

```
In [1]: using DataFrames, Plots, Statistics, JSON, Clp
plotlyjs()
include(joinpath(dirname(pwd()),"src/TuLiPa.jl")); # using Dates, JuMP, HiGHS, CSV, Cluster
```

The WebIO Jupyter extension was not detected. See the [WebIO Jupyter integration documentation](#) for more information.

Demo 2 - Deterministic power market with detailed data

Demo 1 gave an introduction to the TuLiPa framework and how a dataset can be built, and how a problem can be built, updated, solved and results queried. Demo 2 will show that TuLiPa also can be used on a more complete dataset, and with more complex model objects.

Overview of the document:

1 - European power market problem

1.1-1.3 Build, solve and look at solution

1.4 Look at time usage with different types of horizons.

1.5 Compare time usage between JuMP_Prob and HiGHS_Prob.

1.6 Compare time usage with different solvers.

1.7 Generate price-series for hydropower scheduling

1. Power market problem with European dataset

This is a simplified version of the dataset NVE uses for its long-term power market analyses (for example <https://www.nve.no/energi/analyser-og-statistikk/langsiktig-kraftmarkedsanalyse/>). The dataset consist of:

- Detailed thermal units, aggregated hydro (Res, RoR, PHS), inelastic wind and solar, demands (inelastic with rationing price), storages (hydro and battery), transmission (ATC) and price areas (endogenous and exogenous).
- Levels in 2021, 2025, 2030, 2040 and 2050 (e.g. commodity price levels, installed production/transmission/storage capacities etc.)
- Profiles (e.g. availability profiles for transmission or production units, commodity price profiles, weather scenario profiles 1981-2010 for demand, solar, wind and inflow etc.)

We cannot publish the full dataset, but many of the profiles for wind, solar, hydro and demand can be downloaded from <https://www.nve.no/energi/analyser-og-statistikk/verdiasett-for-kraftsystemmodellene/>.

NB!

- In Demo 2 we use the model year 2025. This scenario was made a couple of years ago and results should be considered outdated. A lot has happened in the power market since then. In addition the dataset is very simplified.

1.1 Functions that adds or removes model objects to complete the dataset

```
In [2]: # The hydropower storages in the dataset needs boundary conditions for the state variables
function addStartEqualStopAllStorages!(modelobjects)
    for obj in values(modelobjects)
        if obj isa BaseStorage
            trait = StartEqualStop(obj)
            modelobjects[getid(trait)] = trait
        end
    end
end

# Power balances needs slack variable for when the inelastic supply (wind, solar, RoR) is / needs slack variable for when the inelastic supply (wind, solar, RoR) is /
function addPowerUpperSlack!(modelobjects) # add after object manipulation
    for obj in values(modelobjects)
        if obj isa BaseBalance
            if getid(getcommodity(obj)) == Id("Commodity", "Power")
                balancename = getinstancename(getid(obj))

                varname = "SlackVar_" * balancename
                varkey = Id(FLOW_CONCEPT, varname)
                var = BaseFlow(varkey)

                sethorizon!(var, gethorizon(obj))
                setlb!(var, LowerZeroCapacity())

                arrowname = "SlackArrow_" * balancename
                arrowkey = Id(ARROW_CONCEPT, arrowname)
                arrow = BaseArrow(arrowkey, obj, BaseConversion(PlusOneParam()), 0)
                addarrow!(var, arrow)

                modelobjects[varkey] = var
            end
        end
    end
end

# Remove start-up costs. Does not make sense to have them when the horizon does not have a
function remove_startupcosts!(modelobjects)
    for (id,obj) in modelobjects
        if obj isa StartUpCost
            delete!(modelobjects, id)
        end
    end
end

Out[2]: remove_startupcosts! (generic function with 1 method)
```

1.2 Function that builds, updates and solves the problem, and plot the results

The function runs several scenarios and plot prices, production, demand and hydro storage for each scenario. The function only plots results for chosen price areas.

Unlike Demo 1, the function now support more types of objects. This includes AdaptiveHorizons (horizon built based on residual load), Horizons with offset, SegmentedArrow (for hydropower plants

with PQ-curves), BaseAggSupplyCurve (for aggregated power plants) and ExogenBalance (exogen price areas)

```
In [3]: # Make List of scenarios
function getscenarios(dt; years)
    [TwoTime(getisoyearstart(dt), getisoyearstart(yr)) for yr in years]
end

# Run scenarios and plot results from the whole problem
function runscenarios(scenarios, modelobjects)
    runscenarios(scenarios, modelobjects, values(modelobjects))
end

# Run scenarios and plot results from chosen model objects (e.g. only one price area)
function runscenarios(scenarios, modelobjects, resultobjects)
    numperiods_powerhorizon = getnumperiods(power_horizon)
    numperiods_hydrohorizon = getnumperiods(hydro_horizon)

    # We use the datatime for plotting results
    dt = getdatatime(scenarios[1])

    # Time vector for power_horizon, can be Adaptive
    if power_horizon isa AdaptiveHorizon
        numperiods_data = Int(getduration(hydro_horizon)/power_horizon.unit_duration)
        x1 = [dt + power_horizon.unit_duration*(t-1) for t in 1:numperiods_data]
    else
        numperiods_data = numperiods_powerhorizon
        x1 = [dt + getstartduration(power_horizon, t) for t in 1:numperiods_powerhorizon]
    end

    # Time vector for hydro_horizon
    x2 = [dt + getstartduration(hydro_horizon, t) for t in 1:numperiods_hydrohorizon]

    # Horizons can have offset, assumes its the same for both horizons
    if hasoffset(hydro_horizon)
        x1 = x1 .+ getduration(getoffset(power_horizon))
        x2 = x2 .+ getduration(getoffset(hydro_horizon))
    end

    # Problem can be a HiGHS_Prob or a JuMP_Prob
    # mymodel = JuMP.Model(HiGHS.Optimizer)
    # set_silent(mymodel)
    # prob = JuMP_Prob(collect(values(modelObjects)), mymodel)

    @time prob = HiGHS_Prob(collect(values(modelobjects)))

    # Order result objects into lists
    powerbalances = []
    rhsterms = []
    plants = []
    plantbalances = []
    plantarrows = Dict()
    demands = []
    demandbalances = []
    demandarrows = Dict()
    hydrostorages = []

    for obj in resultobjects # regret using Ids rather than the whole object

        # Powerbalances
        if obj isa BaseBalance
            if getinstancename(getid(getcommodity(obj))) == "Power"
                if !isexogen(obj)
                    push!(powerbalances, getid(obj))
                    for rhsterm in getrhsterms(obj)
                        push!(rhsterms, getid(rhsterm))
                    end
                end
            end
        end
    end
end
```

```

        end
    end

    # Hydrostorages
    if obj isa BaseStorage
        if getinstancename(getid(getcommodity(getbalance(obj)))) == "Hydro"
            push!(hydrostorages,getid(obj))
        end
    end

    # Supply and demands
    if obj isa BaseFlow
        # The type of supply or demand can be found based on the arrows
        arrows = getarrows(obj)

        # Simple supplies and demands
        powerarrowbool = [(getid(getcommodity(getbalance(arrow))) == Id("Commodity", "Power"))
        powerarrows = arrows[powerarrowbool]
        if sum(powerarrowbool) == 1
            if isingoing(powerarrows[1])
                push!(plants,getid(obj))
                push!(plantbalances,getid(getbalance(powerarrows[1])))
            elseif !isingoing(powerarrows[1])
                push!(demands,getid(obj))
                push!(demandbalances,getid(getbalance(powerarrows[1])))
            end
        end

        # Transmissions
        if sum(powerarrowbool) == 2
            for arrow in arrows
                balance = getbalance(arrow)
                if getid(getcommodity(balance)) == Id("Commodity", "Power")
                    if isingoing(arrow) && (balance in resultobjects)
                        push!(plants,getid(obj))
                        push!(plantbalances,getid(balance))
                        if isexogen(balance)
                            plantarrows[getid(obj)] = arrow
                        end
                    elseif !isingoing(arrow) && (balance in resultobjects)
                        push!(demands,getid(obj))
                        push!(demandbalances,getid(balance))
                        if isexogen(balance)
                            demandarrows[getid(obj)] = arrow
                        end
                    end
                end
            end
        end
    end

    # Supplies with SegmentedArrows (hydropower with PQ-kurves)
    pqarrowbool = [arrow isa SegmentedArrow for arrow in arrows]
    pqarrows = arrows[pqarrowbool]
    if sum(pqarrowbool) == 1
        if isingoing(pqarrows[1])
            push!(plants,getid(obj))
            push!(plantbalances,getid(getbalance(pqarrows[1])))
        end
    end

    # Aggregated supplies (thermal power plants aggregated into one or more equivalent
    # TODO: Result should be a sum of all clusters, not separated
    if obj isa BaseAggSupplyCurve
        instance = getinstancename(getid(obj))
        concept = getconceptname(getid(obj))
        balance = getbalance(obj)
        for c in 1:getnumclusters(obj)

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        newname = string(instance, "_", c)
        push!(plants, Id(concept, newname))
        push!(plantbalances, getid(balance))
    end
end
end

# Matrices to store results per time period, scenario and object
prices = zeros(numperiods_data, length(scenarios), length(powerbalances))
rhstermvalues = zeros(numperiods_data, length(scenarios), length(rhsterms))
production = zeros(numperiods_data, length(scenarios), length(plants))
consumption = zeros(numperiods_data, length(scenarios), length(demands))
hydrolevels = zeros(numperiods_hydrohorizon, length(scenarios), length(hydrostorages))

# Update and solve scenarios, and collect results
for (s, t) in enumerate(scenarios)
    @time update!(prob, t)

    @time solve!(prob)

    println("Objective value in scenario $(s): ", getobjectivevalue(prob))

    # Collect results for power production/demand/transmission in GW
    if power_horizon isa SequentialHorizon
        for j in 1:numperiods_powerhorizon

            # Timefactor transform results from GWh to GW/h regardless of horizon period
            timefactor = getduration(gettimedelta(power_horizon, j))/Millisecond(3600000)

            # For powerbalances collect prices and rhsterms (Like inelastic demand, will not change)
            for i in 1:length(powerbalances)
                prices[j, s, i] = getconddual(prob, powerbalances[i], j)/1000 # from €/GWh to GW/h
                for k in 1:length(rhsterms)
                    if hasrhsterm(prob, powerbalances[i], rhsterms[k], j)
                        rhstermvalues[j, s, k] = getrhsterm(prob, powerbalances[i], rhsterms[k], j)
                    end
                end
            end

            # Collect production of all plants
            for i in 1:length(plants) # TODO: Balance and variable can have different horizons
                concept = getconceptname(plants[i])
                if concept != AGGSUPPLYCURVE_CONCEPT
                    arrows = getarrows(modelobjects[plants[i]])
                    pqarrowbool = [arrow isa SegmentedArrow for arrow in arrows]
                    pqarrows = arrows[pqarrowbool]
                    if sum(pqarrowbool) == 1
                        production[j, s, i] = 0
                        for k in 1:length(getconversions(pqarrows[1]))
                            segmentid = getsegmentid(pqarrows[1], k)
                            production[j, s, i] += getvarvalue(prob, segmentid, j)*abs(getconversionvalue(prob, segmentid, k))
                        end
                    else
                        if isexogen(modelobjects[plantbalances[i]])
                            # TODO: Balance and variable can have different horizons
                            arrow = plantarrows[plants[i]]
                            horizon = gethorizon(arrow)
                            conversionparam = _getcontributionparam(arrow)
                            querytime = getstarttime(horizon, j, t)
                            querydelta = gettimedelta(horizon, j)
                            conversionvalue = getparamvalue(conversionparam, querytime, querydelta)
                            production[j, s, i] = getvarvalue(prob, plants[i], j)*conversionvalue
                        else
                            production[j, s, i] = getvarvalue(prob, plants[i], j)*abs(getconversionvalue(prob, plants[i], j))
                        end
                    end
                else
                    production[j, s, i] = getvarvalue(prob, plants[i], j)*abs(getconceptvalue(prob, concept, j))
                end
            end
        end
    end
end

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    end

    # Collect demand of all demands
    for i in 1:length(demands) # TODO: Balance and variable can have different
        if isexogen(modelobjects[demandbalances[i]])
            arrow = demandarrows[demands[i]]
            horizon = gethorizon(arrow)
            conversionparam = _getcontributionparam(arrow)
            querytime = getstarttime(horizon, j, t)
            querydelta = gettimedelta(horizon, j)
            conversionvalue = getparamvalue(conversionparam, querytime, querydelta)
            consumption[j, s, i] = getvarvalue(prob, demands[i], j)*conversionvalue
        else
            consumption[j, s, i] = getvarvalue(prob, demands[i], j)*abs(getcontributionparam(arrow))
        end
    end
end

else # if power_horizon isa AdaptiveHorizon it is more complex (also test switching)
    # Non-consecutive time units have been aggregated in the model, and values need
    acc = 0
    prev_acc = 0
    for mp in 1:numperiods_hydrohorizon
        for block in 1:power_horizon.num_block
            j = (mp-1)*power_horizon.num_block + block
            period = power_horizon.periods[j]
            timefactor = getduration(period)/Millisecond(3600000)
            acc += getlength(period)
            for segment in period.units
                for unit in segment
                    fineperiod = prev_acc + unit
                end
            end
        end
    end

    # For powerbalances collect prices and rhsterms (Like inelasticities)
    for i in 1:length(powerbalances)
        prices[fineperiod, s, i] = getcondual(prob, powerbalances[i])
        for k in 1:length(rhsterms)
            if hasrhsterm(prob, powerbalances[i], rhsterms[k], j)
                rhstermvalues[fineperiod, s, k] = getrhsterm(prob, powerbalances[i], rhsterms[k], j)
            end
        end
    end

    # Collect production of all plants
    for i in 1:length(plants) # TODO: Balance and variable can have different
        concept = getconceptname(plants[i])
        if concept != AGGSUPPLYCURVE_CONCEPT
            arrows = getarrows(modelobjects[plants[i]])
            pqarrowbool = [arrow isa SegmentedArrow for arrow in arrows]
            pqarrows = arrows[pqarrowbool]
            if sum(pqarrowbool) == 1
                for k in 1:length(getconversions(pqarrows[1]))
                    segmentid = getsegmentid(pqarrows[1], k)
                    production[fineperiod, s, i] += getvarvalue(prob, plants[i], segmentid)
                end
            else
                if isexogen(modelobjects[plantbalances[i]])
                    # TODO: Balance and variable can have different
                    arrow = plantarrows[plants[i]]
                    horizon = gethorizon(arrow)
                    conversionparam = _getcontributionparam(arrow)
                    querytime = getstarttime(horizon, j, t)
                    querydelta = gettimedelta(horizon, j)
                    conversionvalue = getparamvalue(conversionparam, querytime, querydelta)
                    production[j, s, i] = getvarvalue(prob, plants[i], j)*conversionvalue
                else
                    production[fineperiod, s, i] = getvarvalue(prob, plants[i], j)
                end
            end
        else
            production[fineperiod, s, i] = getvarvalue(prob, plants[i], j)
        end
    end
end

```

```

                end
            end

            # Collect demand of all demands
            for i in 1:length(demands) # TODO: Balance and variable can have different lengths
                if isexogen(modelobjects[demandbalances[i]])
                    arrow = demandarrows[demands[i]]
                    horizon = gethorizon(arrow)
                    conversionparam = _getcontributionparam(arrow)
                    querytime = getstarttime(horizon, j, t)
                    querydelta = gettimedelta(horizon, j)
                    conversionvalue = getparamvalue(conversionparam, querytime)
                    consumption[j, s, i] = getvarvalue(prob, demands[i], j)
                else
                    consumption[fineperiod, s, i] = getvarvalue(prob, demands[i], j)
                end
            end
            end
            prev_acc = acc
        end
    end

    # Collect hydro storage levels
    for j in 1:numperiods_hydrohorizon
        for i in 1:length(hydrostorages)
            hydrolevels[j, s, i] = getvarvalue(prob, hydrostorages[i], j)/1000 # Gm3 To MWh
        end
    end
end

# Only keep rhsterms that have at least one value (TODO: Do the same for supply and demands)
rhstermtotals = dropdims(sum(rhstermvalues,dims=(1,2)),dims=(1,2))
rhstermsupplyidx = []
rhstermdemandidx = []

for k in 1:length(rhsterms)
    if rhstermtotals[k] < 0
        push!(rhstermsupplyidx, k)
    elseif rhstermtotals[k] > 0
        push!(rhstermdemandidx, k)
    end
end

# Put rhsterms together with supplies and demands
rhstermsupplyvalues = rhstermvalues[:, :, rhstermsupplyidx]*-1
rhstermdemandvalues = rhstermvalues[:, :, rhstermdemandidx]

rhstermsupplynames = [getinstancename(rhsterm) for rhsterm in rhsterms[rhstermsupplyidx]]
rhstermdemandnames = [getinstancename(rhsterm) for rhsterm in rhsterms[rhstermdemandidx]]

supplynames = [[getinstancename(plant) for plant in plants];rhstermsupplynames]
supplyvalues = reshape([vcat(production...);vcat(rhstermsupplyvalues...)],(numperiods,1))

demandnames = [[getinstancename(demand) for demand in demands];rhstermdemandnames]
demandvalues = reshape([vcat(consumption...);vcat(rhstermdemandvalues...)],(numperiods,1))

# Prepare for plotting results
hydronames = [getinstancename(hydro) for hydro in hydrostorages]
powerbalancenames = [split(getinstancename(powerbalance), "PowerBalance_")[2] for powerbalance in powerbalances]

# Plot results for each scenario
for (s, t) in enumerate(scenarios)
    scenyear = string(getisoyear(getscenariotime(t)))
    datayear = string(getisoyear(getdatatime(t)))

    # Plot prices
    display(plot(x1, sum(prices[:,s,:],dims=3), labels=reshape(powerbalancenames,1,length(powerbalancenames)), title="Power Prices"))

```

```

# Plot supplies and demands
# supplychart = areaplot(x1, sum(supplyvalues[:,s,:]), dims=3), labels=reshape(supplynames,1,1,3)
# demandchart = areaplot(x1, sum(demandvalues[:,s,:]), dims=3), labels=reshape(demandnames,1,1,3)
# display(plot([supplychart,demandchart]...), layout=(1,2), size=(1600,500))
supplychart = areaplot(x1, sum(supplyvalues[:,s,:]), dims=(3,2)), title="Supply", ylab="Supply"
demandchart = areaplot(x1, sum(demandvalues[:,s,:]), dims=(3,2)), title="Demand", ylab="Demand"
display(plot([supplychart,demandchart]...), layout=(1,2), size=(900,500))

# Plot storages (only TWh because of our input data)
display(areaplot(x2, sum(hydrolevels[:,s,:]), dims=3), labels=reshape(hydronames,1,1,3))

# Plot List of yearly mean production and demand for each supply/demand
meandemand = dropdims(mean(demandvalues[:,s,:]), dims=1)
meanproduction = dropdims(mean(supplyvalues[:,s,:]), dims=1)
supplydf = sort(DataFrame(Supplyname = supplynames, Yearly_supply_TWh = meanproduction))
demanddf = sort(DataFrame(Demandname = demandnames, Yearly_demand_TWh = meandemand))
supplydf[!, :ID] = collect(1:length(supplynames))
demanddf[!, :ID] = collect(1:length(demandnames))
joineddf = select!(outerjoin(supplydf, demanddf; on=:ID), Not(:ID))
# show(joineddf, allcols=true, allrows=true)

# Check that total supply equals total demand
show(combine(joineddf, [:Yearly_supply_TWh, :Yearly_demand_TWh] .-> sum(skipmissing))
end
end;

```

1.3 - Assemble dataset and run scenarios

Read dataelements stored in two JSON-files (structure and timeseries)

```
In [25]: sti_themadata = "data_fra_thema"
tst = JSON.parsefile(joinpath(sti_themadata, "dataset_thema.json"))
themastructure = getelements(tst)
tse = JSON.parsefile(joinpath(sti_themadata, "tidsserier_thema.json"))
themaseries = getelements(tse, sti_themadata)

elements = vcat(themaseries, themastructure)
length(elements)
```

Out[25]: 9426

Alternatively we could combine the European dataset with our detailed hydropower (full watercourses, restrictions, pq-kurves) dataset for Norway and Sweden (see demo 4)

This would increase the problem size a lot, so we could not continue with this dataset without aggregating it somehow. But it gives the user the possibility to aggregate the hydropower however they want.

NB! We don't continue with this dataset.

```
In [5]: sti_themadata = "data_fra_thema"
tst = JSON.parsefile(joinpath(sti_themadata, "dataset_thema_excl_hydro_nose.json")) # Europe
themastructure = getelements(tst)
tse = JSON.parsefile(joinpath(sti_themadata, "tidsserier_thema.json"))
themaseries = getelements(tse, sti_themadata)

dse = JSON.parsefile("data_fra_dynmodell/tidsserier_detd.json")
detdsseries = getelements(dse);
```

```

dst = JSON.parsefile("data_fra_dynmodell/dataset_detd.json")
detdstructure = getelements(dst);

elements1 = vcat(themaseries, themastructure, detdseries, detdstructure)
length(elements1)

Out[5]: 35314

```

Runsettings to complete the dataset

```

In [26]: # Select the weather scenarios 1981-2010
# Used by RotatingTimeVector to reduce the amount of data
scenarioyearstart = 1981
scenarioyearstop = 2011
push!(elements, getelement(TIMEPERIOD_CONCEPT, "ScenarioTimePeriod", "ScenarioTimePeriod",
                           ("Start", getisoyearstart(scenarioyearstart)), ("Stop", getisoyearstart(scenarioye

# We choose the horizon (time-resolution) of the commodities. We set the duration of the hor
# Having different horizons for different commodities gives flexibility. Here we use it to
# variables connected to power, than variables connected to hydro. We also need the storage

# The hydro horizon is sequential with a weekly time-resolution.
hydro_horizon = SequentialHorizon(13*4, Hour(168))

# The power horizon is an AdaptiveHorizon which is dynamically built based on the residual
# There are 7 clusters, which mean that the power horizon will have 7 periods inside each l
# For each hydro horizon period, units (hours) are grouped together with units that have a
rhsdata = DynamicRHSAGHData("Power") # alternative StaticRHSAGHData("Power", 2021, scenarioye
# rhsdata = StaticRHSAGHData("Power", 2025, scenarioyearstart, scenarioyearstop)
method = KMeansAHMethod() # alternative PercentilesAHMethod()
clusters = 7
unit_duration = Hour(3)
power_horizon = AdaptiveHorizon(clusters, unit_duration, rhsdata, method, 13*4, Hour(168))
# power_horizon = SequentialHorizon(13*4*5, Hour(168))

# Insert horizons into commodities. E.g. all batteries will have the power horizon, since i
function set_horizon!(elements, commodity, horizon)
    # If element already exist, replace horizon with new
    for element in elements
        if element.typename == "BaseCommodity"
            if element.instancename == commodity
                element.value[HORIZON_CONCEPT] = horizon
                return
            end
        end
    end
    # Else, add commodity to element list
    push!(elements, getelement(COMMODITY_CONCEPT, "BaseCommodity", commodity,
                               (HORIZON_CONCEPT, horizon)))
end

# The power horizon will be assigned to everything contributing to the power market, or bas
set_horizon!(elements, "Power", power_horizon)
set_horizon!(elements, "Battery", power_horizon)

# The hydro horizon will be assigned to storages, bypasses and spill variables of hydropow
set_horizon!(elements, "Hydro", hydro_horizon);

```

Convert DataElements into modelobjects

```

In [27]: modelobjects = getmodelobjects(elements);
length(modelobjects)

Out[27]: 1407

```

Simplify market description and add boundary conditions

When the model objects have been created we can manipulate them however we want. In this example we simplify the problem by aggregating areas and power plants, and removing short term storage systems and start-up costs. We also add boundary conditions to storages.

```
In [28]: function simplify!(modelobjects)
    # Aggregate price areas and add power balance slack variables
    # For the new area FRACHE, the transmission line FRA-CHE is transformed into a demand line
    aggzoneareadict = Dict("NLDBEL" => ["NLD", "HUB_NLD", "BEL", "HUB_BEL"],
                           "FRACHE" => ["FRA", "CHE"],
                           "AUTCZE" => ["AUT", "CZE"],
                           "BAL" => ["LTU", "LVA", "EST", "HUB_OST"],
                           "DMK" => ["DK1", "HUB_DK1", "DK2", "HUB_DK2"],
                           "NOS" => ["NO1", "NO2", "NO5"],
                           "NON" => ["NO3", "NO4"],
                           "SEN" => ["SE1", "SE2"],
                           "SES" => ["SE3", "SE4"])
    aggzonedict = Dict()
    for (k,v) in aggzoneareadict
        aggzonedict[Id(BALANCE_CONCEPT, "PowerBalance_" * k)] = [modelobjects[Id(BALANCE_CO...
    end

    aggzone!(modelobjects, aggzonedict)

    # Add slack variable for excessive renewable power
    addPowerUpperSlack!(modelobjects)

    # Start-up-costs are not compatible with aggregatesupplycurve! or AdaptiveHorizon
    remove_startupcosts!(modelobjects)

    # Aggregate all simple plants (only connected to power market, mostly thermal) for each
    aggregatesupplycurve!(modelobjects, 4)

    # Short-term storage systems are only needed when the horizon is fine
    removestoragesystems!(modelobjects, Hour(10))

    # Only calculate AdaptiveHorizon based on residual loads in these areas
    residualloadareas!(modelobjects, ["DEU", "NLDBEL", "POL", "GBR", "BAL"])

    # Storages have state-dependant variables that need a boundary conditions
    # We set the starting storage to be equal to the ending storage, x[0] = x[T] (for horizons > 1)
    addStartEqualStopAllStorages!(modelobjects)
end

simplify!(modelobjects);
```

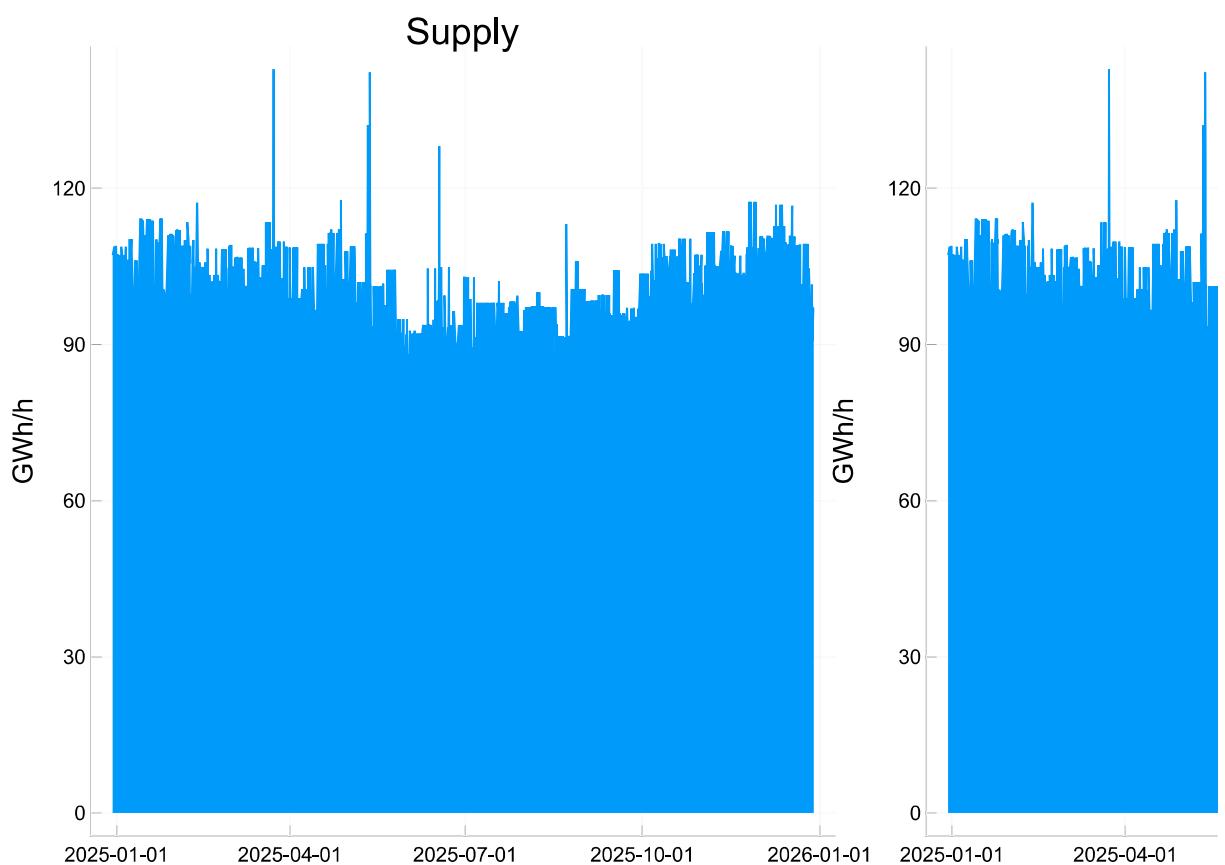
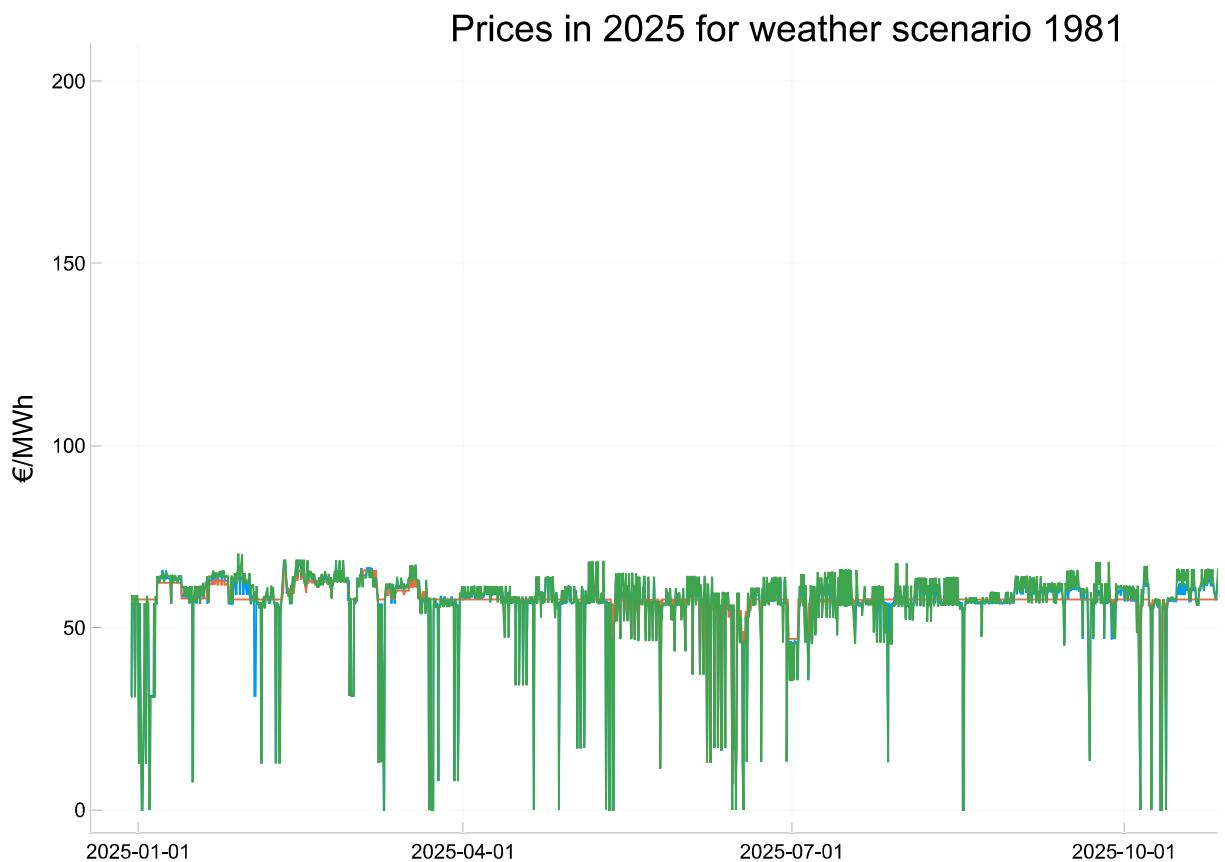
Solve a problem and plot results

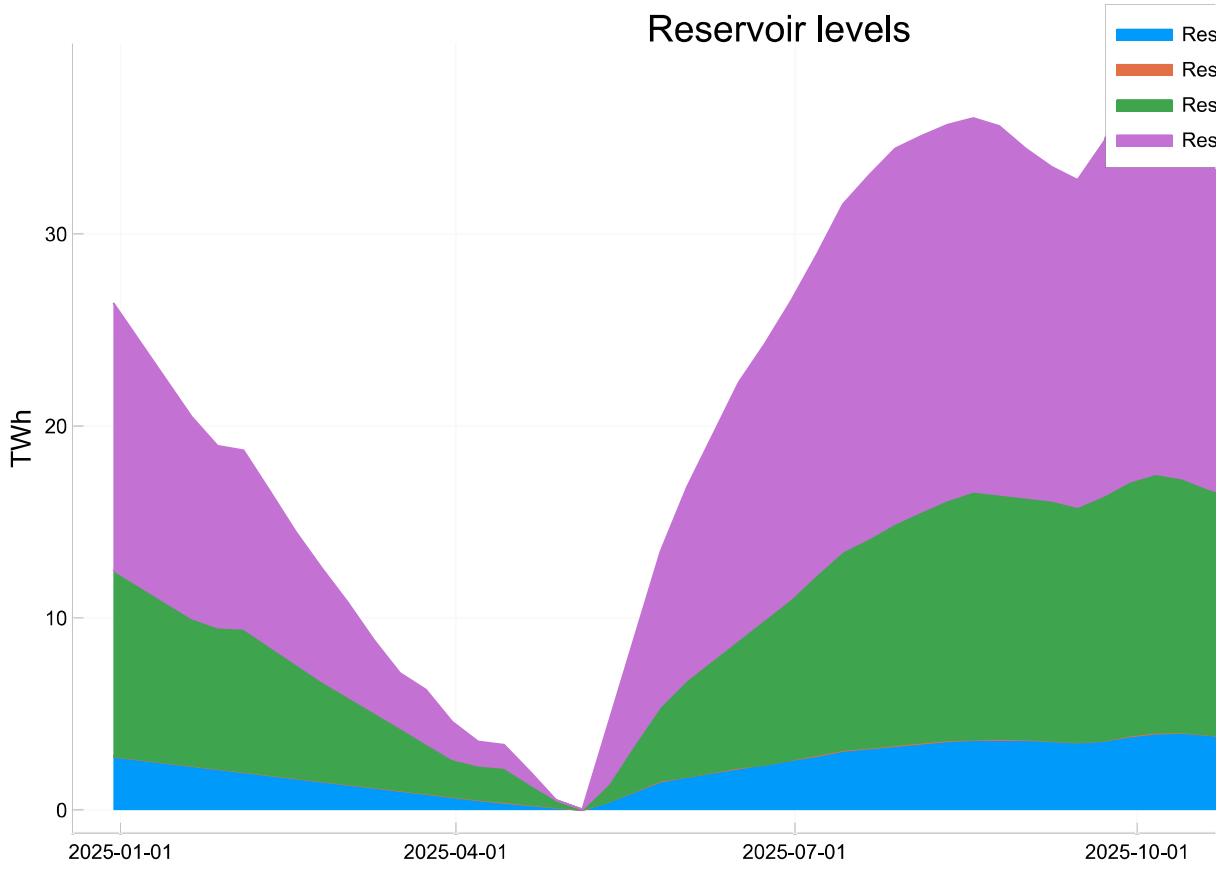
Due to AdaptiveHorizon we get hourly price volatility even though the LP-problem only has seven periods per week. This leads to seven price levels per week, where hours with similar residual loads will have the same price, because they were grouped together into one period.

```
In [29]: # Choose scenarios
scenarios = getscenarios(2025; years=1981:1981)

# Choose areas to see results from
resultobjects = getpowerobjects(modelobjects, ["NOS", "DMK", "DEU"]) #, "NOS", "DMK", "DEU", "FRACHE"
runscenarios(scenarios, modelobjects, resultobjects)
```

```
0.162143 seconds (1.00 M allocations: 81.181 MiB)
0.509293 seconds (4.76 M allocations: 162.221 MiB)
0.940007 seconds
Objective value in scenario 1: 5.357321527781434e10
```





```
1x2 DataFrame
Row | Yearly_supply_TWh_sum_skipmissing  Yearly_demand_TWh_sum_skipmissing
    |          Float64                  Float64
1   |             862.1                  862.1
```

Change power horizon to be with daily resolution

Still the same amount of periods as the adaptive horizon, but the price has a lot less volatility now.

```
In [30]: # Function to change power_horizon in elements List and make List of modelobjects
function get_modelobjects!(elements, new_power_horizon, new_hydro_horizon=nothing)

    # Change power_horizon in elements List
    set_horizon!(elements, "Power", new_power_horizon)
    set_horizon!(elements, "Battery", new_power_horizon)

    # Set new power_horizon to the global variable
    global power_horizon = new_power_horizon

    # If hydro horizon is changed
    if !isnothing(new_hydro_horizon)
        set_horizon!(elements, "Hydro", new_hydro_horizon)
        global hydro_horizon = new_hydro_horizon
    end

    # Create modelobjects and manipulate
    modelobjects = getmodelobjects(elements)
    simplify!(modelobjects)

    return modelobjects
end

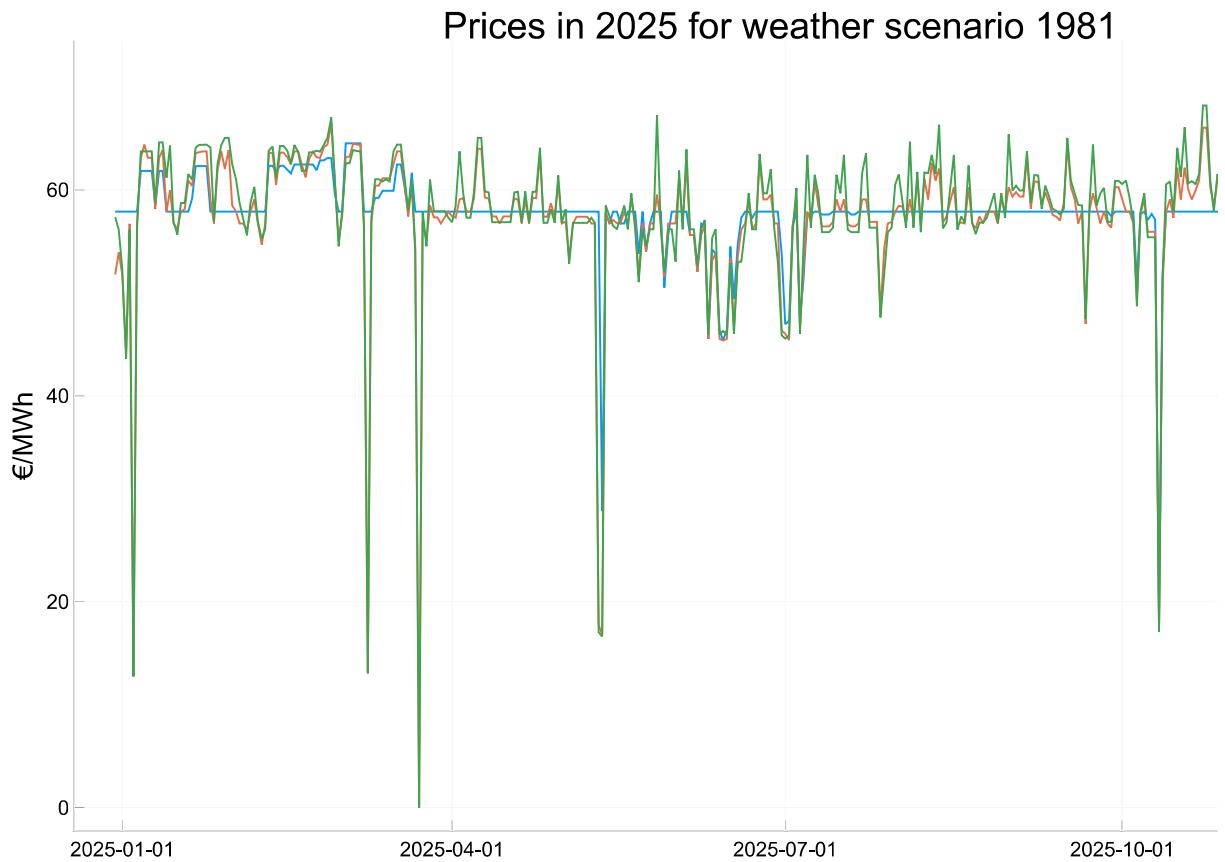
power_horizon = SequentialHorizon(52*7, Day(1))
modelobjects = get_modelobjects!(elements, power_horizon)
```

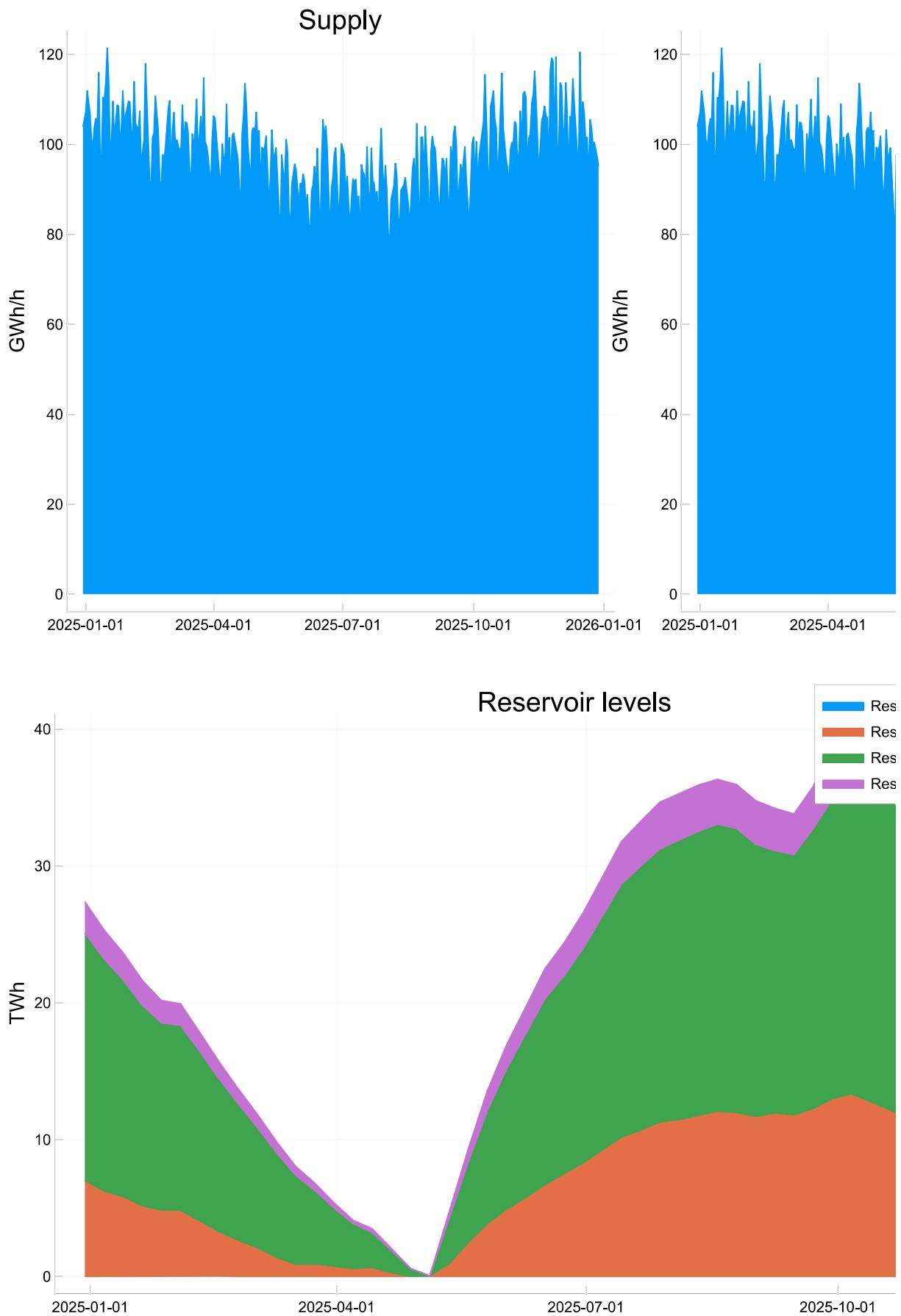
```

# Choose areas to see results from
resultobjects = getpowerobjects(modelobjects, ["DEU", "DMK", "NOS"]) #, "NOS", "DMK", "DEU", "FR"
runscenarios(scenarios, modelobjects, resultobjects);

0.170732 seconds (1.18 M allocations: 86.933 MiB)
0.301693 seconds (3.26 M allocations: 114.350 MiB)
0.941034 seconds
Objective value in scenario 1: 5.320472699786423e10

```





1x2 DataFrame

Row	Yearly_supply_TWh_sum_skipmissing	Yearly_demand_TWh_sum_skipmissing
	Float64	Float64
1	863.472	863.472



Test time use detailed problem

```
In [31]: # Function to change power_horizon in elements list and make list of modelobjects
function get_detailed_modelobjects!(elements, new_power_horizon, new_hydro_horizon)

    # Change power_horizon in elements list
    set_horizon!(elements, "Hydro", new_hydro_horizon)
    set_horizon!(elements, "Power", new_power_horizon)
    set_horizon!(elements, "Battery", new_power_horizon)

    # Set new power_horizon to the global variable
    global hydro_horizon = new_hydro_horizon
    global power_horizon = new_power_horizon

    # Create modelobjects and manipulate
    modelobjects = getmodelobjects(elements)

    # Add slack variable for excessive renewable power
    addPowerUpperSlack!(modelobjects)

    # Storages have state-dependant variables that need a boundary conditions
    # We set the starting storage to be equal to the ending storage, x[0] = x[T] (for horizons)
    addStartEqualStopAllStorages!(modelobjects)

    return modelobjects
end

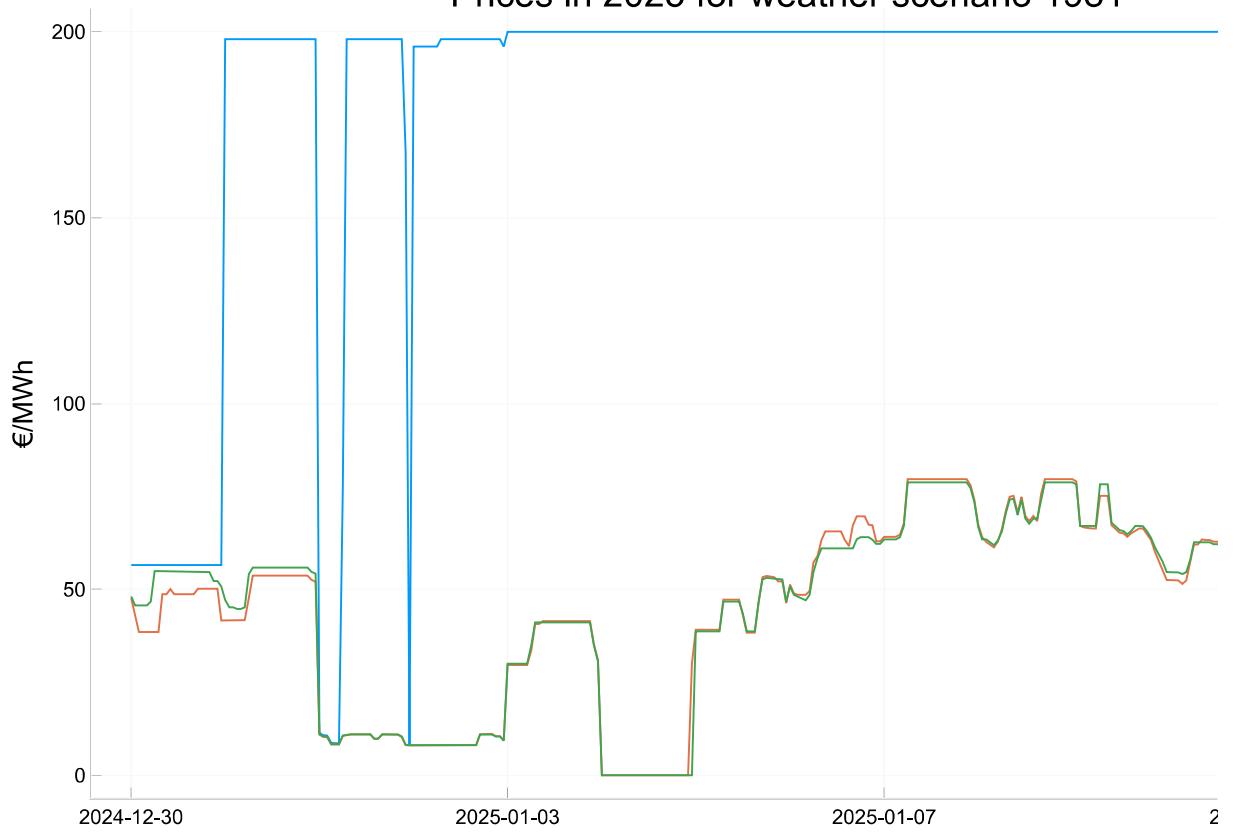
hydro_horizon = SequentialHorizon(14, Day(1))
power_horizon = SequentialHorizon(14*24, Hour(1))
modelobjects = get_detailed_modelobjects!(elements, power_horizon, hydro_horizon)

# Choose areas to see results from
resultobjects = getpowerobjects(modelobjects, ["DEU", "DK1", "NO2"]) #, "NOS", "DMK", "DEU", "FR", "NL", "ES", "IT", "PT", "ES", "PT", "ES", "IT", "DE", "AT", "CH", "SE", "DK1", "NO2"]

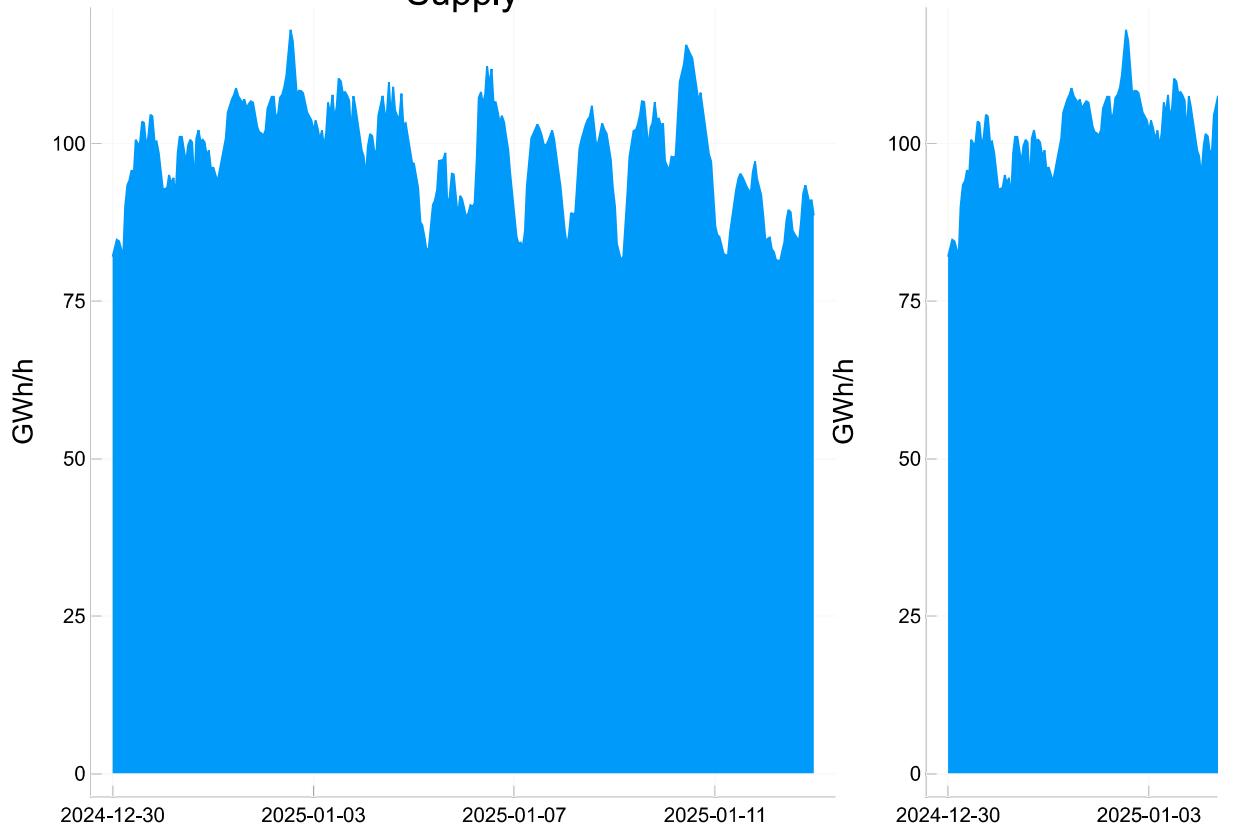
runscenarios(scenarios, modelobjects, resultobjects);

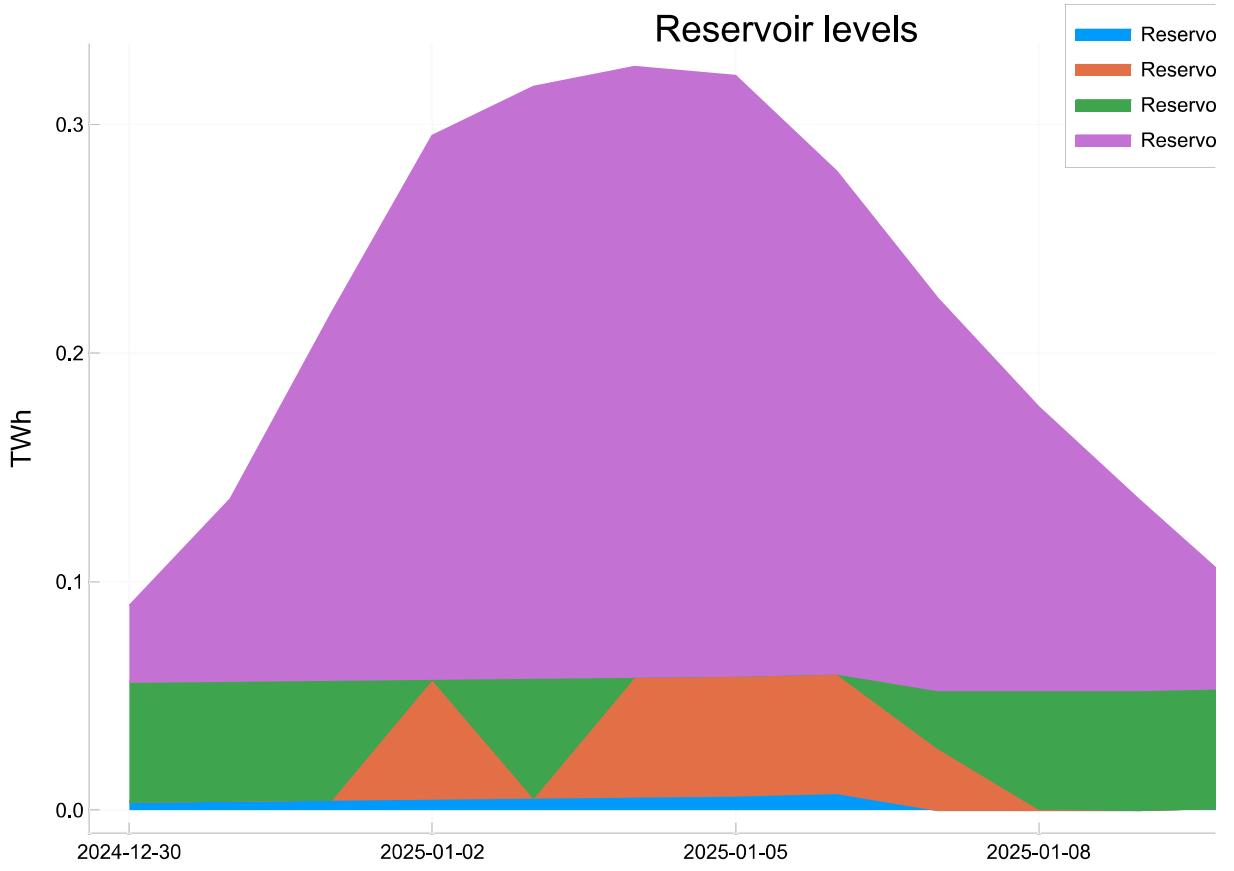
2.137076 seconds (4.66 M allocations: 392.566 MiB, 52.44% gc time)
0.189255 seconds (2.53 M allocations: 72.127 MiB)
16.106352 seconds
Objective value in scenario 1: 2.3719842714987435e9
```

Prices in 2025 for weather scenario 1981



Supply





```
1x2 DataFrame
Row | Yearly_supply_TWh_sum_skipmissing  Yearly_demand_TWh_sum_skipmissing
    |          Float64                  Float64
1   |             860.172                 860.172
```

1.4 - Compare time usage with Adaptive vs Sequential horizon

Sequential daily is fastest since it updates the problem with time-series data for daily periods.

Sequential hourly is slowest since it updates the problem with time-series data for hourly periods. It would give the best prices, but at the cost of being too slow.

Adaptive takes a bit more time to update than sequential daily since we read and cluster hourly time-series data into seven periods per week. However the solvetime is similar to Sequential daily. This shows that Adaptive could be a good compromise between quality and speed.

```
In [32]: function time_usage_horizon(modelobject, scenarios)

    @time prob = HiGHS_Prob(collect(values(modelobjects)))

    for (s, t) in enumerate(scenarios)
        @time update!(prob, t)

        @time solve!(prob)
    end
end

new_hydro_horizon = SequentialHorizon(52, Hour(168))

display("Sequential daily")
new_power_horizon = SequentialHorizon(52*7, Day(1))
```

```

modelobjects = get_modelobjects!(elements, new_power_horizon, new_hydro_horizon)
time_usage_horizon(modelobjects, scenarios)

display("Sequential hourly")
new_power_horizon = SequentialHorizon(52*7*24, Hour(1))
modelobjects = get_modelobjects!(elements, new_power_horizon)
time_usage_horizon(modelobjects, scenarios)

display("Adaptive cluster hours into 7 periods per week")
new_power_horizon = AdaptiveHorizon(clusters, unit_duration, DynamicRHSADData("Power"), KM)
modelobjects = get_modelobjects!(elements, new_power_horizon)
time_usage_horizon(modelobjects, scenarios)

"Sequential daily"
0.174841 seconds (1.18 M allocations: 86.933 MiB)
0.274568 seconds (3.26 M allocations: 114.350 MiB)
0.954871 seconds
"Sequential hourly"
6.430420 seconds (35.37 M allocations: 2.084 GiB, 20.40% gc time)
10.504482 seconds (90.18 M allocations: 2.807 GiB, 31.21% gc time)
69.449921 seconds
"Adaptive cluster hours into 7 periods per week"
0.151033 seconds (1.00 M allocations: 81.181 MiB)
0.512200 seconds (4.76 M allocations: 162.221 MiB)
0.932611 seconds

```

1.5 - Compare time usage of HiGHS_Prob with JuMP_Prob

We made HiGHS_Prob because HiGHS was the fastest open-source solver possible to use with JuMP, but was very slow to update the problem in the JuMP implementation. We therefore implemented HiGHS_Prob directly on the HiGHS package. (Some new PRs has partly solved this problem, but HiGHS_Prob is still noticeably faster.)

We time building, updating and solving the problem for different Probs and solvers, to see the difference. This is of course only a small problem, and solving times could be improved by choosing other solver settings.

```

In [34]: function time_usage_probs(modelobjects, scenarios, opt)
    if opt == "H"
        display("HiGHS_Prob")
        @time prob = HiGHS_Prob(collect(values(modelobjects)))
    elseif opt == "JC"
        display("JuMP_Prob w Clp")
        model = Model(Clps.Optimizer)
        set_silent(model)
        @time prob = JuMP_Prob(collect(values(modelobjects)), model)
    elseif opt == "JH"
        display("JuMP_Prob w HiGHS")
        model = Model(HiGHS.Optimizer)
        set_silent(model)
        @time prob = JuMP_Prob(collect(values(modelobjects)), model)
    end

    for (s, t) in enumerate(scenarios)
        @time update!(prob, t)

        @time solve!(prob)
    end
end

time_usage_probs(modelobjects, scenarios, "H")
time_usage_probs(modelobjects, scenarios, "JH")
time_usage_probs(modelobjects, scenarios, "JC")

```

```

"HiGHS_Prob"
0.162058 seconds (1.00 M allocations: 81.181 MiB)
0.505826 seconds (4.76 M allocations: 162.221 MiB)
0.939175 seconds
"JuMP_Prob w HiGHS"
0.289726 seconds (3.11 M allocations: 128.728 MiB)
0.970802 seconds (5.12 M allocations: 166.085 MiB)
1.566489 seconds (2.32 M allocations: 99.554 MiB)
"JuMP_Prob w Clp"
0.277916 seconds (2.80 M allocations: 122.394 MiB)
0.978563 seconds (5.12 M allocations: 166.085 MiB)
2.607031 seconds (467.22 k allocations: 102.040 MiB)

```

The results show that HiGHS_Prob is fastest for building, updating and solving the problem. This is because it is custom-built for our purpose. The higher time usage of JuMP_Prob w HiGHS actually comes from transferring the JuMP model into HiGHS rather than solving the problem with HiGHS.

We also see that HiGHS_Prob takes more time updating the problem than solving it. This could be improved by using the time-series more efficiently (now querying from time-series is coded very generic). Some possible improvements:

- If data points have constant distance between them, we can make a more efficient getweightedaverage that takes advantage of this
- Many objects can get data from the same time-series. Instead of the same calculations being done several times, we could store the results in an intermediate storage
- We could store the index of the previous time-series query, to quicker look up the next value

1.6 - Compare time usage with Simplex vs IPM

We compare time usage of HiGHS_Prob and JuMP_Prob with Clp, for different solver implementations: dual simplex and interior-point method (IPM). The result shows that HiGHS_Prob with dual simplex is fastest for this specific problem given the default solver settings. With other setting or a different problem (longer horizon / higher resolution / more objects), other combinations could be the fastest.

Overview of solver settings for Clp and HiGHS.

- <https://github.com/jump-dev/Clp.jl>
- <https://github.com/jump-dev/HiGHS.jl>

```
In [35]: function time_usage_solver(modelobjects, scenarios, opt)
    if opt == "HS"
        display("HiGHS_Prob dual simplex")
        @time prob = HiGHS_Prob(collect(values(modelobjects)))
        Highs_setStringValue(prob, "solver", "simplex")
    elseif opt == "HI"
        display("HiGHS_Prob ipm")
        @time prob = HiGHS_Prob(collect(values(modelobjects)))
        Highs_setStringValue(prob, "solver", "ipm")
    elseif opt == "JCS"
        display("JuMP_Prob w Clp dual simplex")
        model = Model(Clps.Optimizer)
        set_optimizer_attribute(model, "SolveType", 0)
        set_silent(model)
        @time prob = JuMP_Prob(collect(values(modelobjects)), model)
    elseif opt == "JCI"
        display("JuMP_Prob w Clp ipm")
        model = Model(Clps.Optimizer)
        set_optimizer_attribute(model, "SolveType", 4)
        set_silent(model)
        @time prob = JuMP_Prob(collect(values(modelobjects)), model)
```

```

    end

    for (s, t) in enumerate(scenarios)
        @time update!(prob, t)

        @time solve!(prob)
    end
end

time_usage_solver(modelobjects, scenarios, "HS")
time_usage_solver(modelobjects, scenarios, "HI")
time_usage_solver(modelobjects, scenarios, "JCS")
time_usage_solver(modelobjects, scenarios, "JCI")

"HiGHS_Prob dual simplex"
0.169661 seconds (1.00 M allocations: 81.181 MiB)
1.258970 seconds (4.76 M allocations: 162.221 MiB, 55.89% gc time)
0.937266 seconds

"HiGHS_Prob ipm"
0.153379 seconds (1.00 M allocations: 81.181 MiB)
0.504131 seconds (4.76 M allocations: 162.221 MiB)
3.800384 seconds

"JuMP_Prob w Clp dual simplex"
0.278241 seconds (2.80 M allocations: 122.394 MiB)
0.992424 seconds (5.12 M allocations: 166.085 MiB)
2.607747 seconds (467.22 k allocations: 102.040 MiB)

"JuMP_Prob w Clp ipm"
0.278965 seconds (2.80 M allocations: 122.394 MiB)
0.995247 seconds (5.12 M allocations: 166.085 MiB)
2.367710 seconds (467.22 k allocations: 102.040 MiB)

```

1.7 - Generate price-series for hydropower scheduling

In demo 4 we need an exogen price to optimize a watercourse against. We generate a 15 year price series for Denmark using the model year 2025 and the weather scenarios 1981-1995.

```

In [36]: function make_price_series(elements)

    # Horizons can also be made from a starting and ending DateTime, and the duration D of
    # This will generate a horizon of N periods of duration D, and the last period will be
    weeks = 4
    hydro_horizon = SequentialHorizon(getisoyearstart(1981), getisoyearstart(1996), Week(weeks))
    power_horizon = AdaptiveHorizon(7, Hour(1), DynamicRHSADData("Power"), KMeansAHMethod(7))

    set_horizon!(elements, "Power", power_horizon)
    set_horizon!(elements, "Battery", power_horizon)
    set_horizon!(elements, "Hydro", hydro_horizon)

    modelobjects = getmodelobjects(elements)
    simplify!(modelobjects)

    @time prob = HiGHS_Prob(collect(values(modelobjects)))

    datayear = getisoyearstart(2025)
    scenarioyear = getisoyearstart(1981)
    t = FixedDataTwoTime(datayear, scenarioyear)
    @time update!(prob, t)
    @time solve!(prob)

    # We query the price from Denmark (since NOS price is too flat)
    id = Id(BALANCE_CONCEPT, "PowerBalance_DMK")
    balance = modelobjects[id]
    horizon = gethorizon(balance)

    # Generate and store price param as elements
    _values = [getcondual(prob, id, s) for s in 1:getnumperiods(horizon)]
    generate_param(_values, scenarioyear, horizon, id)

```

```

end

# Function to generate and store price param as elements
function generate_param(values::Vector{Float64}, dt::DateTime, horizon::AdaptiveHorizon, id)
    # Distribute values in AdaptiveHorizon periods to hours that represents the clusters
    points = []
    for t in 1:getnumperiods(horizon)
        value = values[t]
        timedelta = gettimedelta(horizon, t)
        startduration = getstartduration(horizon, t)
        for unit_range in timedelta.units
            for i in unit_range
                point_dt = dt + startduration + ((i-1) * timedelta.unit_duration)
                point = (point_dt, value)
                push!(points, point)
            end
        end
    end
    sort!(points)
    _index = [Dates.format(p[1], "yyyy-mm-dd HH:MM:SS") for p in points] # TODO: Change to
    _values = [p[2] for p in points]

    # Plot
    display(plot(_index, _values, label=getinstancename(id), size=(900,500)))

    # Store in dataelements
    e = []
    push!(e, (TIMEINDEX_CONCEPT, "VectorTimeIndex", "IndexPriceDMK",
              ("Vector", _index)))
    push!(e, (TIMEVALUES_CONCEPT, "VectorTimeValues", "ValuesPriceDMK",
              ("Vector", _values)))
    push!(e, (TIMEVECTOR_CONCEPT, "RotatingTimeVector", "ProfilePriceDMK",
              (TIMEINDEX_CONCEPT, "IndexPriceDMK"), (TIMEVALUES_CONCEPT, "ValuesPriceDMK")))
    push!(e, (PARAM_CONCEPT, "MeanSeriesParam", "PriceDMK",
              ("Level", 1),
              ("Profile", "ProfilePriceDMK")))

    open("priceDMK.json", "w") do f
        JSON.print(f, e)
    end
end

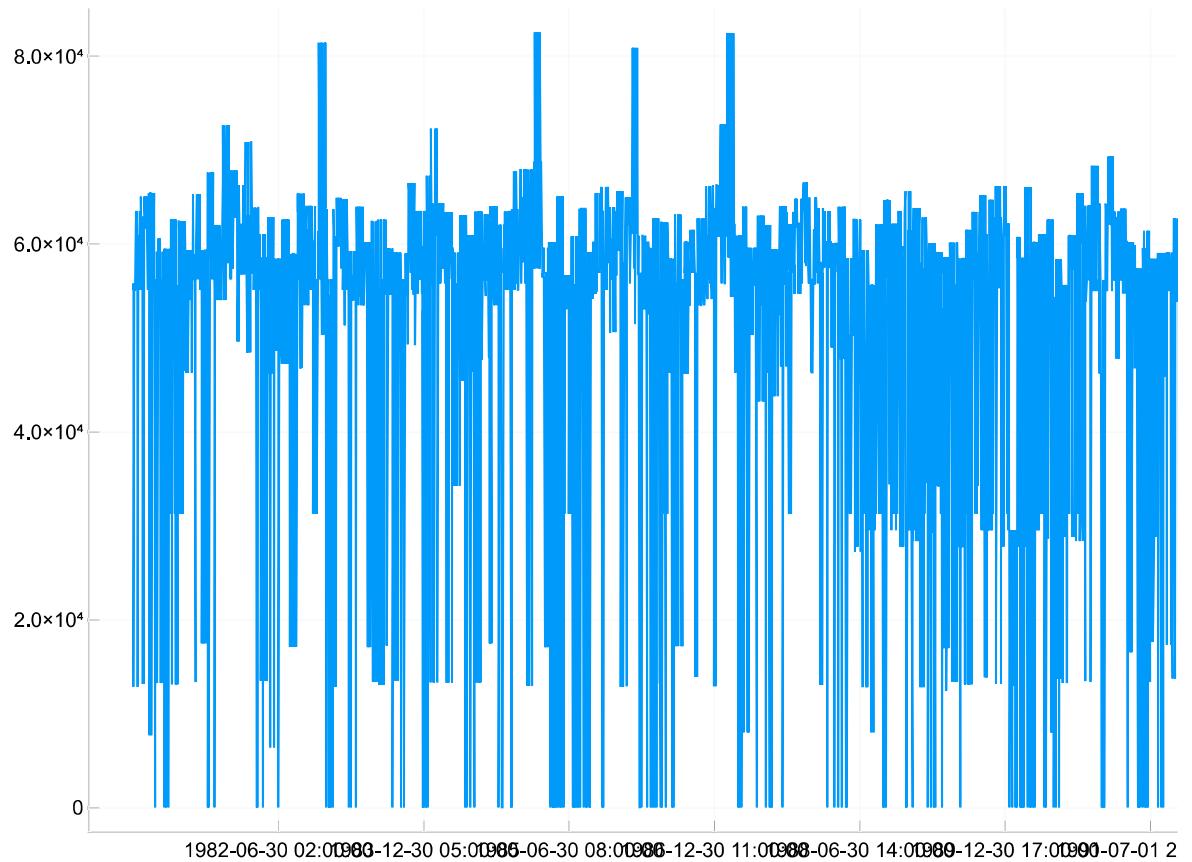
make_price_series(elements)

```

```

0.688229 seconds (4.33 M allocations: 319.431 MiB)
11.526492 seconds (78.36 M allocations: 1.873 GiB, 8.52% gc time)
6.059711 seconds

```



```
In [ ]:
```

```
◀ ▶
```