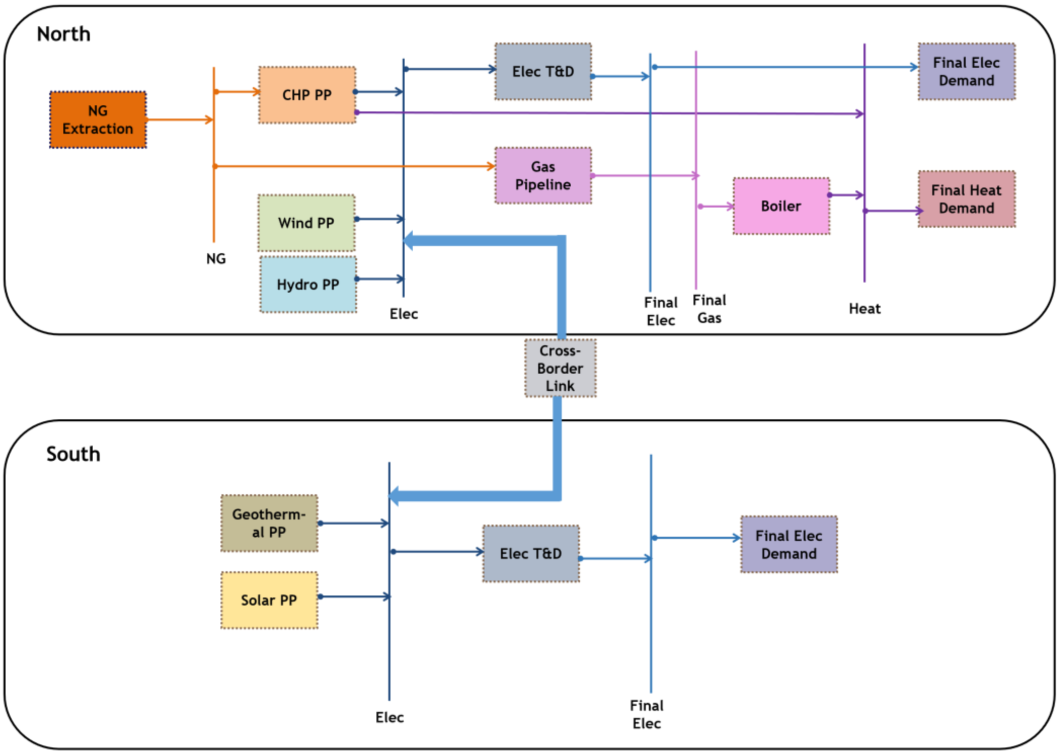
Tutorial 1: Operational Multi-Node Example

This example analyzes the energy system of a hypothetical region (Utopia) which is divided into two locations: Utopia-north and Utopia-south.

The Reference Energy System of the northern region includes a natural gas extraction technology, two renewable power supply technologies (Wind and Hydro), and one conventional power plant (Combined Heat and Power) which converts the natural gas fuel to both heat and electricity. Moreover, two types of transmission (Electricity Transmission and Distribution and Gas Pipelines) are considered for transporting the electricity and gas to the demand side. The transmitted electricity is directly entered into the final electricity demand technology, while the transmitted gas is converted by gas boilers to heat which ultimately enters the final heat demand technology.

On the other hand, the Reference Energy System of the southern region consists of only two renewable power supply technologies (Geothermal and Solar). The produced electricity from these power plants is then delivered to the Final Electricity Demand technology after passing through the local Electricity Transmission and Distribution.

The two locations can do a bilateral electricity trade through the installed Cross Border Transmission Link.



1. Building the excel-based structural input (set) files:

Considering that there are two locations in the Utopia region, three excel files are required:

- **"global.xlsx"**: indicating the technologies and carriers within the global (whole Utopia) energy system, the locations, the modelling years, and the time steps within each year
- **"reg1.xlsx"**: indicating the Reference Energy System of the northern region
- **"reg2.xlsx"**: indicating the Reference Energy System of the northern region

Note: The name of the excel files must be determined as above. It is not possible to include arbitrary file names

Name	Date modified	Type	Size
global.xlsx	2021-11-18 15:24	Microsoft Excel W...	205 KB
reg1.xlsx	2021-11-12 16:17	Microsoft Excel W...	12 KB
reg2.xlsx	2021-11-18 15:24	Microsoft Excel W...	12 KB

1.1"global" excel file:

As it is described in the building model documentation, the structural input excels consists of several tables for different sets of the model. The first table in the global file is **"Regions"** including the locations of the study and the name of each location as below:

Region	Region_name
reg1	Utopia_north
reg2	Utopia_south

The second table is **"Technologies_glob"** which includes all the technologies within the Utopia regardless of the location, their name, and categories as shown below. Please note that the technology categories must be chosen from **Supply, Conversion, Conversion_plus, Transmission, and Storage categories** and can not be anything different from the mentioned names.

Technology	Tech_name	Tech_category
NG_extraction	Natural Gas Extraction	Supply
CHP_PP	Combined Heat and Power	Conversion_plus
Geo_PP	Geothermal Power Plant	Supply
Solar_PP	Solar Power Plant	Supply
Wind_PP	Wind Power Plant	Supply
Hydro_PP	Hydro Power Plant	Supply
Elec_transmission	Electricity Transmission	Transmission
Gas_pipeline	Natural Gas Pipeline	Transmission
Boiler	Gas Boiler	Conversion
Elec_demand	Final Electricity Demand	Demand
Heat_demand	Final Heat Demand	Demand

After global technologies, global carriers must be indicated in the table **"Carriers_glob"**. In this table, all the carriers with their names and types must be included as below. The allowed carrier types are **Resource, Intermediate, and Demand**.

Carrier	Carr_name	Carr_type
NG	Fuel Natural Gas	Resource
Elec	Electricity	Intermediate
Elec_final	Final Electricity	Demand
Gas_final	Final Gas	Intermediate
Heat	Heat	Demand

Ultimately, the time horizon and temporal resolution of the model must be determined by "Years" and "Timesteps" tables respectively.

Year	Year_name
Y0	2021

Considering that in this case study, the temporal resolution is hourly (8760 hours within the year), we avoided bringing the full table in this tutorial. The "Timesteps" table must include the intra-year time slices, their names, and their length fraction compared to the whole year which is 1/8760 in this case.

Timeslice	Timeslice_name	Timeslice_fraction
1	h1	0,000114155
2	h2	0,000114155
3	h3	0,000114155
4	h4	0,000114155
5	h5	0,000114155
6	h6	0,000114155
7	h7	0,000114155
8	h8	0,000114155
9	h9	0,000114155
10	h10	0,000114155
11	h11	0,000114155
12	h12	0,000114155
13	h13	0,000114155
14	h14	0,000114155
15	h15	0,000114155
16	h16	0,000114155
17	h17	0,000114155
18	h18	0,000114155
19	h19	0,000114155
20	h20	0,000114155
21	h21	0,000114155
22	h22	0,000114155
23	h23	0,000114155
24	h24	0,000114155

1.2 “reg1” excel file:

The regional excel files consist of regional technologies, carriers, and the interconnections among them based on the Reference Energy System. The first table of regional files is named **“Technologies”** where the user must indicate all the technologies within the specific location (Utopia-north) as shown below:

Technology	Tech_name	Tech_category
NG_extraction	Natural Gas Extraction	Supply
CHP_PP	Combined Heat and Power	Conversion_plus
Wind_PP	Wind Power Plant	Supply
Hydro_PP	Hydro Power Plant	Supply
Elec_transmission	Electricity Transmission	Transmission
Gas_pipeline	Natural Gas Pipeline	Transmission
Boiler	Gas Boiler	Conversion
Elec_demand	Final Electricity Demand	Demand
Heat_demand	Final Heat Demand	Demand

The second table is named **“Carriers”** which is dedicated to determining all the carriers within the Utopia-north.

Carrier	Carr_name	Carr_type
NG	Fuel Natural Gas	Resource
Elec	Electricity	Intermediate
Elec_final	Final Electricity	Demand
Gas_final	Final Gas	Intermediate
Heat	Heat	Demand

The connections among the technologies and carriers within the reference energy system are determined by “Carrier-input” and “Carrier_output” tables. In the former, the input carriers of the technologies, and in the latter, the output carriers of technologies are represented. Please note that the “Supply” technologies and “Demand” technologies should not be included in **“Carrier-input”** and **“Carrier-output”** tables respectively because the “Supply” category of technologies just provide energy carrier to the system without any conversion process and the “Demand” category just sinks and removes the demand energy carriers from the system.

Carrier Input

Technology	Carrier_in
CHP_PP	NG
Elec_transmission	Elec
Gas_pipeline	NG
Boiler	Gas_final
Elec_demand	Elec_final
Heat_demand	Heat

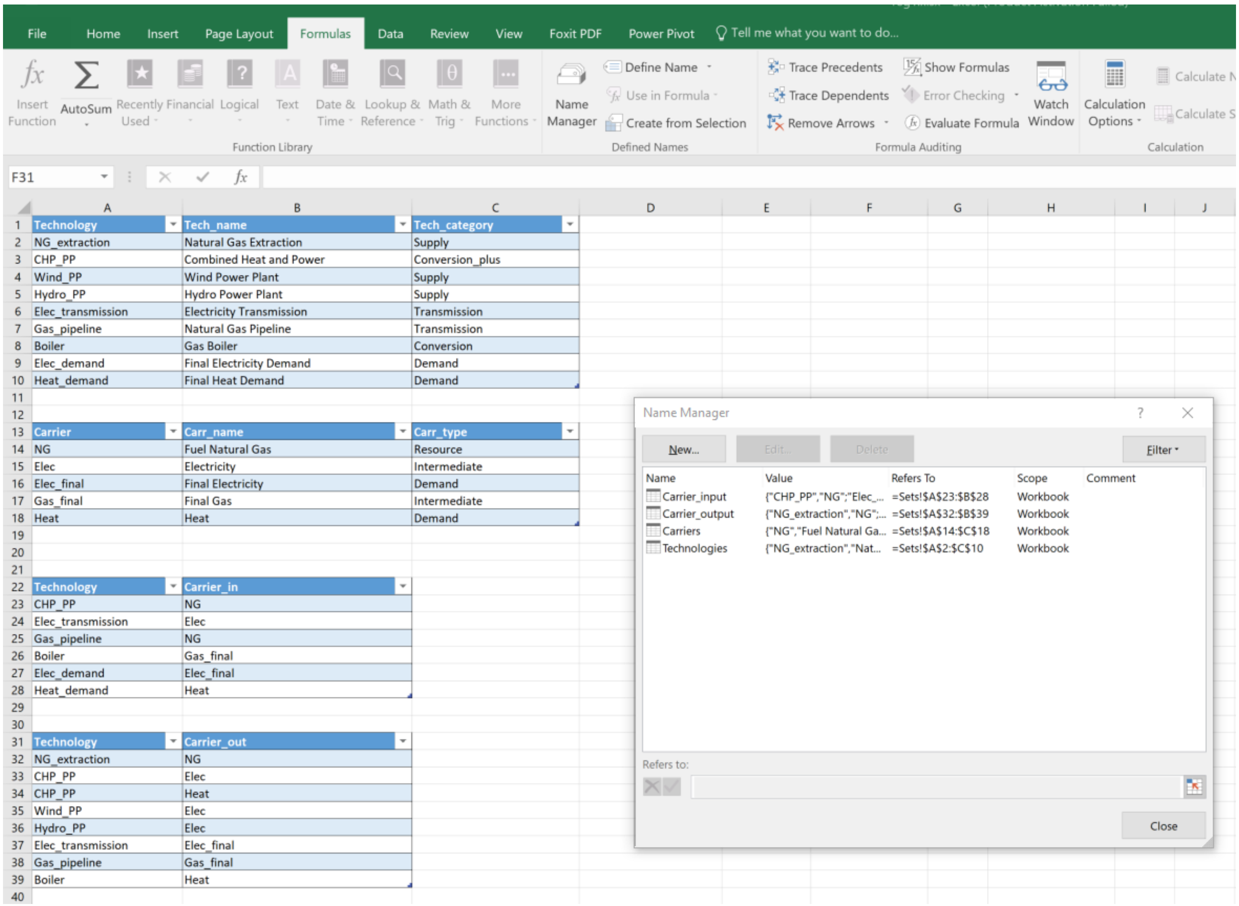
Carrier Output

Technology	Carrier_out
NG_extraction	NG
CHP_PP	Elec
CHP_PP	Heat
Wind_PP	Elec
Hydro_PP	Elec
Elec_transmission	Elec_final
Gas_pipeline	Gas_final
Boiler	Heat

There are a few important things to note about the structural input files:

- The name of the tables are fixed and cannot be chosen at will by the user. All the table names must be indicated as mentioned above. However, in case of any potential error, the Hypatia model delivers proper warnings to the user after reading the set files. The table names can be fixed in the excel files through the following path as shown in the following figure.

Formulas tab of the ribbon > Name Manager > Edit > Name



- The name of the columns in each table must be exactly as the indicated names in this tutorial. There are also warning and exception errors for the possible mistakes in the column names.

- If there are similar technologies in various regions, their names must be identical in different “reg” set files and therefore, only one name as the representative of that technology in all the regions must be included in the “Technologies_glob” in the “global” set file. For example, if there is a Hydropower plant in all the considered locations within the geographical coverage of the model, one single name such as “Hydro PP” must be considered in all the regional set files and this name should be brought only once in the “global” set file.

2. Initializing the Hypatia model by reading the excel-based set files

After specifying all the sets of the model, it is time to initialize the Hypatia model and read the structural input files.

Importing the hypatia model

In [ ]:
```
from hypatia import Model
```

Intializing the hypatia model by passing the optimization mode and the path of the structural input files (sets of the model)

In [ ]:
```
utopia = Model(
    path = 'sets',
    mode = 'Operation'
)
```

3. Creating the excel-based parameter files

Now the model can create the parameter files with their default values through running the following commands.
After running this command line, we are going to open the created parameter files and fill them with the model data.

In [ ]:
```
#utopia.create_data_excels(
#    path = 'parameters'
#)
```

In this case, as we have a multi-node approach, it is expected to see the following files in the given path:

- Two files for regional parameters named **"parameters_reg1.xlsx"** and **"parameters_reg2.xlsx"**
- One file for global parameter and constraints named **"parameters_global.xlsx"**
- One file for parameters related to the possible connections among the regions which is named **"parameter_connections.xlsx"**.

4. Filling the parameter files with the input data

Now it is time to insert the input data in their related parameter files.

4.1 Regional parameter files:

In this case study, we are focusing on the operational mode of the energy system. Therefore, the following sheets can be found in the excel files:

- **Specific fixed and variable operation and maintenance costs:** These costs must be defined on an annual basis for each technology within each category. Different units can be considered for different technologies. In this case, the variable cost of all technologies is defined in USD/MWh except for Natural Gas Extraction variable cost which is based on USD/BOE (dollars per barrel of oil equivalent). All the fixed costs are assumed to be equal to zero as they are not going to affect the optimization process.

Tech_category	Supply			Conversion_plus	Transmission		Conversion
Technology	NG_extraction	Wind_PP	Hydro_PP	CHP_PP	Elec_transmission	Gas_pipeline	Boiler
Years							
Y0	38.56	5.707763	8.561644	10.2739726	0	0	0.570776256

F_OM | V_OM | Residual_capacity | Max_production | Min_production | Capacity_factor_tech | Tech_efficiency | Specific_emission

- **Fixed taxes and subsidies:** Annual taxes and subsidies per unit fixed cost of a technology which are considered equal to zero in this case
- **Carbon tax:** Apart from the above mentioned costs, carbon tax can be also defined in the Hypatia model for different fossil fuel based technologies. It must be indicated per unit of produced CO2-equivalent emissions from each technology. In this specific case, this parameter has been left with its defaukt value which is equal to zero.

	A	B	C	D	E	F
1	Tech_category	Supply			Conversion_plus	Conversion
2	Technology	NG_extraction	Wind_PP	Hydro_PP	CHP_PP	Boiler
3	Years					
4	Y0	0	0	0	0	0

F_OM | V_OM | Residual_capacity | Max_production | Min_production | Capacity_factor_tech | Tech_efficiency | Specific_emission | **Carbon_tax**

- **Residual capacity:** The total installed capacity of each technology before starting the modelling horizon. In the operational mode, the total capacity of technologies in the specific modelling year must be given exogenously and only the hourly dispatch of technologies are going to be optimized. The residual capacity sheet is exactly where the user must indicate the exogenous capacity of each technology within the energy system. Again, the unit of capacity can differ from one technology to another. In this case, all the units are based on MW except for the Natural Gas Extraction and Boiler which are based on the number of installed extraction units.

Tech_category	Supply			Conversion_plus	Transmission		Conversion
Technology	NG_extraction	Wind_PP	Hydro_PP	CHP_PP	Elec_transmission	Gas_pipeline	Boiler
Years							
Y0	200	22110	39810	70000	20000	7000	45000

F_OM | V_OM | Residual_capacity | Max_production | Min_production | Capacity_factor_tech | Tech_efficiency | Specific_emission

- **Max/Min production:** These parameters are useful when the user aims to do scenario analysis and provide an upper and lower limit for the annual production of each technology. In this case, the Business as Usual (BAU) scenario is considered, and therefore, no limits are applied on the production.
- **Technology capacity factor:** This parameter allows to consider the planned outages or operation and maintenance time of each technology. It is the average capacity of a plant divided by its nominal total capacity. In this case, it is assumed that the capacity factor of all the technologies is equal to 1.
- **Resource capacity factor:** This parameter allows us to consider the availability of resources (especially for renewable technologies) in each time slice of the year. It is the max production of one unit capacity of each technology in each time slice based on the variable resource availability. In this case, the full 8760 hours of the modelling year has been considered, therefore, the resource capacity factors must be given in the time-series format. The values for the first 24 hours of the year are shown in the following. It is assumed that all the resources in Utopia-north are fully available except for the wind and hydro power plants. These parameter are taken from the renewable.ninja website (Renewables.Ninja, n.d.) for a hypothetical location in northern Europe.

	A	B	C	D	E	F	G	H	I
1		**Tech_category**	**Supply**			**Conversion_plus**	**Transmission**		**Conversion**
2		**Technology**	**NG_extraction**	**Wind_PP**	**Hydro_PP**	**CHP_PP**	**Elec_transmission**	**Gas_pipeline**	**Boiler**
3	**Years**	**Timesteps**							
4	**Y0**	**1**	1	0.793	0.584652	1	1	1	1
5		**2**	1	0.758	0.468877	1	1	1	1
6		**3**	1	0.692	0.468556	1	1	1	1
7		**4**	1	0.583	0.452888	1	1	1	1
8		**5**	1	0.46	0.463797	1	1	1	1
9		**6**	1	0.38	0.463476	1	1	1	1
10		**7**	1	0.344	0.469866	1	1	1	1
11		**8**	1	0.28	0.469037	1	1	1	1
12		**9**	1	0.2	0.447701	1	1	1	1
13		**10**	1	0.15	0.459251	1	1	1	1
14		**11**	1	0.147	0.460695	1	1	1	1
15		**12**	1	0.146	0.451925	1	1	1	1
16		**13**	1	0.146	0.454118	1	1	1	1
17		**14**	1	0.172	0.463316	1	1	1	1
18		**15**	1	0.21	0.445936	1	1	1	1
19		**16**	1	0.184	0.437487	1	1	1	1
20		**17**	1	0.218	0.432781	1	1	1	1
21		**18**	1	0.367	0.466096	1	1	1	1
22		**19**	1	0.59	0.569198	1	1	1	1
23		**20**	1	0.816	0.832299	1	1	1	1
24		**21**	1	0.886	0.876043	1	1	1	1
25		**22**	1	0.897	0.715909	1	1	1	1
26		**23**	1	0.886	0.645722	1	1	1	1
27		**24**	1	0.894	0.48	1	1	1	1

... Fix_taxsub | Emission_cap_annual | AnnualProd_perunit_capacity | Demand | **capacity_factor_resource** | Max_production_h | Min_pr ...

- **Technology efficiency**: The technical efficiency in the Hypatia model is basically the ratio between the output carrier to the input carrier of a conversion, conversion-plus or a transmission technology. Considering the fact that the units of the carrier production and carrier consumption of each technology can be different in this model, the technology efficiency (output/input activity ratio) can be higher or lower than one. In this case study, the input energy carrier of both CHP plant and boiler is natural gas in the unit of barrels of oil equivalent (BOE) and their output is either heat or electricity in MWh. The efficiency of these technologies is around 0.8 based on the IEA ETSAP dataset if the input and output activities hold the same unit. However, considering the converting ratio of MWh to BOE, it can be said that for each BOE natural gas, these technologies can provide around 1.3024 MWh output. Moreover, in this case, the efficiency of all the transmission technologies has been considered equal to 0.9 (assuming 10% within the links).
- **Specific emission:** In the Hypatia model the GHG emissions in terms of CO2 equivalent values can be considered. In this case, 0.305 ton/boe of production has been considered for Natural Gas Extraction technology.

Tech_category	Supply			nversion_p	Conversion
Technology	NG_extraction	Wind_PP	Hydro_PP	CHP_PP	Boiler
Years					
Y0	0.305	0	0	0	0

F_OM | V_OM | Residual_capacity | Max_production | Min_production | Capacity_factor_tech | Tech_efficiency | Specific_emission

- **Annual emission limit:** Allows to put an upper limit for thetotal annual emission of each region. This case study follows a BAU logic, therefore, no annual emission cap has been defined
- **Annual production per unit of capacity:** The amounts of output activity per each unit of installed capacity of each technology in each year of the modelling horizon. In this case study, each unit of Natural Gas extraction is assumed to produce 1320000 BOE of natural gas, each boiler unit can produce 44 MWh and each MW capacity of the power generation and transmission technologies can produce 8760 MWh per year.

Tech_category	Supply			Conversion_plus	Transmission		Conversion
Technology	NG_extraction	Wind_PP	Hydro_PP	CHP_PP	Elec_transmission	Gas_pipeline	Boiler
Performance Parameter							
AnnualProd_Per_UnitCapacity	1320000	8760	8760	8760	8760	8760	44

... Tech_efficiency | Specific_emission | Carbon_tax | Fix_taxsub | Emission_cap_annual | **AnnualProd_perunit_capacity** | Demand

- **Demand:** In this case, the time series demand for both final electricity demand and final heat demand has been given to the model for 8760 hours of the year. Only 24 hours of the data is shown in the following figure.

Years	Timesteps	Elec_demand	Heat_demand
Y0	1	9778.69	3813.953794
	2	9634.18	3810.182136
	3	9633.9	3850.519556
	4	9707.48	3910.99467
	5	9919.41	4011.210158
	6	9964.3	4245.854909
	7	10150.46	4799.133862
	8	10184.09	5023.582081
	9	10226.24	4764.741148
	10	10395.05	4518.36652
	11	10432.06	4327.755219
	12	10425.19	4180.143343
	13	10547.72	4086.285442
	14	10847.29	4015.892017
	15	11022.25	3966.356044
	16	11021.11	3950.118595
	17	11074.88	4003.182093
	18	11064.12	4070.642459
	19	10849.56	4173.299538
	20	10465.52	4186.987148
	21	10731.69	4096.062307
	22	10541.76	4031.535001
	23	10136.25	3982.209673
	24	9849.41	3877.752775

... Tech_efficiency | Specific_emission | Carbon_tax | Fix_taxsub | Emission_cap_annual | AnnualProd_perunit_capacity | **Demand**

It should be noted that the data for the Utopia-south region can be inserted following the same instruction of Utopia-north parameter file. The data in “parameters_global.xlsx” are all based on the default values as no global scenarios are considered for this specific case study.

4.2. “parameters-connections” file:

The cross-border links have almost the same techno-economic parameters as the regional technologies including fixed and variable costs, residual capacity, capacity factor, efficiency, and annual production per each unit of capacity. In this case study, among all the possible connections for all the global carriers considered within Utopia, it is assumed that the northern and southern regions have only the bilateral trade of electricity. Therefore, the residual capacity of all the links for all the carriers except the electricity must be indicated equal to zero, and consequently, the user must be only concerned with the parameters that are related to this link and can leave the others with their default values. The capacity unit of the electricity cross-border link is based on MW in the case study.

Line	reg1-reg2				
Transmitted Carrier	NG	Elec	Elec_final	Gas_final	Heat
Years					
Y0	0	40000	0	0	0

F_OM | V_OM | Residual_capacity | Capacity_factor_line | Line_efficiency | AnnualProd_perunit_capacity

Ready

5. Reading the input data

After filling out the parameter files, it is time to ask the model to read the input data following the below command line.

In [ ]:

```
utopia.read_input_data(
    path = 'parameters'
)
```

6. Running the model

Now we can run the model by giving the preferred solver, verbosity and the force_rewrite parameter which avoids overwriting the output results when it is equal to False and allows to overwrite them by taking a backuo from the previous results when it is equal to True.

In [ ]:

```
utopia.run(
    solver = 'scipy',
    verbosity = True,
)
```

7. Exporting the raw results to csv files

There is the possibility to export the raw results into the csv files by passing the arbitary folder path and force_rewrite parameter which avoids to overwrite the results when it is equal to False.

In [ ]:

```
utopia.to_csv(path='results')
```

8. Visualizing the raw results

After solving the model, we can visualize the raw results by importing the plotting tool of the Hypatia model but before that, we need to ask the model to create the configuration excel file for indicating the desired information on technologies, fuels and regions.

In [ ]:

```
# utopia.create_config_file(path=r'config.xlsx')
```

In [ ]:

```
from hypatia import Plotter
```

Now, it is the time to initiallize the plotter class by passing the model's name, the created config file for the plots and the hourly resolution boolean parameter. The latter is True when the model has a hourly stepwise resolution and False when the timesteps are not in a hourly basis.

In [ ]:

```
myplots = Plotter(utopia,config=r'config.xlsx',hourly_resolution= True)
```

In [ ]:
```
# Sketching the hourly dispatch of the technologies for a given time horiz
myplots.plot_hourly_prod_by_tech(
    path = r'plots/dispatch.html',
    tech_group='Power Generation',
    regions = ['reg1','reg2'],
    year = 2021,
    start="01-01 00:00:00",
    end="01-03 23:00:00",
)
```

In [ ]:
```
# Sketching the hourly dispatch of the technologies for the whole modellin
myplots.plot_hourly_prod_by_tech(
    path = r'plots/full_dispatch.html',
    tech_group='Power Generation',
    regions = ['reg1','reg2'],
    year = 2021,
    start="01-01 00:00:00",
    end="12-29 23:00:00",
)
```

In [ ]:
```
# Skething the prduction and consumption share of each technology includin
myplots.plot_fuel_prod_cons(
    path = r'plots/prod_con_share.html',
    years = [2021],
    fuel_group = "Electricity",
    regions = ['reg1','reg2'],
    trade=True,
)
```

In [ ]:
```
# Sketching the annual CO2-equivalent emissions
myplots.plot_emissions(
    path = r'plots/emissions.html',
    regions = ['reg1','reg2'],
    tech_group = 'Resource Extraction',
)
```