Hands-on exercise 3: Adding a new technology

In this tutorial we will begin by giving an overview of the input files that MUSE requires to run. We will then show how to modify these files to add a new technology to the model.

Input Files

MUSE is made up of a number of different input files (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/index.html). These can be broadly split into two types:

- Simulation settings (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/toml.html)
- Simulation data (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/inputs_csv.html)

Simulation settings specify how a simulation should be run. For example, which sectors to run, for how many years, the benchmark years and what to output. In this context, benchmark years are the years in which the model is solved. In the examples following, we solve for every 5 years, ie. 2020, 2025, 2030...

Simulation data, on the other hand, parametrises the technologies involved in the simulation, or the number and kinds of agents.

To create a customised case study it is necessary to edit both of these file types.

Simulation settings are specified in a TOML file. TOML (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/toml_primer.html) is a simple, extensible and intuitive file format well suited for specifying small sets of complex data.

Simulation data is specified in CSV (https://en.wikipedia.org/wiki/Comma-separated_values) files. This is a common format used for larger datasets, and is made up of columns and rows, with a comma used to differentiate between entries.

MUSE requires at least the following files to successfully run:

- a single simulation settings TOML file (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/toml.html) for the simulation as a whole
- a file indicating initial market price projections (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/projections.html)
- a file describing the commodities in the simulation (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/commodities.html)
- for generalized sectors:
  - a file descring the agents (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/agents.html)
  - a file descring the technologies (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/technodata.html)
  - a file descring the input commodities (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/commodities_io.html) for each technology
  - a file descring the output commodities (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/commodities_io.html) for each technology
  - a file descring the existing capacity (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/existing_capacity.html) of a given sector
- for each preset sector:
  - a csv file describing consumption for the duration of the simulation

For a full description of these files see the input files section (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/index.html). To see how to customise an example, continue on this page.

Addition of solar PV

In this section, we will add solar photovoltaics to the default model. To achieve this, we must modify some of the input files shown in the above section. To create a copy of the default model files, run:

```
python -m muse --model default --copy PATH/TO/COPY/THE/MODEL/TO
```

You can modify the files in your favourite spreadsheet editor or text editor such as VSCODE, Excel, Numbers, Notepad or TextEdit.

Technodata Input

Within the default folder you'll find a `settings.toml` file, `input` folder and `technodata` folder. To add a technology within the power sector, we must open the `technodata` folder followed by the `power` folder.

At this point, we must note that we require consistency in input and output units. For example, if capacity is in PJ, the same basis would be needed for the output files `CommIn.csv` and `CommOut.csv` . In addition, across sectors a commodity needs to maintain the same unit. In these examples, we use the unit petajoule (PJ).

We will first edit the `CommIn.csv` file, which specifies the commodities consumed by solar photovoltaics.

The table below shows the original `CommIn.csv` version in normal text, and the added column and row in **bold**.

ProcessName	RegionName	Time	Level	electricity	gas	heat	CO2f	wind	solar
Unit	-	Year	-	PJ/PJ	PJ/PJ	PJ/PJ	kt/PJ	PJ/PJ	**PJ/PJ**
gasCCGT	R1	2020	fixed	0	1.67	0	0	0	**0**
windturbine	R1	2020	fixed	0	0	0	0	1	**0**
solarPV	**R1**	**2020**	**fixed**	**0**	**0**	**0**	**0**	**0**	**1**

We must first add a new row at the bottom of the file, to indicate the new solar photovoltaic technology:

- we call this technology `solarPV`
- place it in region `R1`
- the data in this row is associated to the year 2020
- the input type is [fixed (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/commodities_io.html)](https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/commodities_io.html)
- solarPV consumes solar

As the solar commodity has not been previously defined, we must define it by adding a column, which we will call `solar` . We fill out the entries in the solar column, ie. that neither `gasCCGT` nor `windturbine` consume `solar` .

We repeat this process for the file: `CommOut.csv` . This file specifies the output of the technology. In our case, solar photovoltaics only output `electricity` . This is unlike `gasCCGT` which also outputs `CO2f` (carbon dioxide).

ProcessName	RegionName	Time	electricity	gas	heat	CO2f	wind	solar
Unit	-	Year	PJ/PJ	PJ/PJ	PJ/PJ	kt/PJ	PJ/PJ	**PJ/PJ**
gasCCGT	R1	2020	1	0	0	91.67	0	**0**
windturbine	R1	2020	1	0	0	0	0	**0**
solarPV	**R1**	**2020**	**1**	**0**	**0**	**0**	**0**	**0**

Similar to the the `CommIn.csv` , we create a new row, and add in the solar commodity. We must ensure that we call our new commodity and technologies the same as the previous file for MUSE to successfully run. ie `solar` and `solarPV` . Please note that we use flat forward extension of the values when only one value is defined. For example, in the `CommOut.csv` we only provide data for the year 2020. Therefore for the benchmark years, 2025, 2030, 2035... we assume the data remains unchanged from 2020.

The next file to modify is the `ExistingCapacity.csv` file. This file details the existing capacity of each technology, and a decommissioning profile across the time framework. For this example, we will set the existing capacity to be 0. Please note that the model interpolates linearly between years.

ProcessName	RegionName	Unit	2020	2025	2030	2035	2040	2045	2050
gasCCGT	R1	PJ/y	1	1	0	0	0	0	0
windturbine	R1	PJ/y	0	0	0	0	0	0	0
solarPV	**R1**	**PJ/y**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Finally, the `Technodata.csv` file contains parametrisation data for the technology, such as the cost, growth constraints, lifetime of the power plant and fuel used. We will only display the some of the parameters, as the table is too large to display in full. The remaining parameters will be copied from the `windturbine` technology. You can see the full file [here (https://github.com/EnergySystemsModellingLab/MUSE_OS/blob/v1.2.1/docs/tutorial-code/1-add-new-technology/1-introduction/technodata/power/Technodata.csv)](https://github.com/EnergySystemsModellingLab/MUSE_OS/blob/v1.2.1/docs/tutorial-code/1-add-new-technology/1-introduction/technodata/power/Technodata.csv), and details about each parameter [here (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/technodata.html)](https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/technodata.html).

ProcessName	RegionName	Time	cap_par	cap_exp	...	Fuel	EndUse	Agent1
Unit	-	Year	MUS$2010/PJ_a	-	...	-	-	New
gasCCGT	R1	2020	23.78234399	1	...	gas	electricity	1
windturbine	R1	2020	36.30771182	1	...	wind	electricity	1
solarPV	**R1**	**2020**	**30**	**1**	**...**	**solar**	**electricity**	**1**

Again, flat forward extension is used. Therefore, as we only provide data for the benchmark year 2020, 2025 and the following benchmark years will keep the same characteristics.

Global inputs

Next, navigate to the `input` folder. We must now edit each of the files found here to add the new `solar` commodity. Due to space constraints we will not display all of the entries contained in every input. You can be view the edited files in full here (https://github.com/EnergySystemsModellingLab/MUSE_OS/tree/main/docs/tutorial-code/1-add-new-technology/1-introduction).

Commodities are defined in the `GlobalCommodities.csv` file. Here we give the commodities a commodity type, CO2 emissions factor and heat rate. For this file, we will add the `solar` commodity, with zero CO2 emissions factor and a heat rate of 1.

Commodity	CommodityType	CommodityName	CommodityEmissionFactor_CO2	HeatRate	Unit
Electricity	Energy	electricity	0	1	PJ
Gas	Energy	gas	56.1	1	PJ
Heat	Energy	heat	0	1	PJ
Wind	Energy	wind	0	1	PJ
CO2fuelcomsbustion	Environmental	CO2f	0	1	kt
Solar	**Energy**	**solar**	**0**	**1**	**PJ**

The `Projections.csv` file details the initial market prices for the commodities. The market clearing algorithm will update these throughout the simulation, however an initial estimate is required to start the simulation. As solar energy is free, we will indicate this by adding a final column. Please note that the unit row is not read by MUSE, but used as a reference for the user. The units should be consistent across all input files for MUSE; MUSE does not carry out any unit conversion.

RegionName	Attribute	Time	electricity	gas	heat	CO2f	wind	solar
Unit	-	Year	MUS$2010/PJ	MUS$2010/PJ	MUS$2010/PJ	MUS$2010/kt	MUS$2010/PJ	**MUS$2010/PJ**
R1	CommodityPrice	2010	14.81481472	6.6759	100	0	0	**0**
R1	CommodityPrice	2015	17.89814806	6.914325	100	0.052913851	0	**0**
...	...	...	...	...	...	...	...	**...**
R1	CommodityPrice	2100	21.39814806	7.373485819	100	1.871299697	0	**0**

It is also possible to model import and export of commodities, using the `BaseYearImport.csv` and `BaseYearExport.csv` files, along with the `base_year_import` and `base_year_import` settings in the settings file (https://muse-os.readthedocs.io/en/v1.2.1/user-guide/../inputs/toml.html). However we will not do this here.

Settings

Finally, we must make a small change to the `settings.toml` file. As `solar` is a renewable resource that isn't produced by any process defined in the model, we must add it to `excluded_commodities` in `settings.toml`, like so:

```
excluded_commodities = ["wind", "solar"]
```

This will ensure MUSE excludes `solar` from its internal supply-fulfillment checks.

Running our customised simulation

Now we are able to run our simulation with the new solar power technology. To do this, we run the following command in the command line:

```
python -m muse settings.toml
```

If the simulation has run successfully, you should now have a folder in the same location as your `settings.toml` file called `Results`. The next step is to visualise the results using the data analysis library `pandas` and the plotting library `matplotlib`.

In [1]:

```
import matplotlib.pyplot as plt
import pandas as pd
```

First, we will import the `MCACapacity.csv` file using pandas, and print the first 5 lines with the `head()` command. (Make sure to change the file path as appropriate.)

In [2]:

```
mca_capacity = pd.read_csv(
    "../tutorial-code/add-new-technology/1-introduction/Results/MCACapacity.csv"
)
mca_capacity.head()
```

Out[2]:

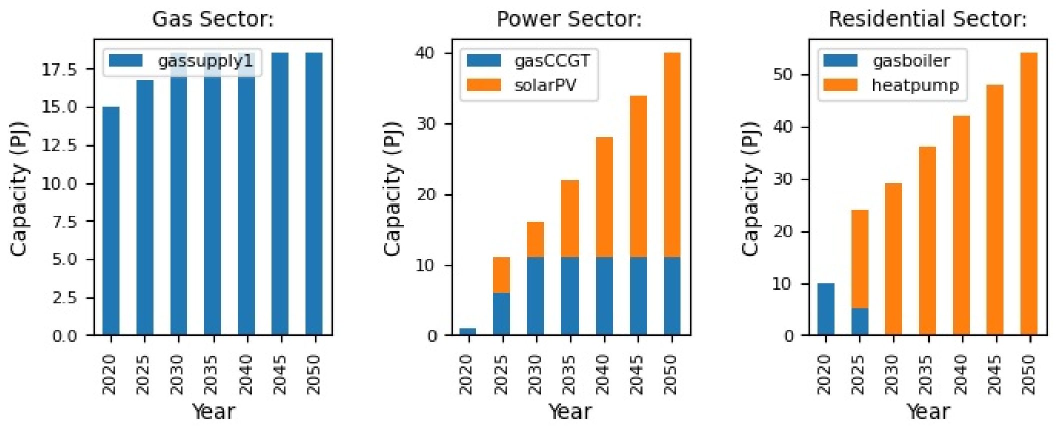
	agent	capacity	dst_region	installed	region	sector	technology	type	year
0	A1	10.0	R1	2020	R1	residential	gasboiler	newcapa	2020
1	A1	1.0	R1	2020	R1	power	gasCCGT	newcapa	2020
2	A1	15.0	R1	2020	R1	gas	gassupply1	newcapa	2020
3	A1	5.0	R1	2020	R1	residential	gasboiler	newcapa	2025
4	A1	19.0	R1	2020	R1	residential	heatpump	newcapa	2025

We will now visualise the results:

In [3]:

```
fig, axes = plt.subplots(1, 3)
all_years = mca_capacity["year"].unique()
for ax, (sector_name, sector_data) in zip(axes, mca_capacity.groupby("sector")):
    sector_capacity = sector_data.groupby(["year", "technology"]).sum().reset_index()
    sector_capacity.pivot(
        index="year", columns="technology", values="capacity"
    ).reindex(all_years).plot(kind="bar", stacked=True, ax=ax)
    ax.set_ylabel("Capacity (PJ)")
    ax.set_xlabel("Year")
    ax.set_title(f"{sector_name.capitalize()} Sector:", fontsize=10)
    ax.legend(title=None, prop={"size": 8})
    ax.tick_params(axis="both", labelsize=8)

fig.set_size_inches(8, 2.5)
fig.subplots_adjust(wspace=0.5)
```



We can now see that there is `solarPV` capacity in the power sector. That's great and means it worked!

We can see that `solarPV` has a higher uptake than `gasCCGT` , and has entirely replaced `windturbine` in of the sector, which is likely due to the lower `cap_par` (capital cost) which makes it more favourable for investment. We can investigate this by changing the `cap_par` value for `solarPV` , which we will do in the next section.

Change Capital costs of Solar

Now, we will observe what happens if we increase the capital price of solar to be more expensive than wind in the year 2020, but then reduce the price of solar in 2040. By doing this, we should observe an initial investment in wind in the first few benchmark years of the simulation, followed by a transition to solar as we approach the year 2040.

To achieve this, we have to modify the `Technodata.csv`, `CommIn.csv` and `CommOut.csv` files in the `power` sector.

First, we will amend the `Technodata.csv` file as follows:

ProcessName	RegionName	Time	cap_par	cap_exp	...	Fuel	EndUse	Agent1
Unit	-	Year	MUS$2010/PJ_a	-	…	-	-	New
gasCCGT	R1	2020	23.78234399	1	…	gas	electricity	1
gasCCGT	**R1**	**2040**	**23.78234399**	**1**	**…**	**gas**	**electricity**	**1**
windturbine	R1	2020	36.30771182	1	…	wind	electricity	1
windturbine	**R1**	**2040**	**36.30771182**	**1**	**…**	**wind**	**electricity**	**1**
solarPV	R1	2020	**40**	1	...	solar	electricity	1
solarPV	**R1**	**2040**	**30**	**1**	**...**	**solar**	**electricity**	**1**

Here, we increase `cap_par` for `solarPV` to 40 in the year 2020, and create a new row for 2040 with a reduced `cap_par` of 30.

MUSE uses interpolation for the years which are unknown. So in this example, for the benchmark years between 2020 and 2040 (2025, 2030, 2035), MUSE uses interpolated `cap_par` values. The interpolation mode can be set in the `settings.toml` file, and defaults to linear interpolation. This example uses the default setting for interpolation.

Note that we must also provide entries for 2040 for the other technologies, `gasCCGT` and `windturbine`. For this example, we will keep these the same as before, copying and pasting the rows.

Next we will modify the `CommIn.csv` file.

For this step, we have to provide the input commodities for each technology, in each of the years defined in the `Technodata.csv` file. So, for this example, we are required to provide entries for the years 2020 and 2040 for each of the technologies. For now, we won't change the 2040 values compared to the 2020. Therefore, we just need to copy and paste each of the entries for each of the technologies, as shown below:

ProcessName	RegionName	Time	Level	electricity	gas	heat	CO2f	wind	solar
Unit	-	Year	-	PJ/PJ	PJ/PJ	PJ/PJ	kt/PJ	PJ/PJ	PJ/PJ
gasCCGT	R1	2020	fixed	0	1.67	0	0	0	0
gasCCGT	**R1**	**2040**	**fixed**	**0**	**1.67**	**0**	**0**	**0**	**0**
windturbine	R1	2020	fixed	0	0	0	0	1	0
windturbine	**R1**	**2040**	**fixed**	**0**	**0**	**0**	**0**	**1**	**0**
solarPV	R1	2020	fixed	0	0	0	0	0	1
solarPV	**R1**	**2040**	**fixed**	**0**	**0**	**0**	**0**	**0**	**1**

We must do the same for the `CommOut.csv` file. For the sake of brevity we won't show you this, but the link to the file can be found here (https://github.com/EnergySystemsModellingLab/MUSE_OS/blob/v1.2.1/docs/tutorial-code/1-add-new-technology/2-scenario/technodata/power/CommOut.csv).

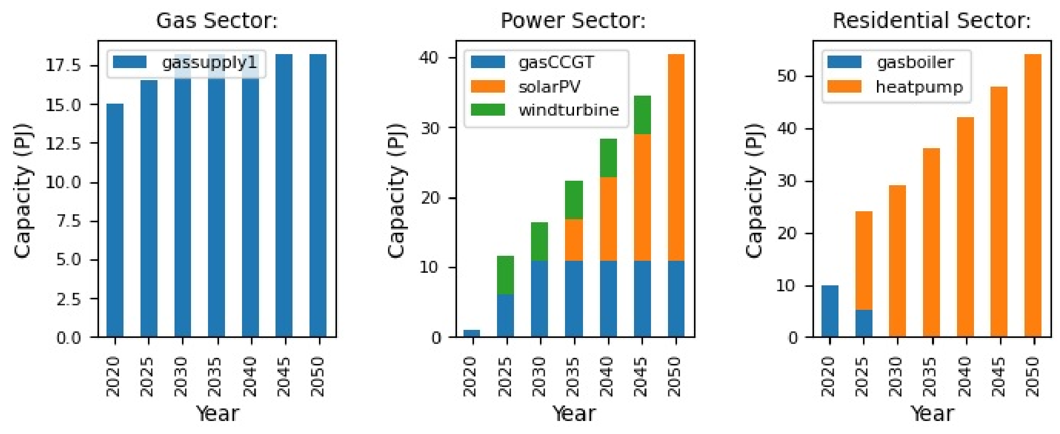
We will now rerun the simulation, using the same command as previously, import the new `MCACapacity.csv` file again, and visualise the results:

In [4]:

```python
mca_capacity = pd.read_csv(
    "../tutorial-code/add-new-technology/2-scenario/Results/MCACapacity.csv"
)

fig, axes = plt.subplots(1, 3)
all_years = mca_capacity["year"].unique()
for ax, (sector_name, sector_data) in zip(axes, mca_capacity.groupby("sector")):
    sector_capacity = sector_data.groupby(["year", "technology"]).sum().reset_index()
    sector_capacity.pivot(
        index="year", columns="technology", values="capacity"
    ).reindex(all_years).plot(kind="bar", stacked=True, ax=ax)
    ax.set_ylabel("Capacity (PJ)")
    ax.set_xlabel("Year")
    ax.set_title(f"{sector_name.capitalize()} Sector:", fontsize=10)
    ax.legend(title=None, prop={"size": 8})
    ax.tick_params(axis="both", labelsize=8)

fig.set_size_inches(8, 2.5)
fig.subplots_adjust(wspace=0.5)
```



From the results, we can see that `windturbine` now outcompetes `solarPV` in the year 2025. However, between the years 2025 and 2050, as the capital cost of `solarPV` decreases, the share of `solarPV` begins to increase.

For the full example with the completed input files see here (https://github.com/EnergySystemsModellingLab/MUSE_OS/tree/main/docs/tutorial-code/1-add-new-technology/2-scenario).

Summary

In this tutorial we have shown how to add a new technology to the model, and how to modify the parameters of this technology. Have a go at modifying some of the other parameters to see how this affects investment decisions.