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Fachgebiet Wirtschafts- und Infrastrukturpolitik

Energy Economics - Energy Sector Modeling

Homework 2

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1 Task 1: Data, Sets and Parameters

a) *Describe how information regarding technology and location of power plants is implemented in the model and how, meaning with what syntax, you can access it.*

External data is provided via csv files which are located in a subfolder named 'data'. These files contain information on technology and location of power plants as well as demand time series and renewable energy sources (RES) time series. Additionally zonal information includng network transfer capacities (NTC) and marginal costs are provided in these files.

All of these datasets are imported into Julia by using the following syntax.

```
# load data from csv
plant_data = loadtable("data/plant_data.csv")
```

After importing the raw .csv files, data sets are derived from certain columns/rows, that are selected and saved in an array format. Or a dictionary is created by filtering relevant information.

```
# select "plant" column
PLANTS = select(plant_data, :plant)
# convert to array
PLANTS = convert(Array, PLANTS)
# or create dictionary containing filtered
# information from data table
PLANT_TECH = Dict()
for tech in TECH
    PLANT_TECH[tech] = convert(Array, select(
    filter(row-> row.technology == tech, plant_data),
    :plant))
end
```

Afterwards another dictionary, containing all data sets, is created to ensure easy access and readibility.

```
# create dictionary containing data arrays
sets = Dict("Plants" => PLANTS
            "Plant_Tech" => PLANT_TECH)
```

The dictionary can be accessed by indexing. As an example: all biomass plants within the sets dictionary can be accessed with the following code.

```
# print all plants powered by biomass
println(sets["Plant_Tech"]["Biomass"])
```

b) *Describe and contrast the different sets PLANTS, DIPS, NONDISP, CONV and RES. Why can the distinction be useful and where is it used in the model?*

- PLANTS: Array of strings containing the name of each plant
- DISP: Array of strings containing all dispatchable plants.
- NONDISP: Array of string containing all plants that are non dispatchable.
- CON: Array of strings containing all conventional plants
- RES: Array of strings that contains all renewable energy plants

The sets DISP, NONDISP, CON and RES are all subsets of PLANTS. DISP and NONDISP dicriminate between dispatchable and non dispatchable power plants while CON and RES is referring to conventional and renewable energy plants. None of the subsets are mutually exclusive because all power plants fall in two subsets. The combinations are as follows:

- DISP - CONV (hard coal, lignite, nuclear, natural gas)
- DISP - RES (biomass)
- NONDISP - RES (solar, wind)

Distinction is useful to set up constraints and objective function properly. The objective function minimizes the sum of total costs incurred by dispatchable power plants, with nonzero marginal costs, whereas nondispatchables are not considered due to their zero marginal costs. As for constraints, it is more intuative to refer to a subset of certain power plants than to use a lookup table or search for all suitale power plants which are affected by the constraint. To evaluate power generation profiles from renewables, it is useful to dinstinguish between RES and CON.

c) *The maximum generation from renewables is defined by the installed capacity and the zonal availaility. Explain what information is needed to account for the zonal RES generation and how this is done in the data processing.*

To calculate zonal generation, information on the zonal availability, the technology type of each plant, maximum generation of each plant, a list of all pv and wind plants, as well as the zonal location of each power plant is necessary. Based on this input, RES generation is calculated for each RES plant on an hourly basis and stored in the array g_res. This RES generation is later fed into the model as a parameter.

Codewise, the availability time series are previously loaded into Julia as data tables and are now allocated to the zones. After that a combined wind and solar availability array is created and then converted to a named array. The power plant generation time series is then calculated by using the combined availability array and multiplying it with the installed capacity for each RES in every zone. The resulting array g_res_array is again converted to the named array g_res.

```julia
# array containing available wind energy in each zone
availability_wind_array = hcat([columns(wind_availability,
    Symbol(z)) for z in ZONES]...)
# array containing available solar energy in each zone
availability_pv_array = hcat([columns(pv_availability,
    Symbol(z)) for z in ZONES]...)
# combine wind and solar availability arrays
combined_avail_array = reshape(hcat(
    availability_wind_array, availability_pv_array),
    8760, 4, 2)
# NamedArray containing wind and solar availability
# for each zone
availability = NamedArray(combined_avail_array,
    (hours, ZONES, ["Wind", "Solar"]),
    ("Hour", "Zone", "Technology"))
# array with RES power generation for each zone
g_res_array = zeros(length(NONDISP), length(hours))
for (i,plant) in enumerate(NONDISP),
 (j,hour) in enumerate(hours)
    g_res_array[i, j] = availability[hour,
    ZONE_PLANTS[plant], TECH_PLANTS[plant]].*g_max[plant]
end
# convert to NamedArray
g_res = NamedArray(g_res_array, (NONDISP, hours),
        ("Plants", "Hours"))
```

2 Task 2: Equations and Variables

a) *Introduce a new positive variable EX to allow exchange between zones. There is a variable for all combinations between zones, therefore indices are (from-)zones, (to-)zones, hours.*

In Julia the new variable is implemented in the @variables section to allow zonal exchanges.

```julia
@variables transport_problem begin
    ...
    EX[ZONES, ZONES, HOUR] >= 0 #Exchange between zones
end
```

b) *Update the energy-balance to account for zonal demand and generation plus exchange to the considered zone from other zones, minus exchange from the considered tone to all other zones. Make sure this applies to generation and demand from storages and renewables.*

The updated energy balance constraint can be modelled as follows, so that it allows zonal exchange under the condition that the energy balance in the zones and in total is not violated.

```
@constraint(transport_problem, Market_Clearing[zone=ZONES,
 hour=HOUR],
    sum(G[disp, hour] for disp in intersect(
     DISP, PLANT_ZONE[zone]))
    + sum(G_RES[nondisp, hour] for nondisp in intersect(
     NONDISP, PLANT_ZONE[zone]))
    + sum(G_stor[stor, hour] for stor in intersect(
     STOR, STOR_ZONE[zone]))
    ==
    demand[hour, zone]
    - sum(EX[from_zone, zone, hour] for from_zone in ZONES)
    + sum(EX[zone, to_zone, hour] for to_zone in ZONES)
    + sum(D_stor[stor, hour] for stor in intersect(
     STOR, STOR_ZONE[zone])));
```

c) *Implement a new constraint to upper-bound the exchange capacity. The parameter ntc is available from the param dictionary.*

To account for the exchange capacity between zones, the following constraint is added.

```
@constraint(transport_problem, NTC[to_zone=ZONES,
 from_zone=ZONES,hour=HOUR],
    EX[from_zone, to_zone, hour] <= ntc[from_zone, to_zone]);
```

3 Task 3: Results

a) *Set the net transfer capacities for all zones to zero and take a look at the resulting price for all zones.*

The network transfer capacity can be set to zero by multiplying the whole ntc array with zero. Since there is no way of exchanging energy between zones, each zone can only match their demand with the installed technologies in the zone. This results in large price differences due to the installed conventional technology, number of storages and installed renewables. Figure 1 shows the prices of all four zones for the first 168 hours. The overall lowest costs are in the eastern zone due to the availability of a pumped storage with no marginal costs.

Although the south has also a pumped storage available, the overall energy costs throughout all time steps are constant at \$20 per MW h. The southern pumped storage never gets filled because of the high marginal costs of natural gas and lack of other, cheaper technologies in the zone.

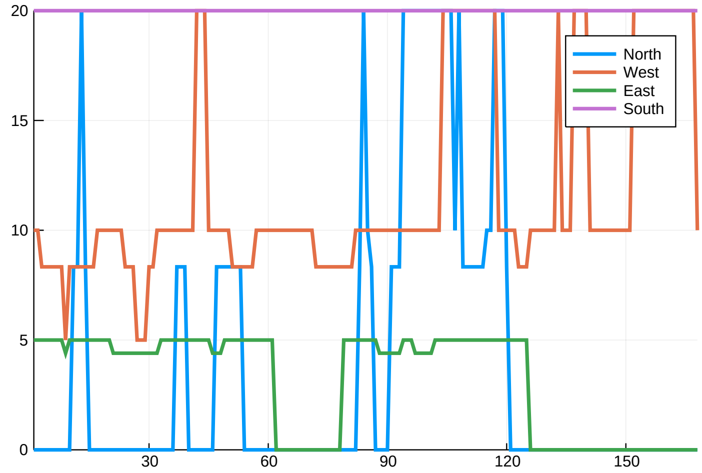

Figure 1: Price tendencies for all four zones in the first 168 hours

It is further notable that the northern region shows the highest volatility regarding its energy prices. Due to the lack of storages, expensive conventional technologies have to be used in times of low RES infeed.

b) *Set the network transfer capacities for all zones to a very high value, such that there is no upper bound for the exchange. How can you tell that there is no congestion?*

To simulate unlimited exchange capacities, the ntc values are multiplied by 10000. The model is then executed again to calculated the prices for all zones. Figure 2 shows the energy costs for all zones.

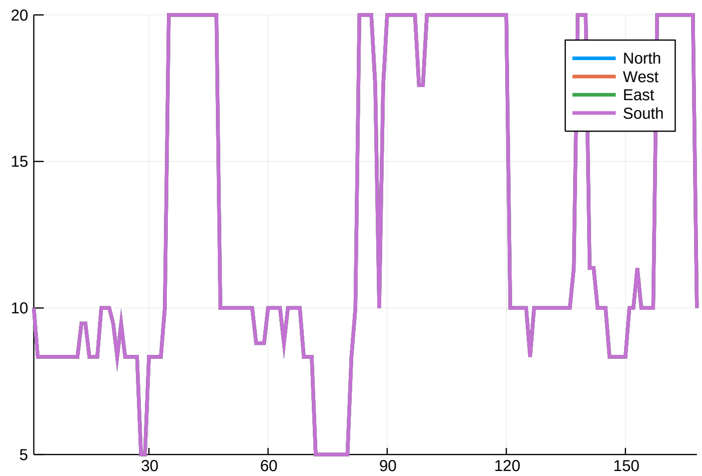

Figure 2: Price tendencies for all four zones in the first 168 hours with no exchange limitations

Since there is no limit for exchange, there is no congestion and all prices are exactly the same.

c) *Use the network transfer capabilities from the data-set at 100% and 50%. Compare the prices to the ones from sutasks a) and b). Describe and explain the differences.*

Lastly two cases are observed. The first case applies the nominal NTCs at 100%, while the second case applies them at 50% rate. Figure 3 shows the energy prices for all four zones with nominal network transfer capacities and fig. 4 shows them at half their value. It's clearly observable that in both cases prices are volatile and increase

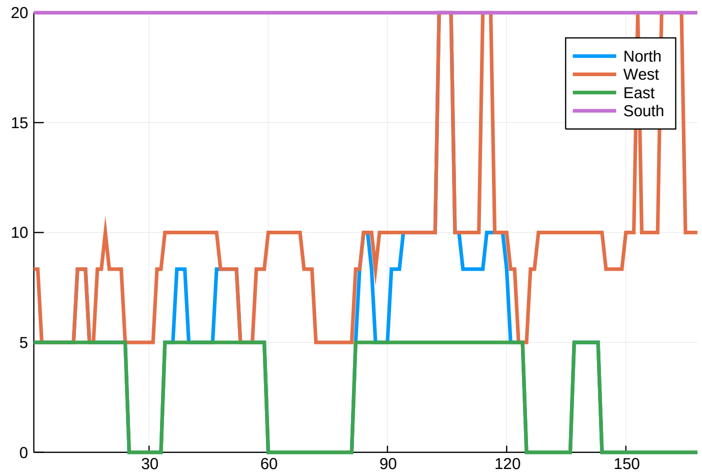

Figure 3: Price tendencies for all four zones in the first 168 hours with given NTCs

in times of peak load. When the transfer capacities reach their limits (transmission line constraint is binding), market splitting occurs, meaning all four zones have different energy prices. Comparing to the previous subtasks, energy prices are generally lower. Especially for the northern and western zone, the peak loads are not compensated by domestic generation but by obtaining energy from cheaper technologies from the other zones. Namely the eastern region has higher energy costs throughout the whole times series in favor of lowering the overall energy prices of all zones. The only region that doesn't profit from a joint market is the southern zone as it still serves almost all of its demand by domestic generators, keeping the price constant at \$20 per MW h.

Further comparing the two simulation cases, it becomes visible that market splitting occurs more often when NTCs are at half their value. This is a direct answer to congested transmission lines that are dedicated for exchange. Since they can carry only half the energy in contrast to the nominal NTC, congestion forces the markets to split up. Interestingly not all markets are splitted, more often it can be seen that two or three zones share the same market because their transmission lines have not been congested.

It is also notable that in the second case more wind curtailment can be seen in the northern zone, since excess energy can't be stored or transmitted due to congested lines.

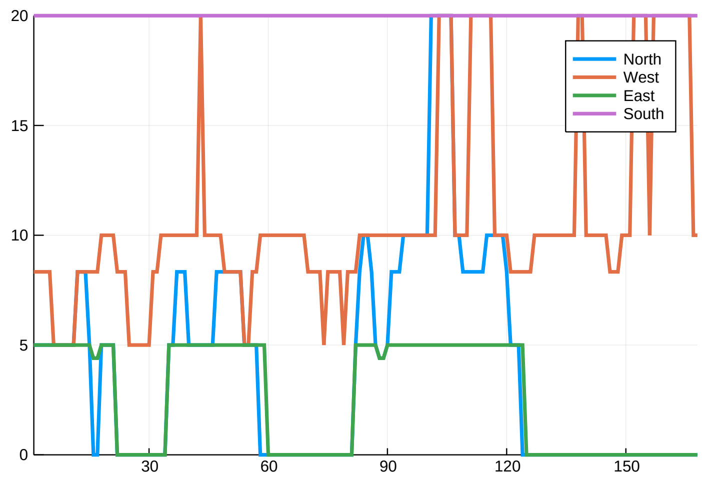

Figure 4: Price tendencies for all four zones in the first 168 hours with given NTCs at 50%

Lastly it can be observed that the energy prices in the first case with nominal NTCs are slightly less volatile compared to the second case with half the nominal NTC value.

d) *In the lecture we talked about the energy-only market, market-coupling and market splitting. Describe these concepts and put them into context to the modeled system. Explain how these concepts are represented in the model and if not, what additional constraints/representations are missing. Refer to the paper by Ehrenmann and Smeers.*

Energy-Only Market: This type of market design implies that only energy is traded and power plants get compensated for their actual power generation. Other services such as providing operative reserves, namely spinning and non-spinning reserves, are not compensated or rewarded. The model at hand represents an energy-only market since only energy is traded. Energy generation costs are minimized and the price for energy is determined by aggregate supply (merit order) and demand, as well as possible transmission line congestions. The market for operating reserves is not modelled and power plants such as natural gas plants don't get rewarded for reserving power for peak load times.

Market Coupling: A mechanism of connecting at least two neighbouring energy markets with means of cross-border interconnectors such that the overall economic welfare is increased due to market integration, is usually refered to as market coupling. If preliminary settlement of energy markets leads to different market prices in neighbouring countries, or zones, electricity can be traded between the two zones such that the overall efficiency is increased and the price difference decreases. A representation of market coupling in the model could be done by assuming that the settled energy price in each zone is a function of its net imports. Based on these inverse demand functions, the energy trade between zones is settled on an interzonal market [1].

Furthermore, the model at hand could be improved regarding its market coupling by preliminarily clearing each zone's energy balance. Afterwards interzonal trading can be admitted.

Market Splitting: Market splitting divides a single energy market into two or more zones due to lack of intraline capacity, resulting in line congestions. The subzones will then have different prices and trading etween subzones is allowed. Market splitting can be seen in subtask 3c, where market splitting between two or more zones occurs temporarily as a result of line congestions. As explained in [1, p. 16], the zones resulting from market splitting can be fixed or variable. The latter can be observed in the transport model.

References

[1] Andreas Ehrenmann, Yves Smeers, *Inefficiencies in European Congestion Management Proposals*, Utilities policy journal, Volume 13, Pages 135-152, Pergamon, 2005.