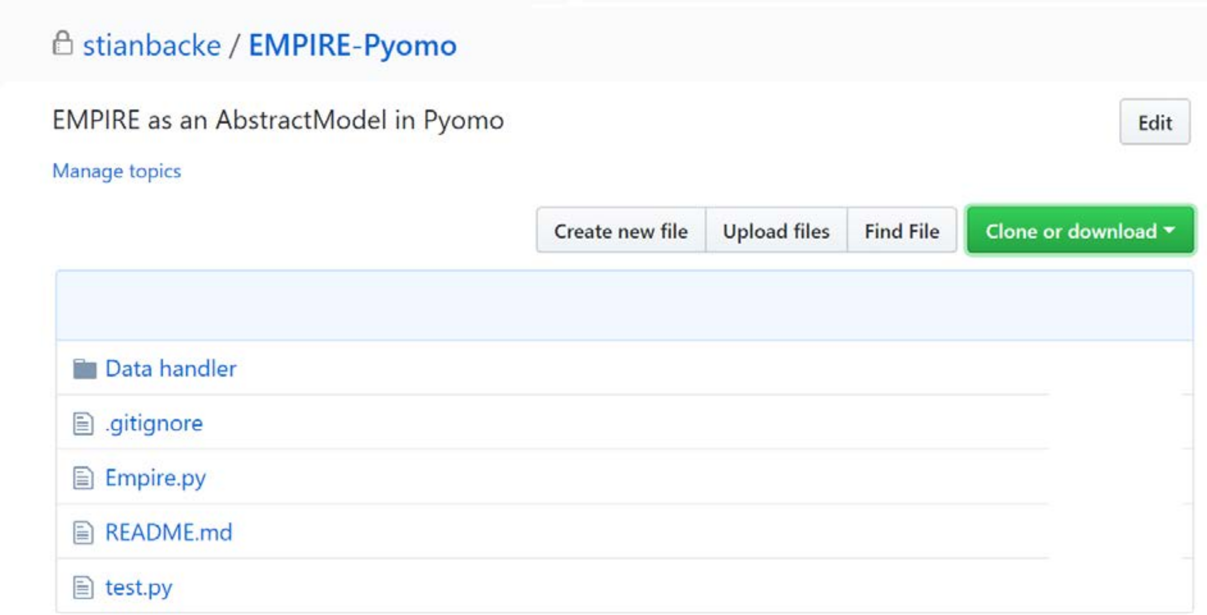


Figure 1 EMPIRE in the GitHub repository. To download, press the green button.

The script for building, solving and generating results is called 'Empire.py'. An additional script called 'test.py' can be used to test the model with random dummy data and does not read any external input (all input is initialized in the script). This is useful to test if Pyomo and a third-party solver is installed properly.

The script for generating input data is called 'reader.py' and is in the folder 'Data handler'. The script 'reader.py' reads Excel workbooks where the needed data is stored and generates the tab-files, which are the input for the EMPIRE model. There is an additional script called 'Input_Script.py' that defines functions for 'reader.py'.

2.2 Licensing

The EMPIRE model and all additional files in the git repository are licensed under the MIT license. In short, that means you can use and change the code of empire, but always must make sure to track your changes, before reuploading it. Furthermore, you can change the license in your redistribution but must mention the original author. We appreciate, if you inform us about changes and send a merge request via git.

For further information please read the LICENSE file, which contains the license text, or go to https://opensource.org/licenses/MIT

2.3 Required Software

The EMPIRE model is available in the Python-based, open-source optimization modelling language Pyomo. To run the model, make sure Python, Pyomo and a third-party solver like SCIP or CPLEX is installed and loaded to the respective computer or cluster. More information on how to install Python and Pyomo can be found here: http://www.pyomo.org/installation.

2.4 Running

When all Pyomo and the preferred solver has been installed, the model is run by running the script 'Empire.py' in a Python interface. Make sure the .tab-files to be used for input are in the same folder as the script 'Empire.py'. The code is run by using the following commands:

```
C:\Users\name> cd <path_to_folder>                   #Change directory
C:\Users\name\path_to_folder> python Empire.py       #Run the code
```

Note that building the instance in Pyomo for a base case of EMPIRE can take around 40 min. Therefore, it is good to run the 'test.py' first to confirm whether your computer or cluster connects to the preferred solver or not.

2.5 Mathematical Description

EMPIRE is a multi-horizon stochastic linear program, and it has been designed to support capacity expansion of the power system. The model represents a network of nodes and arcs where decisions are made in two temporal scales: investment time steps and operational time steps. Operational decisions are subject to uncertainty that is discretized in several stochastic scenarios.

The abstract stochastic programming model can be formulated in the following way:

$$
\begin{aligned}
\min z = \sum_{i \in \mathcal{I}} \delta_i \big(c_i x_i + \vartheta \sum_{\omega \in \Omega} \pi_\omega \sum_{h \in \mathcal{H}} q_i y_{i,h,\omega}\big) \quad && (1) \\
s.t. \quad a_i x_i \le b_i, \quad & i \in \mathcal{I}, & (2) \\
x_i \ge 0, \quad & i \in \mathcal{I}, & (3) \\
w_i y_{i,h,\omega} + t_{i,h,\omega} x_i \le h_{i,h,\omega}, \quad & i \in \mathcal{I},\ h \in \mathcal{H},\ \omega \in \Omega, & (4) \\
y_{i,h,\omega} \ge 0, \quad & i \in \mathcal{I},\ h \in \mathcal{H},\ \omega \in \Omega. & (5)
\end{aligned}
$$

where the set $\mathcal{I}$ represents investment periods, the set $\mathcal{H}$ represents operational periods and the set Ω represents a set of operational scenarios. The variables x_i represent investment decisions in investment period $i \in I$, while the variables $y_{i,h,\omega}$ represent operational decisions in operational period $h \in \mathcal{H}$ and scenario $\omega \in \Omega$ within investment period $i \in \mathcal{I}$. These variables are also dependent on node (location) and asset type (generator, storage, transmission).

The expression (1) is the objective function identifying total costs for investing and operating assets in the system. The total costs are quantified by summing over all time periods, both investment and operational. The term $\delta_i = (1+r)^{-n(i-1)}$ discounts all future costs at an annual discount rate of r with n years in between each investment period such that all costs are given with respect to the value in the first investment period. The term $\vartheta = \alpha \sum_{j=0}^{n} (1+r)^{-j}$ scales operational costs to annual values through α and discounts this annual operational cost n years ahead (until the next investment period). The input c_i represent investment costs and q_i represent operational costs in investment period $i \in \mathcal{I}$. Since the operational decisions are subject to uncertainty, the operational costs in (1) represent the *expected* operational costs by scaling with π_ω representing the probability that scenario $\omega \in \Omega$ will occur.

Constraints (2)-(3) make sure investments in all assets are bounded, that the lifetime of the asset is considered across the investment periods and that there are no negative investments. Constraints (4)-(5) make sure operation of assets is bounded by investment decisions and asset availability, that supply balances demand (and possibly lost load), that energy levels in storages is balanced, that thermal generators have limited up-ramping capabilities, that policies (e.g. emission caps) are respected and that operation of assets is not negative. The input w_i represent type dependent operational specifications for assets, while $t_{i,h,\omega}$ represent scenario dependent operational specifications. The latter input data affect the value of investment decisions in different operational scenarios.

For a more detailed mathematical formulation, see https://www.ntnu.edu/web/iot/empire

The EMPIRE formulation supports investment decisions in power generation, storage and transmission with an objective of minimizing total system cost (simulates perfect competition). The strength of the model is that these investment decisions are made linked with the operation of the assets to satisfy demand.

EMPIRE is generally used to investigate pathways for decarbonizing the power sector in Europe. However, this is instance specific, meaning the abstract model could be used for other places than

Europe or other sectors than power (e.g. capacity expansion of a gas system) that can be modelled as a network flow.

3 Input Data

The EMPIRE Model reads text files with ending '.tab', which provide all needed sets and data. For editing and storing the data excel files can used. If the excel files are used, the text files must be generated before starting EMPIRE.

There are excel input files in total of which eight contain actual data and one is to provide the sets. The data excel files are sorted by the following themes: Generation Technologies, Transmission between Countries, Storage Technologies, Seasonal Data, Stochastic Data, and the use in each Country (Node). These files contain multiple tables regarding for example investment costs and capacity.

In the following, the content of the data files and the set file is described. Therefore, the general structure of all files is given. Afterwards, one will have a closer look at each file and the contained tables.

3.1 Structure of the Input Files

For the structure we must differentiate between the data files and the set file. The difference between these two file types, is that where in the data files actual values are given to different combination of variables (e.g. Technologies and Countries as variables and the belonging investment costs as values), in the set file only the names of the variables are stored within groups.

Every Excel data file contains multiple worksheets. In every sheet is exactly one data table and some additional data. The first row in every sheet is for the source, where the data is from; the second one is for a brief description of the table. The rows beneath contain the table with header and values.

Therefore, the tables are looking like the table beneath, with different numbers of columns and values.

Source		
Description		
Column Name 1	Column Name 2	Value
Entry 1.1	Entry 2.1	value 1
Entry 1.2	Entry 2.2	value 2

The following part is only necessary, if we plan to public our data. Otherwise this should be written as a suggestion for calculated data.

Some of the values are not given plain but need calculations before given into the EMPIRE model. Hence, there is a calculation file. Within this, data is stored that is needed for a variation of calculations which are made in the model building phase of EMPIRE.

The structure of the set file is quite different. Instead of a table each sheet, the sheets are separated by groups. There are two different kinds of sheets. In the first kind are some columns filled with the names of variables. Every sheet contains a group and every column a type of this group (e.g. Group Storage with types Dependent Storage, etc.). The other kind of sheets contain existing connections between different (or the same) groups (e.g. Technologies per Country).

3.2 Description of the Input Files

3.2.1 Sets

The set file contains is for defining all variables used in the model. Each sheet contains another group of variables or existing connection between variables. One can add more variables to these columns. Every variable used in the data files must be defined in this file.

In the following the six different groups of variables and a short description of them is given:

- **Nodes**
  This sheet contains one column. The name of the column is 'Node' and it contains all countries that should be used in the model
- **Times**
  This sheet contains all variables that have time reference. It is divided into five columns:
  - **Period:** years to be calculated, represented as numbers (1:= 2010 to 9:=2050)
  - **Operational Hour:**
  - **Season**
  - **Scenario:** names of scenarios that can be used within EMPIRE
- **Storage**
  This sheet contains different four types of energy storages and one column with all of them:
  - **Storage:** This column contains all types of used storages, that are additionally categorized in the other columns
  - **Dependent Storage**
- **Technologies**
  This sheet contains all the technologies for generating energy in one column
- **Generator**
  This sheet contains all types of generators that can be used in the model. They may rely on the same technology.
  - **Generator:** This column contains all types of used storages, that are additionally categorized in the other columns
  - **Hydro Generator**
  - **Hydro Generator with Reservoir**
  - **Thermal Generators**

- **Line Type**
  This sheet contains different line types

Additionally, to the sheets for initializing variables, there are sheets for defining assignments between different variables. Each sheet contains two columns with the values assigned to each other.

- **Hours of Season**: existing hours in a season
- **Storage at Nodes:** available storages per country
- **Directional Lines:** existing Connections between countries
- **Line Type of Directional Lines:** existing line types at the connection between countries
- **Generators of Node:** available generators per country
- **Generators of Technologies:** usable generators with a technology

3.2.2 Generator

The file Generator.xlsx' contains different data regarding the generator technologies. It covers the following categories, stored in separate sheets:

- **Capital Costs**
  - This sheet contains the amount of capital costs per MW of all generator technologies in all defined periods. Therefore, it contains three colums:
    - Generator Technology
    - Period
    - Capital Costs in Euro per MW
- **Fixed OM Costs**
  - This sheet contains the fixed annual operation and maintenance costs for generator technologies in euro per MW. Therefore, it contains three columns:
    - Generator Technology
    - Period
    - Fixed OM Costs in Euro per MW
- **Variable OM Costs**
  - This sheet contains the operation dependent operation and maintenance costs for generator types in euro per MW. Therefore, it contains three columns:
    - Generator Technology
    - Variable OM Costs in Euro per MW
- **Fuel Costs**
  - This sheet contains period dependent fuel costs for generator technologies. Therefore, it contains three columns:
    - Generator Technology
    - Period
    - Fuel Costs in Euro per GJ
- **CCS Costs TS Variable**
  - This sheet contains costs of transporting and storing captured CO2. Therefore, it contains two columns:

    - Period
    - CCS TS costs in euro per tCO2
- **Efficiency**
  - This sheet contains efficiency of converting fuel to electricity for generator types in each period. Therefore, it contains three columns:
    - Generator Technology
    - Period
    - Generator Efficiency
- **Ref Initial Cap**
  - This sheet contains the capacity in the reference investment period (2015). Therefore, it contains three columns:
    - Node
    - Generator Technology
    - Generator Reference Initial Capacity in MW
- **Scale Factor Initial Cap**
  - This sheet contains the share of capacity that retired compared to the reference period (2015). Therefore, it contains three columns:
    - Generator Technology
    - Period
    - Generator Retirement Factor Initial Capacity
- **Initial Capacity**
  - This sheet contains the capacity in the investment period (2015). Therefore, it contains four columns:
    - Node
    - Generator Technology
    - Period
    - Generator initial Capacity in MW
- **Maximum Built Capacity**
  - This sheet contains the capacity in MW for all generators in all defined countries and periods that can maximally be built. Therefore, it contains four columns:
    - Node
    - Generator Technology
    - Period
    - Maximum Built Capacity in MW
- **Maximum Installation Capacity**
  - This sheet contains the maximum capacity that can exist of a generator. Therefore, it contains three columns:
    - Node
    - Generator Technology
    - Maximum Installed Capacity in MW
- **Ramp Rate**
  - This sheet contains the maximum change of output from one hour to the previous one for thermal generators. Therefore, it contains two columns:
    - Thermal Generator

  - Ramp Rate
- **Generator Availability**
  - This sheet contains an availability factor for all defined generators. Therefore, it contains two columns:
    - Generator
    - Availability
- **CO2 Content**
  - This sheet contains the CO2 intensity of generator type depending on fuel. Therefore, it contains two columns:
    - Generator Technology
    - CO2 Content in tCO2/GJ
- **Lifetime**
  - This sheet contains the Lifetime of a generator type in years. Therefore, it contains two columns:
    - Generator Technology
    - Lifetime

3.2.3 Nodes

The file Node.xlsx' contains the data for interconnections between all specified countries. These categories are stored in separate sheets:

- **Node Lost Load Cost**
  - This sheet contains the cost of not generating electricity in an hour
  - . Therefore, it contains the following columns:
    - Node
    - Period
    - Node Lost Load Cost
- **Electric Annual Demand**
  - This sheet contains the annual demand in nodes used to adjust hourly load profiles. Therefore, it contains the following columns:
    - Nodes
    - Period
    - Electric Adjustment in MW per hour

3.2.4 General

The file 'General.xlsx' contains the data the scale factor for all defined seasons. These can be the four regular ones or additionally, peak seasons. It contains only one table with the season listed and the corresponding scales.

- **Season Scale**
  - This sheet contains the annual scaling of each representative season. Therefore, it contains the following columns:
    - Season

        - Season Scale
- **CO_2 Cap**
    - This sheet contains the maximum allowed annual emissions for an investment period. Therefore, it contains the following columns:
        - Period
        - CO2 Cap (in kton CO2)
- **CO2 Price**
    - This sheet contains the assumed CO2 price from the EU ETS. Therefore, it contains:
        - Period
        - CO2 price in euro per tCO2

3.2.5 Stochastic

- **Electric Load Raw**
    - This sheet contains an hourly load profile for representative seasons. Therefore, it contains four columns:
        - Node
        - Operational Hour
        - Scenario
        - Electric Load in MW
- **Stochastic Availability**
    - This sheet contains the hourly (maximum) availability of non-dispatchable generation. Therefore, it contains five columns:
        - Node
        - Intermittent Generators
        - Operational Hour
        - Scenario
        - Generator Stochastic Availability
- **Hydro Generator Maximum Seasonal Production**
    - This sheet provides the maximum production of hydro generators with reservoir in different scenarios for all defined countries, seasons and operational hours. Currently, there is only one of these generators, so there is no extra column for it. If one has more of these, they have to add another column. Therefore, it contains five columns:
        - Node
        - Season
        - Operational Hour
        - Scenario
        - Production
- **Hydro Generator Maximum Annual Production**
    - This sheet provides the maximum production of hydro generators with reservoir per year. Currently, there is only one of these generators, so there is no extra column for it. If one has more of these, they have to add another column. Therefore, it contains two columns:
        - Node
        - Production

3.2.6 Storages

The file 'Storage.xlsx' contains different data regarding the storage technologies. It covers the following categories, stored in separate sheets:

- **Power Initial Capacity**
  - This sheet provides the initial capacity of power storages for all periods. Therefore, it contains the following three columns:
    - Nodes
    - Storage Types
    - Period
    - Initial Capacity
- **Power Capital Costs**
  - This sheet provides the capital cost for investing in power storage. Therefore, it contains the following three columns:
    - Storage Type
    - Period
    - Capital Cost in Euro per MW
- **Power Fixed OM Costs**
  - This sheet provides the fixed operation and maintenance cost for investing in power storage. Therefore, it contains the following three columns:
    - Storage Type
    - Period
    - Fixed OM Costs in Euro per MW
- **Power Max Built Capacity**
  - This sheet provides the maximum capacity of power storages that can be built in a period. Therefore, it contains the following three columns:
    - Nodes
    - Storage Types
    - Period
    - Max Built Capacity
- **Power Max Installed Capacity**
  - This sheet provides the maximum of installed capacity of power storages. Therefore, it contains the following three columns:
    - Nodes
    - Storage Types
    - Max installed Capacity
- **Energy Capital Costs**
  - This sheet provides the capital cost for investing in energy storage. Therefore, it contains the following three columns:
    - Storage Type
    - Period

  - Capital Cost in Euro per MW
- **Energy Fixed OM Costs**
  - This sheet provides the fixed operation and maintenance cost for investing in energy storage. Therefore, it contains the following three columns:
    - Storage Type
    - Period
    - Fixed OM Costs in Euro per MW
    -
- **Energy Initial Capacity**
  - This sheet provides the initial capacity of energy storages for all periods. Therefore, it contains the following three columns:
    - Nodes
    - Storage Types
    - Period
    - Initial Capacity
- **Energy max Built Capacity**
  - This sheet provides the maximum capacity of energy storages that can be built in a period. Therefore, it contains the following three columns:
    - Nodes
    - Storage Types
    - Period
    - Max Built Capacity
- **Energy Max Installed Capacity**
  - This sheet provides the maximum of installed capacity of energy storages. Therefore, it contains the following three columns:
    - Nodes
    - Storage Types
    - Max installed Capacity
- **Storage Initial Energy Level**
  - This sheet provides the initial energy level of a storage as a percentage of the installed Energy Capacity. Therefore, it contains two columns:
    - Storage Type
    - Initial Energy Level as percentage of Installed Energy Capacity
- **Storage Charge Efficiency**
  - This sheet contains the efficiency of charging a storage (non-spillage during charging). Therefore, it contains the following columns:
    - Storage Type
    - Storage Charging Efficiency
- **Storage Discharge Efficiency**
  - This sheet contains the efficiency of discharging a storage (non-spillage during discharging). Therefore, it contains the following columns:
    - Storage Type

        - Storage Discharging Efficiency
- **Storage Power to Energy**
    - This sheet contains the required ratio between installed power and energy storage. Therefore, it contains the following columns:
        - Storage Type
        - Storage Ratio
- **Storage Bleed Efficiency**
    - This sheet contains the hourly percentage of spillage. Therefore, it contains the columns:
        - Storage Type
        - Storage Bleed Efficiency
- **Lifetime**
    - This sheet contains the lifetime in years of storages. Therefore, it contains the columns:
        - Storage Type
        - Lifetime

3.2.7 Transmissions

Names of the File, number of contained tables, does it contain calculations

- **Line Efficiency**
    - This sheet provides information on the efficiency of delivering electricity to demand in percent of the lines interconnecting the nodes. Therefore, it contains three columns:
        - From Node: Original Country
        - To Node: Destination Country
        - Line Efficiency: Percentage of sent energy that reaches destination. This is a way to account for losses.

- **Max Install Capacity**
    - This sheet provides the maximum allowed capacity of transmission between nodes in the given investment period. Therefore, it contains four columns:
        - From Node
        - To Node
        - Period
        - Max Install Capacity in MW
- **Length**
    - This sheet contains the assumed length of transmission lines between two nodes
        - From Node
        - To Node
        - Line length in km
- **Line Type Capital Costs**
    - This sheet contains the cost per MWkm of investing in a transmission with a given line type. Therefore, it contains three columns:

    - Line Type
    - Period
    - Type Capital Costs in Euro per MWkm
- Line Type Fixed OM Cost
  - This sheet contains the cost for operation and maintenance of transmission lie types. Therefore, it contains three columns:
    - Line Type
    - Period
    - Fixed OM Cost in Euro per MW
- **Maximum Built Capacity**
  - This sheet provides information about the already built transmission capacity in the system. It contains 4 columns:
    - InterconnectorLinks: Original Country
    - To Node: Destination Country
    - Period
    - Transmission Maximum Built Capacity

- **Initial Capacity**
  - This sheet provides information about the initial transmission capacity. It contains 4 columns:
    - InterconnectorLinks: Original Country
    - To Node: Destination Country
    - Period
    - Transmission Initial Capacity
- Lifetime
  - This sheet contains the lifetime of Transmission Lines in years. Therefore, it contains the following columns:
    - From Node
    - To Node
    - Lifetime

3.3 Calculation

Before building the model, calculations have to take place with parts of the given input data. The calculation is wrote in python within the EMPRIE code. The formulas are described here to explain how to achieve the final input data.

- **WACC (ProjectDiscountRate)**
  - The sheet, WACC, presents the value of project discount rate. It contains one column.
      - WACC

- *This Data is used for the following calculations:*
  - ✓ *Investment Costs Generator*
  - ✓ *Generator Marginal Costs*
  - ✓ *Storage Power Investment Costs*
  - ✓ *Storage Electric Investment Costs*

✓ *Transmission Investment Cost*

- **Discount Rate**
  - The sheet, DiscountRate, presents the value of discount rate. It contains one column.
    - DiscountRate *(D)*

- *This Data is used for the following calculations:*
  - ✓ *Investment Costs Generator*
  - ✓ *Generator Marginal Costs*
  - ✓ *Storage Power Investment Costs*
  - ✓ *Storage Electric Investment Costs*
  - ✓ *Transmission Investment Cost*

- **Retirement Generator**
  - The sheet, RetirementGenerator, indicates the retirement factor for different nodes, generator technology and period. It contains four columns.
    - Node
    - Generator Technology
    - Period
    - RetirementFactor *(RF)*

- *This Data is used for the following calculations:*
  - ✓ *Generator Initial Capacity*

- **CCS Rem Frac Generator**
  - The sheet, CCSRemFracGenerator, indicates the • CCS Rem Frac factor for different generator technology and period. It contains three columns.
    - Generator Technology
    - Period
    - CCSRemFrac *(CR)*

- *This Data is used for the following calculations*
  - ✓ *Investment Costs Generator*
  - ✓ *Generator Marginal Costs*

- **CO2 Content Generator (CCG)**
  - The sheet, co2ContentGenerator, is used to calculate the generated CO2/MWh for all defined generators. Therefore, it contains four columns:
    - Generator
    - Period
    - Tech Heat Rate [GJ/MWh] (*THR)*
    - CO2 Content [tCO2/GJ] (*CO)*

- Calculation formula

$$CCG = THR * (1 - CO)$$

- *This Data is used for the following calculation:*
  - ✓ *Investment Costs Generator*
  - ✓ *Generator Marginal Costs*

- **Lifetime Generator**
  - The sheet, LifetimeGenerator, presents the lifetime of the generators. Therefore, it contains the following columns:
    - GeneratorTechnology
    - Lifetime [year] *(L_G)*

- *This Data is used for the following calculations:*
  - ✓ *Investment Costs Generator Storage*

- **Lifetime Storage**
  - The sheet, LifetimeStorage, presents the lifetime of electricity to heat. Therefore, it contains the following columns:
    - StorageTechnology
    - Lifetime [year] *(L_S)*

- *This Data is used for the following calculations:*
  - ✓ *Storage Power Investment Costs*
  - ✓ *Storage Electric Investment Costs*

- **Lifetime Transmission**
  - The sheet, LifetimeTransmission, presents the lifetime transmissions. Therefore, it contains the following columns:
    - FromNode
    - ToNode
    - Lifetime [year] *(L_{TM})*

- *This Data is used for the following calculations:*
  - ✓ *Transmission Investment Cost*

- **Investment Costs Generator (ICG)**
  - The sheet, InvestmentCostsGenerator, calculates the investment costs per MW for all defined generators in all periods. Therefore, it contains six columns
    - Converter Technology
    - Period *(P)*
    - Capital Costs *(C)*
    - Fixed O&M *(F)*
    - CCS T&S Fix *(CF)*

- Calculation formula

$$ICG = \left(\frac{1-(1+D)^{-min((9-P+1)*5,L_G)}}{1-\frac{1}{1+D}}\right)\left(\frac{WACC}{(1+WACC)-(1+WACC)^{(1-,L_G)}}C+F\right)*1000*CF*CR*THR*CO$$

- *WACC (project discount rate) is presented in the sheet "WACC" which described above.*
- *D (discount rate) is presented in the sheet "Discount Rate" which described above.*
- *THR and CO is the column value which is presented in sheet "CO2 Content Generator" described above*
- *CR is the column value which is presented in sheet "CCS Rem Frac Generator" described above*
- L_G *(Lifetime storage) is presented in the sheet "Lifetime storage" which described above.*
-

$$L_G$$

- **Generator Marginal Costs (GMC)**
  - This sheet, GeneratorMarginalCosts, is used to calculate the marginal costs in Euro per MW for all generators in all defined periods. Therefore, it contains seven columns:
    - Generator Technology
    - Period
    - CCS_T&S *(CT)*
    - Variable O&M *(V)*
    - Fuel Type *(FT)*
    - Fuel Price *(FP)*
    - CO2 Price *(CP)*
  - Calculation formula

$$GMC = \begin{cases} V + THR * (FP + (1-CR) * \mathrm{CP} * CO) + (CF * CO * CR * CT); & FT > 0 \\ V; & FT < 0 \end{cases} FT$$

- *THR and CO is the column value which is presented in sheet "CO2 Content Generator" described above*
- *CR is the column value which is presented in sheet "CCS Rem Frac Generator" described above*

- **Generator Initial Capacity (GIC)**
  - The sheet, InitialCapacity2015Generator, is used to calculate the initial capacity in MW for all defined countries and periods. Therefore, it contains three columns:
    - Node
    - Generator Technology
    - Initial Capacity 2015 (*IC)*
  - Calculation formula

$$GIC = IC * (1 - RF)$$

- *RF is the column value which is presented in sheet "Retirement Factor" described above*

- **Node Electric Demand (NED)**

- The sheet, NodeElectricDemand, is used to calculate the demand of electricity in MHw per hour. Therefore, it contains the following columns:
    - Nodes
    - Period
    - Node Annual Demand [MWh/year]
    - Average annual demand [MWh/h]: (*Aad)*
    - Average base-profile demand [MWh/h]: (*Abd)*

- Calculation formula

$$NED = Aad - Abd$$

- **Storage Power Investment Costs (SPIC)**
    - The sheet, InvestmentCostsPowerStorage, is used to calculate the investment of power storages for all periods. Therefore, it contains the following five columns:
        - Storage Types
        - PWCapitalCost [€/kWh] *(PC)*
        - PWFixedO&M [€/kWh] *(PF)*
        - Period *(P)*

    - Calculation formula

$$SPIC = \begin{cases} \left(\frac{WACC}{(1 + WACC) - (1 + WACC)^{(1-L_s)}} PC + PF\right)\left(\frac{1-(1+D)^{-min((9-P+1)*5, L_s)}}{1-\frac{1}{1+D}}\right) * 1000; & L_s > 0 \\ 0; & L_s < 0 \end{cases}$$

- *WACC (project discount rate) is presented in the sheet "WACC" which described above.*
- *D (discount rate) is presented in the sheet "Discount Rate" which described above.*
- *L_s (life time of storage) is presented in the sheet "lifetime storage" which described above*

- **Storage Electric Investment Costs (SEIC)**
    - The sheet, InvestmentCostsElectricStorage, is used to calculate the investment of Electric storages for all periods. Therefore, it contains the following five columns:
        - Storage Types
        - ENCapitalCost [€/kWh] *(EC)*
        - ENFixedO&M [€/kWh] (*EF)*
        - Period *(P)*

    - Calculation formula

$$SEIC = \begin{cases} \left(\frac{WACC}{(1 + WACC) - (1 + WACC)^{(1-L_s)}} EC + EF\right)\left(\frac{1-(1+D)^{-min((9-P+1)*5, L_s)}}{1-\frac{1}{1+D}}\right) * 1000; & L_s > 0 \\ 0; & L_s < 0 \end{cases}$$

- *WACC (project discount rate) is presented in the sheet "WACC" which described above.*

- *D (discount rate) is presented in the sheet "Discount Rate" which described above.*
- *L_s (life time of storage) is presented in the sheet "lifetime storage" which described above*

- **Transmission Maximum Installed Capacity (TMIC)**
  - The sheet, MaxInstallCapacityTransmission, provides calculations to assess the maximum installed capacity. It contains 5 columns:
    - InterconnectorLinks: Original Country
    - To Node: Destination Country
    - Period
    - Max Raw Not Adjust With InitCap [MWh] *(MR)*
    - Transmission Initial Capacity [MWh] *(TIC)*
  - Calculation formula

$$TMIC = \begin{cases} MR; & MR \geq TIC \\ TIC; & MR < TIC \end{cases}$$

- **Transmission Investment Cost (TIC)**
  - The sheet, InvestmentCostsTransmission, is used to calculate the investment costs. It contains 7 columns:
    - InterconnectorLinks: Original Country
    - To Node: Destination Country
    - Period
      - TypeCost *(TC)*
      - LineLength *(LL)*
      - FixedO&M *(Fom)*
      - Period *(p)*
  - Calculation formula

$$TIC = \left[\frac{\text{WACC}}{\left((1+\text{WACC})-(1+\text{WACC})^{(1-L_{TM})}\right)*TC*LL+Fom}\right]*\frac{(1-(1+TC)^{L_{TM}})}{1-\frac{1}{1+D}}$$

- *WACC (project discount rate) is presented in the sheet "WACC" which described above.*
- *D (discount rate) is presented in the sheet "Discount Rate" which described above.*
- *L_{TM}(lifetime transmission) is presented in the sheet "lifetime transmission" which described above.*

4 Output Data

4.1 Output Files

EMPIRE's standard output encompasses nine csv files containing all relevant results. Each file contains one or several tables with figures ordered by year, technology, country, etc. The most common recurring categories amongst all worksheets are:

Name	Meaning	Unit	Availability
ExpectedAnnualCurtailment_GWh:	Expected Annual Curtailment of renewable energy in Gigawatts hour per investment period	GWh	Total for Europe, by generator type per country
CO2factor_TonPerMWh	Hourly CO2 factor per investment period	Tons per MWh	Average expected for Europe, by country and scenario
Price_EuroPerMWh	Hourly energy price for Europe per investment period	Euro per MWh	Average expected for Europe, by country and scenario
ExpectedAnnualCurtailedRES_MWh	Expected annual variable renewable energy curtailment per investment period	GWh	Total for Europe, by generator type per country
LossesChargeDischarge_GWh	Losses in charge and discharge of storage per investment period	GWh/MWh	Total expected annual for Europe, total expected annual by storage type, hourly by country and scenario
LossesTransmission_GWh	Losses in transmission per investment period	GWh/MWh	Total expected annual for Europe, total expected annual by transmission line, hourly by country and scenario
InvCap_MW	Asset capacity built per investment period	MW	Total for Europe, per asset type and country
InstalledCap_MW	Asset capacity existing in investment period	MW	Total for Europe, per asset type and country
DiscountedInvestmentCost_Euro	Total discounted investment cost in asset capacity per investment period	Euro	Total for Europe, per asset type and country
genExpectedAnnualProduction_GWh	Total expected annual production from generator per investment period	GWh	Total for Europe, per generator type and country
transmisionExpectedAnnualVolume_GWh	Expected annual transmission volume between two countries per investment period	GWh	Per transmission line
ExpectedAnnualDischargeVolume_GWh	Annual discharge volume from storage per investment period	GWh	Total for Europe, per storage type and country
storEnergyLevel_MWh	Storage hourly operational energy level per investment period	MWh	Per storage type and country
NetFlowOut_MW	Hourly net transmission out from country per investment period	MW	Per country
LoadShed_MW	Hourly load shedding	MW	Per country
NetDischarge_MW	Hourly net discharge from storage per investment period	MW	Per storage type and country

4.1.1 results_output_curtailed_prod.csv

Curtailed production shows the expected amount of curtailed energy from variable renewable energy sources per year, in gigawatt hour. It is comprise by four columns, as follows:

- **Node**
- **RESGeneratorType**
- **Period**
- **ExpectedAnnualCurtailment_GWh**

4.1.2 results_output_EuropePlot.csv

This is file contains a subset of the results found in "Europe_Summary", for purposes of easy and fast visualization. There are three tables in this file, which are:

- *genInstalledCap_MW*

This table shows the generation installed capacity for the whole Europe, per year and per technology.

  - **Period**
  - **List of all generator types**

- *genExpectedAnnualProduction_GWh*

This table shows the expected annual energy production for the whole Europe.

  - **Period**
  - **List of all generator types**

- *storPWInstalledCap_MW*

This table shows the expected storage installed capacity per year and for the whole Europe

  - **Period**
  - **List of all storage types**

4.1.3 results_output_EuropeSummary.csv

This output file gathers all relevant generation and storage resulting values for the 9 periods simulated. It shows how much generation installed capacity, storage installed capacity and energy annual production exist at the end of each year, for each technology. Its comprise by:

- Europe-wide average and total values per year
  - **Period**
  - **AvgExpectedCO2factor_TonPerMWh:** Average expected CO2 factor in tons per MWh
  - **AvgELPrice_EuroPerMWh:** Average electricity price in euros per MWh
  - **TotExpectedAnnualCurtailedRES_MWh:** Total expected annual curtailed renewable energy sources (RES) in MWh
  - **TotExpectedAnnualLossesChargeDischarge_GWh:** Total expected annual losses associated to storage charge and discharge, in GWh.

  - **ExpectedAnnualLossesTransmission_GWh:** Total expected annual losses associated to transmission, in GWh.
- Europe-wide generation relevant values per year and per technology
  - **GeneratorType**
  - **Period**
  - **genInvCap_MW**
  - **genInstalledCap_MW**
  - **TotDiscountedInvestmentCost_EuroPerMW**
  - **genExpectedAnnualProduction_GWh**
- Europe-wide storage relevant values per year
  - **StorageType**
  - **Period**
  - **storPWInvCap_MW**
  - **storPWInstalledCap_MW**
  - **storENInvCap_MWh**
  - **storENInstalledCap_MWh**
  - **TotDiscountedInvestmentCostPWEN_EuroPerMWMWh**
  - **ExpectedAnnualDischargeVolume_GWh**

4.1.4 results_output_gen.csv

This file shows the most relevant figures for generation, categorizing them per country and year.

- **Node**
- **GeneratorType**
- **Period**
- **genInvCap_MW**
- **genInstalledCap_MW**
- **genExpectedCapacityFactor**
- **DiscountedInvestmentCost_EuroPerMW**
- **genExpectedAnnualProduction_GWh**

4.1.5 results_output_Operational.csv

This file comprises results showing the hourly dispatch of electricity among all the nodes, periods and scenarios.

- **Node**
- **Period**
- **Scenario**
- **Season**
- **Hour**
- **Load**
- **ElectricityGeneratorCategories**
- **PriceEURperMWh**
- **MargCO2_kgCO2perMWh**

- **storEnergyLevel_MWh: Sum of storage energy level for the country and all the storage in that particular country.**
- **NetCharge_MW**
- **LossesElectricStorage_MW**
- **NetFlowOut_MW**
- **LossesFlowOut_MW**
- **LoadShed_MW**

4.1.6 results_output_stor.csv

This file shows the most relevant figures for storage, categorizing them per country and year.

- **Node**
- **StorageType**
- **Period**
- **storPWInvCap_MW**
- **storPWInstalledCap_MW**
- **storENInvCap_MWh**
- **storENInstalledCap_MWh**
- **DiscountedInvestmentCostPWEN_EuroPerMWMWh**
- **ExpectedAnnualDischargeVolume_GWh**
- **ExpectedAnnualLossesChargeDischarge_GWh**

4.1.7 results_output_transmision.csv

This file contains all the relevant figures regarding the transmission of energy among the 31 European countries considered in EMPIRE, categorizing it per year and transmission link (country of origin-country of destination).

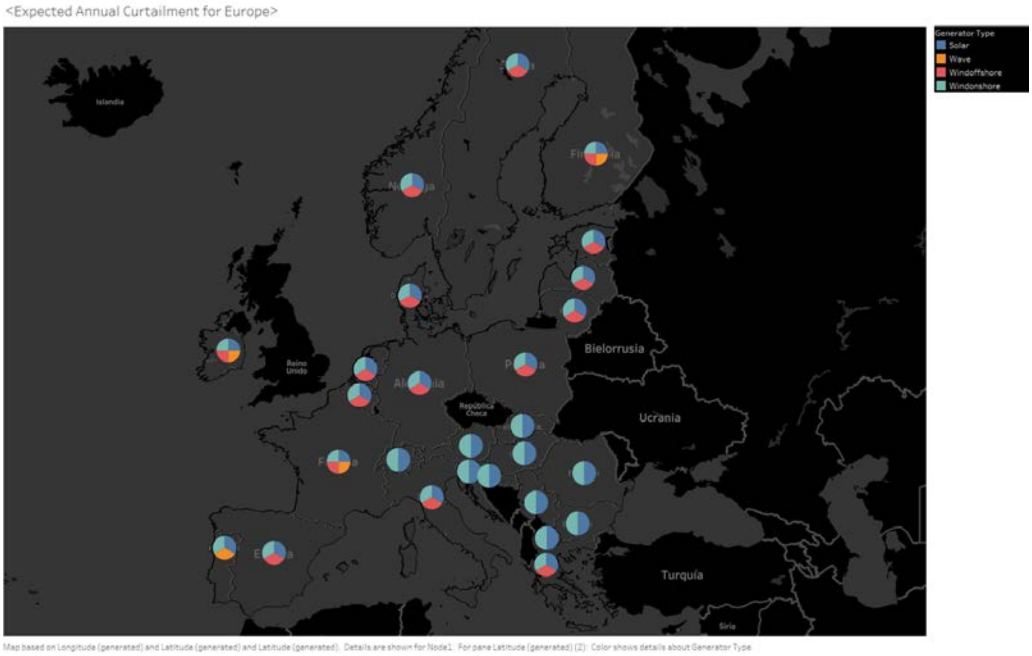
- **BetweenNode**
- **AndNode**
- **Period**
- **transmisionInvCap_MW**
- **transmisionInstalledCap_MW**
- **DiscountedInvestmentCost_EuroPerMW**
- **transmisionExpectedAnnualVolume_GWh**
- **ExpectedAnnualLosses_GWh**

4.2 Typical EMPIRE charts

From each of the output files, meaningful charts can be created depending on the information there given. Typical charts for most files are below.

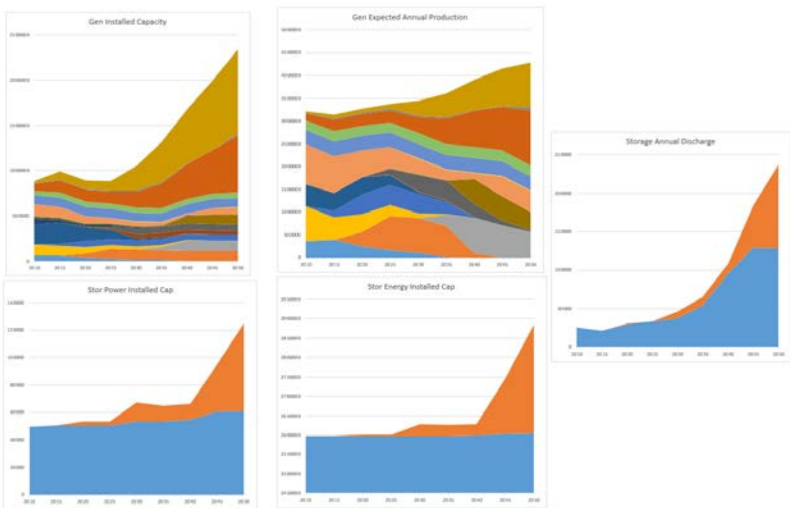
4.2.1 results_output_curtailed_prod.csv

This file shows all the information regarding curtailed energy for Europe. From the chart below one can see the amount of energy curtailed annually for 2050, per country.



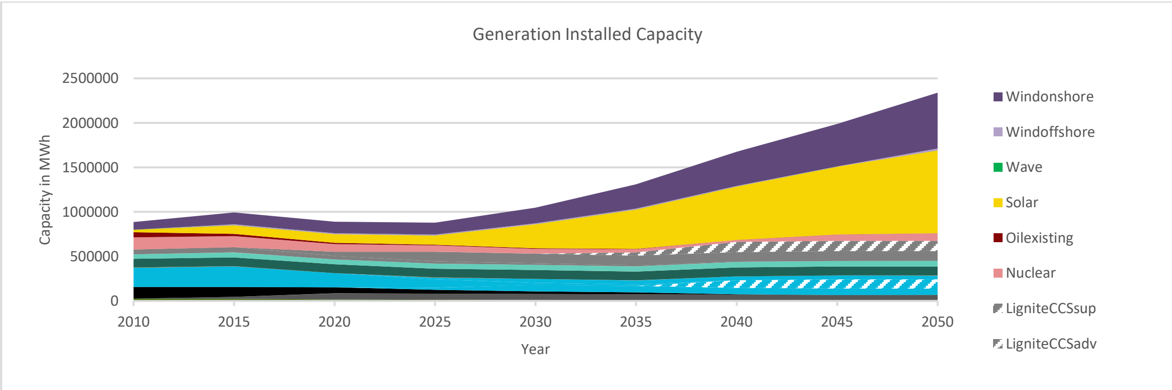
4.2.2 results_output_EuropePlot.csv

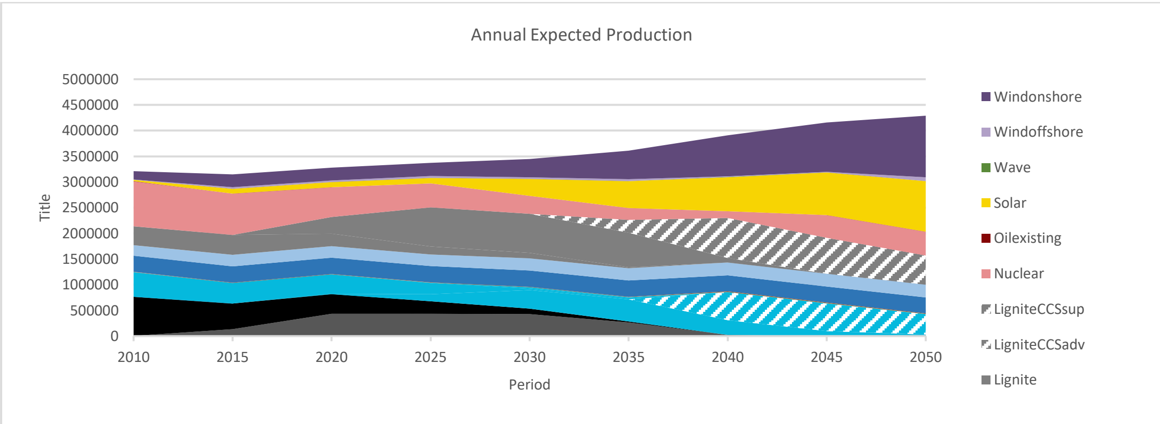
Europe plot file is designed to provide a quick overview of the results in a way that is easy to plot in excel. A figure example is shown below.



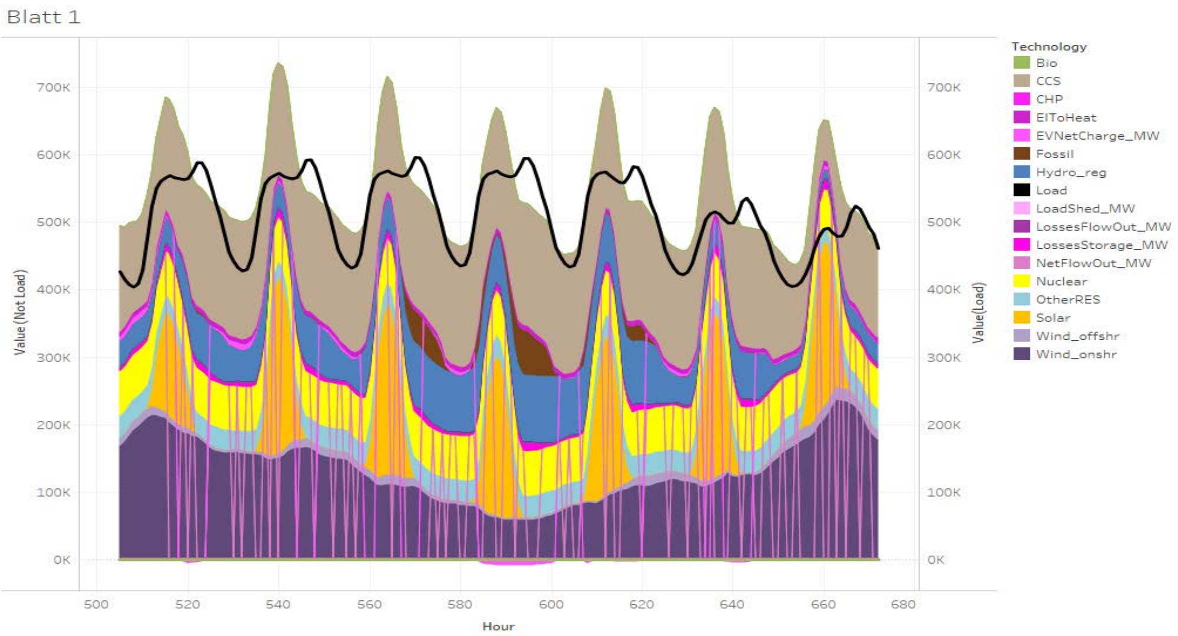
4.2.3 results_output_gen.csv

In this file, the results for generation are stored. From here, charts like the generation installed capacity or the annual generation production for the whole time horizon can be plotted.



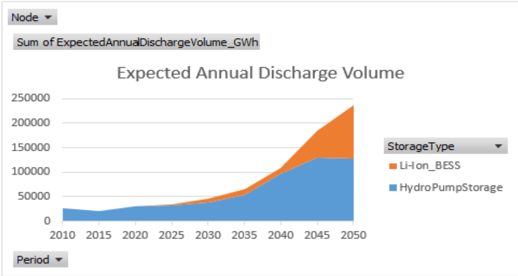


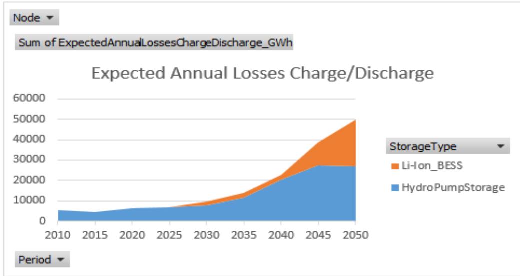
4.2.4 results_output_OperationalEL.csv

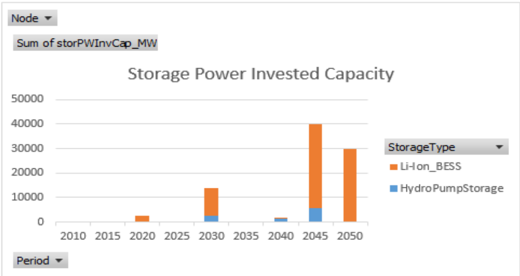


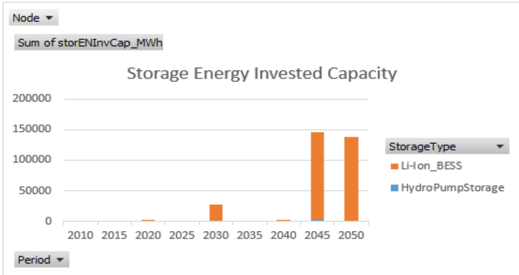
4.2.5 results_output_stor.csv

From this file, all the relevant information of storage is shown. The following figure shows typical charts forecasting the role of different kind of storage technologies in the system.









4.2.6 results_output_transmision.csv

To visualize the interaction and energy exchange between countries in Europe, EMPIRE can provide the necessary data to geographically plot the intra-European energy transmission paths and capacities. In the figure below, each transmission link has its own colour and their thickness is equivalent to the expected annual capacity (this figure corresponds to the values for 2050.

<Europe Transmission Map>