Utopia: the testing model

energyRt: making energy systems modeling as simple as linear regression in R

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Contents

Intoduction

This tutorial demonstrates the application of `energyRt` package to develop a **Reference Energy System** (RES, or **Energy system optimization**) model and conduct standard analysis, i.e. run scenarios, optimize several alternative development pathways of the simplified energy system. The initial (base-year) structure of the discussed below an example of RES is flexible. The following features can be easily adjusted:
* number of regions and the model GIS-info (the *map*),
* the model horizon and annual time-steps ("milestone years"),
* number and levels of sub-annual time-steps ("time slices"),
* technological options, commodities, storage, supply, and demand,
* interregional trade and trade with the rest of the world (ROW),
* constraints on the model variables.

The `energyRt` package provides a set of S4 classes, methods, and functions to design the model elements, such as technologies, commodities, supply, demand, and constraints, save them in a `model` object, process the data and save it in a format readable by solver-software (currently GAMS or GLPK/Mathprog), run the model code in the solver-software, read the results back to R, and manipulate the data to produce charts and tables.

Disclosure note: The `energyRt` package is a by-product of the authors' more than a decade energy-modeling-related research, teaching, and training. It evolved from an attempt to simplify our own everyday's life by automating repeating steps, to save more time for studies themselves. Though the project has been open-source from its very beginning, we think, it has (finally) reached the point where it can be helpful to others, for those who start learning RES models and for more experienced energy modelers, interested in developing state-of-the-art models and studies. We also convinced that being open means being able to learn from others, from broad modeling community, and is beneficial for any project.

This Vignette tutorial can be acquired from the `energyRt/vignetts` folder (or https://github.com/olugovoy/energyRt/vignettes). It can be run step-by-step or at once to reproduce the results below. Playing with parameters and data is highly recommended for learning the package and the RES-models. This is the first beta-version of the package and the tutorial. Please report bugs, issues, thoughts here: https://github.com/olugovoy/energyRt/issues.

Prerequisites

We assume that `R` (https://www.r-project.org/) and `RStudio` (https://www.rstudio.com/) has been already installed, and a scholar has some basic knowledge of `R`. The next step is to have installed `energyRt`, the solver software (`GAMS` or `GLPK`) and `LaTeX`. The detailed installation steps are available on the package website (https://github.com/olugovoy/energyRt/).

```
# Choose your solver-software
mysolver = "GAMS"
# mysolver = "GLPK"

if (T) {
  # Installation of required packages - if not installed.
  mypks <- rownames(installed.packages())
  if (!any(mypks == "devtools")) install.packages("devtools")
  if (!any(mypks == "energyRt")) devtools::install_github("energyRt") # not enough - see above
  if (!any(mypks == "scales")) install.packages("scales")
  if (!any(mypks == "tidyverse")) install.packages("tidyverse")
  if (!any(mypks == "lubridate")) install.packages("lubridate")
  if (!any(mypks == "spdep")) install.packages("spdep")
}
```

```r
# Load required packages
library(energyRt)
library(scales)
library(tidyverse)
library(lubridate)

# Set color palette for figures
# palette(RColorBrewer::brewer.pal(11, "Paired"))
palette(RColorBrewer::brewer.pal(11, "Set3"))
```

Utopia map

Let's start with a multi-region map for the model. Below we use GIS info of this imaginary country for visualization of results and also to calculate some parameters for renewables, like solar radiation, and distances between regions. Several options of 11-region map with arbitrary GIS info is saved in `energyRt/data` folder and compared on the figure below.

Available options

```r
par(mfrow = c(2, 2), mar = seq(0.1, 4))
maps <- c("utopia_island", "utopia_continent", "utopia_squares", "utopia_honeycomb")
for (i in 1:4) {
  gis <- get(data(list = maps[i])) # load map
  plot(gis, col = 1:length(gis), main = maps[i], bg = "aliceblue")
  cn <- get_labpt_spdf(gis) # get coordinates of the regions' centers
  text(cn$x, cn$y)
}
```

```r
rm(gis, list = ls(pattern = "utopia_")) # clean-up
dev.off() # reset graphical parameters
```

Certainly, any other map in `SpatialPolygonsDataFrame` (spdf) format and with saved names of regions in `@data$region` column of the spdf object can be used instead. For this particular example lets pick `utopia_honeycomb` map and keep the 7 first regions for the simulation.

```r
data("utopia_honeycomb") #, package = "energyRt")
gis <- utopia_honeycomb; rm(utopia_honeycomb)
gis <- gis[1:7,]
# gis <- gis[-c(8:9),]

# Often used parameters
(reg_names <- as.character(gis@data$region)) # Region names
(nreg <- length(reg_names)) # Number of regions
reg_centers <- getCenters(gis) # Coordinates of the regions' centers
# rownames(reg_centers) <- reg_centers$region

if (F) {
  # Basic map - skipped
  par(mfrow = c(1, 1), mar = seq(0.1, 4))
  plot(gis, col = 1:length(gis), main = paste("Utopia", length(gis), "regions"),
       bg = "aliceblue")
```

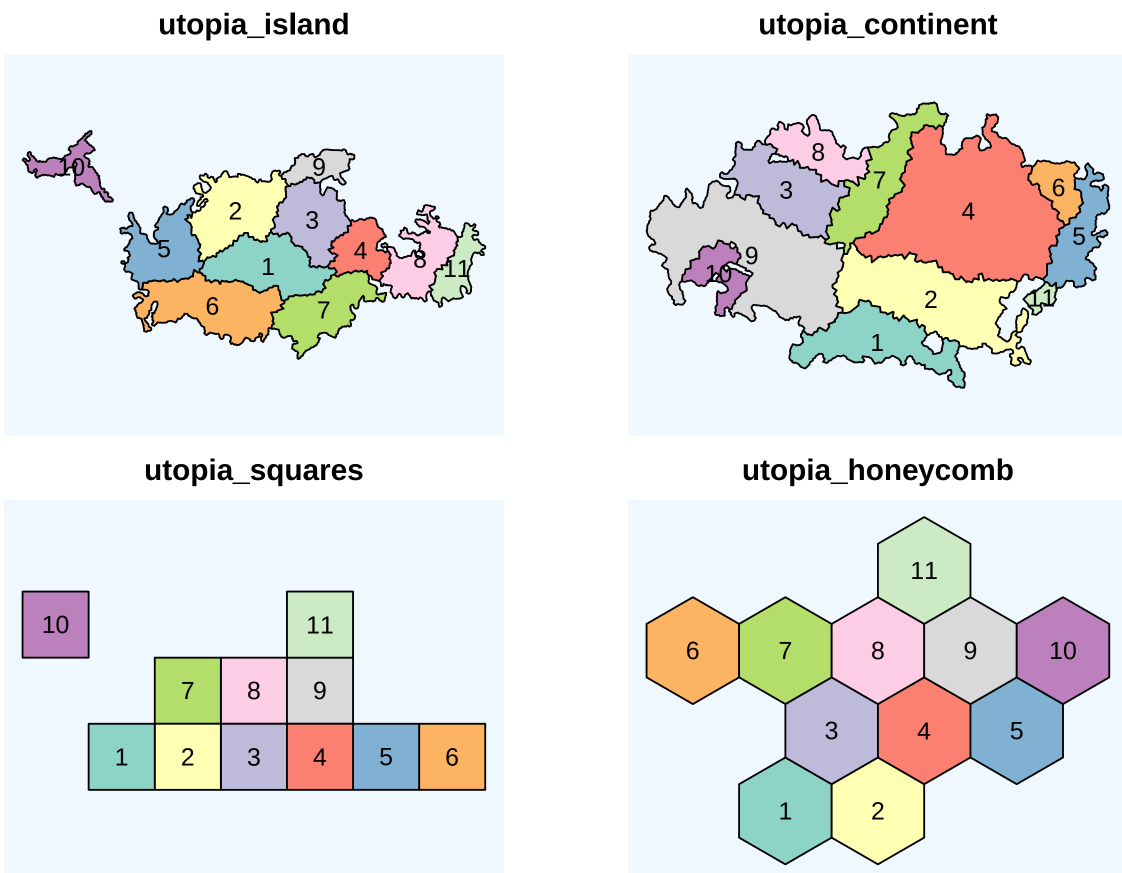


Figure 1: Map options for Utopia models, up to 11 regions.

```r
  text(reg_centers$x, reg_centers$y, labels = reg_names)
  class(gis)
}
```

Mapping with ggplot

Further we will rely on `ggplot` package for figures and maps, which requires the intput data in `data.frame` format, here are the required conversions and the final map.

```r
# Converting spdf to data.frame
ggis <- gis %>%
  fortify(region = "region") %>%
  as_tibble()

ggplot(ggis, aes(long,lat, group = group)) +
  geom_polygon(aes(fill = id), colour = rgb(1,1,1,0.5)) +
  # geom_polygon(aes(fill = id), colour = "white", size = 1) +
  theme(legend.position="none") +
  coord_quickmap() +
  theme_void() + theme(plot.title = element_text(hjust = .5)) +
  scale_fill_brewer(palette = "Set3") +
  labs(fill = "Region", title = paste("Utopia", length(gis), "regions")) +
  geom_text(data = reg_centers, aes(x, y, label = region), inherit.aes = FALSE)
```

Sub-annual time resolution

Here are examples of sub-annual time hierarchy (time-slices or `slices`), from one to four levels. The number of levels and their names are flexible (except the upper 'ANNUAL' level). The names of the levels are important, they are used as key-words in the definition of commodities and technologies.

Annual (default)

For some models, sub-annual time granularity is not needed and can be dropped. This also assumed by default, if slices are not specified, the model will have the annual resolution. Though we can also define this for demonstration of the time-level structures.

```r
# 1 time slice - ANNUAL
timeslices1 <- list(
  ANNUAL = "ANNUAL" # This level should present in every time-slices structure
)
```

Seasons and typical hours

We can add more levels - seasons or months, weeks, and hours. They should be saved in nested lists. Here is an example with seasons (Winter, Summer, spRing, Autumn), and hours (Day, Night, Peak). The first element in each list is the share of this particular slice in the level. The sum of shares on each level should be equal to one.

```r
# 4x3 = 24 slices
timeslices2 <- list(
```

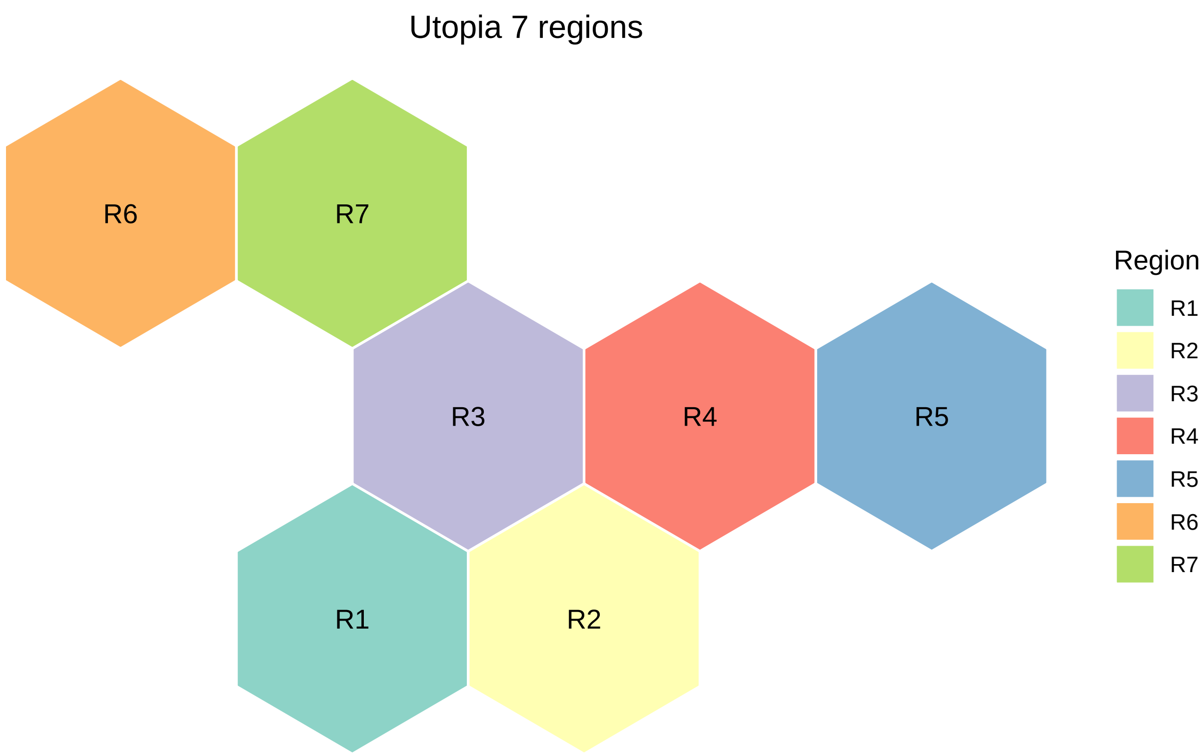


Figure 2: The selected map for the Utopia model using ggplot.

```r
  ANNUAL = "ANNUAL", # required
  # SEASON = c(W = list(1/4,
  # For consistency with other structures, lets rename SEASON to MONTH
  MONTH = list(
    W = list(1/4, # share of the Winter season in the year
             HOUR = list(
               D = 9/24, # share of day-hours in Winter
               N = 12/24, # share of night-hours in Winter
               P = 3/24)), # share of peak hours in Winter
    R = list(1/4, # share of the spRing season in the year
             HOUR = list(
               D = 11/24, # share of day-hours in spRing
               N = 11/24, # share of night-hours in spRing
               P = 2/24)), # share of peak hours in spRing
    S = list(1/4, # share of the Summer season in the year
             HOUR = list(
               D = 12/24, # share of day-hours in Summer
               N = 9/24, # share of night-hours in Summer
               P = 3/24)), # share of peak hours in Summer)
    A = list(1/4, # share of the Autumn season in the year
             HOUR = list(
               D = 11/24, # share of day-hours in Autumn
               N = 11/24, # share of night-hours in Autumn
               P = 2/24)) # share of peak hours in Autumn)
    )
  )
```

Four seasons and the three groups of hours will result in 12 sub-annual time-slices. If the spring and fall have similar parameters and can be aggregated into one season, reducing the total number of slices to 9. Though there might be reasons to separate them if, for example, the final demand is significantly different in the seasons, or some resources (like hydro-power) have a different profile in autumn and spring.

Months and representative day hours

It is probably more natural to operate with real months and real hours, and easier from a data perspective. The following example has 12 months and 24 hours for each month, considering one representative day per month. Therefore this will result in 288 time slices per every year of the model. However, higher granularity comes with a computational penalty. Though for our toy model with only a few technologies, this is not a level of concern yet. If we disregard the differences in the length of the months, then the definition of time slices will be even easier - we won't have to specify any shares, they will be assumed as equal during the model compilation.

```r
# 24*1*12 = 288 time slices, two sub-annual levels
timeslices3 <- list(
  ANNUAL = "ANNUAL", # this name is fixed, should not be changes
  MONTH = paste0("m", formatC(1:12, width = 2, flag = "0")),
  HOUR = paste0("h", formatC(0:23, width = 2, flag = "0"))
)
```

We have defined 3 different options of sub-annual time steps. The first option has only one level ("ANNUAL"), and two others also have months (or seasons) and groups of typical hours. The following definition of the model objects will rely on the chosen time structure. For example, some commodities or technologies can have higher granularity and will appear in the hour-level equations. Whereas others may have annual or season/month-level time resolution, that means they will appear only in their level balance equations. The names of slice levels and slices should be consistent across the model objects. Therefore the time-structure is fixed, model-specific. To make it a bit more flexible for playing with alternative specifications, we can have several time-structure with the same names of levels, like in lists `timeslices2` and `timeslices3` above. They both have "ANNUAL", "MONTH", and "HOUR" levels. Though the names of the slice-elements will be different, and we will have to avoid using them in the model specification.

```
# Now let's create names for the slices, the elements of the time-slices set
# They will be auto-generated in the model, but we may need them in definition of technologies and othe

# timeslices1 <- list(
#   ANNUAL = "ANNUAL", MONTH = list(1, HOUR = list(H = 1))
# )

# timeSlices(timeslices1) # Experimental -- not working yet
timeSlices(timeslices2)
timeSlices(timeslices3)

# Choose time slices level
timeslices <- timeslices2
timeslices <- timeslices3

slc <- timeSlices(timeslices)
(nslc <- length(slc$slice))
(nmon <- length(timeslices$MONTH))
(nhou <- nslc/nmon)
```

We will assign the time slices to the model-object later, but may also need the structure and/or names of the slices in the definition of other objects, such as technologies, demand, and supply, therefore useful to have them ready.

Electric power sector

Electric generation is likely the most often modeled sector of RES. It has a number of alternative technological options which can be evaluated and compared with RES-models. The minimum set for the model is a declaration of commodities, technologies, supply, demand, and basic system parameters, like time-slices, as discussed above.

Commodities

A "commodity" notion in the model is a generalization of goods, services, or emissions. Commodities link processes such as supply, technologies, demands as input or output. The minimum requirements to declare commodity is its name. Additional parameters can be stored in the class `commodity` for information and processing, most of the slots are currently reserved to be used in user-defined functions. The preferred way to create the class and fill it with data is the `newCommodity()` function as shown below.

```
COA <- newCommodity(
  name = "COA", # the name as it appears in the solver-software and the model sets
  description = "Generic coal", # just a comment
  emis = list( # emissions, associated with fuels combustion (see the flags in technologies)
    comm = "CO2", # this commodity (CO2) is emmited when the fuel (COA) is used
    unit = "kt/PJ", # the unit of emissions for refference
    mean = 100 # i.e. 100 kt of CO2 emmitted per one unit of energy (1 PJ)
    ),
```

```r
  type = "fossil fuel", # reserved for filtering, optional
  slice = "ANNUAL", # 'ANNUAL' means no sub-annual granularity for the commodity
  color = "brown" # reserved for output figures, optional
)

OIL <- newCommodity(
  name = "OIL",
  description = "Oil and oil products",
  emis = list(
    comm = "CO2",
    mean = 80
  ),
  slice = "ANNUAL"
)

GAS <- newCommodity(
  name = "GAS",
  description = "Natural gas",
  emis = list(
    comm = "CO2",
    unit = "kt/PJ",
    mean = 70
  ),
  LHV = list( # Low heating value
    unit = "kt/PJ", # == kg/GJ
    mean = 50 # energy content
  ),
  slice = "MONTH" # This commodity will appear in month-level equations
)

CH4 <- newCommodity(
  name = "CH4",
  description = "Methan emmisions",
  slice = "HOUR"
)

BIO <- newCommodity(
  name = "BIO",
  description = "Generic biomass, all types",
  type = "renewable fuel", # reserved for filtering, optional
  slice = "ANNUAL"
)

# More energy commodities with less details
ELC <- newCommodity('ELC', description = "Electricity", slice = "HOUR")
HVE <- newCommodity('HVE', description = "High voltage electricity", slice = "HOUR")
UHV <- newCommodity('UHV', description = "Ultra high voltage electricity", slice = "HOUR")
NUC <- newCommodity("NUC", description = "Nuclear fuel", slice = "ANNUAL")
HYD <- newCommodity("HYD", description = "Hydro energy", slice = "HOUR")
SOL <- newCommodity('SOL', description = "Solar energy", slice = "HOUR")
WIN <- newCommodity('WIN', description = "Wind energy", slice = "HOUR")

# Emissions
```

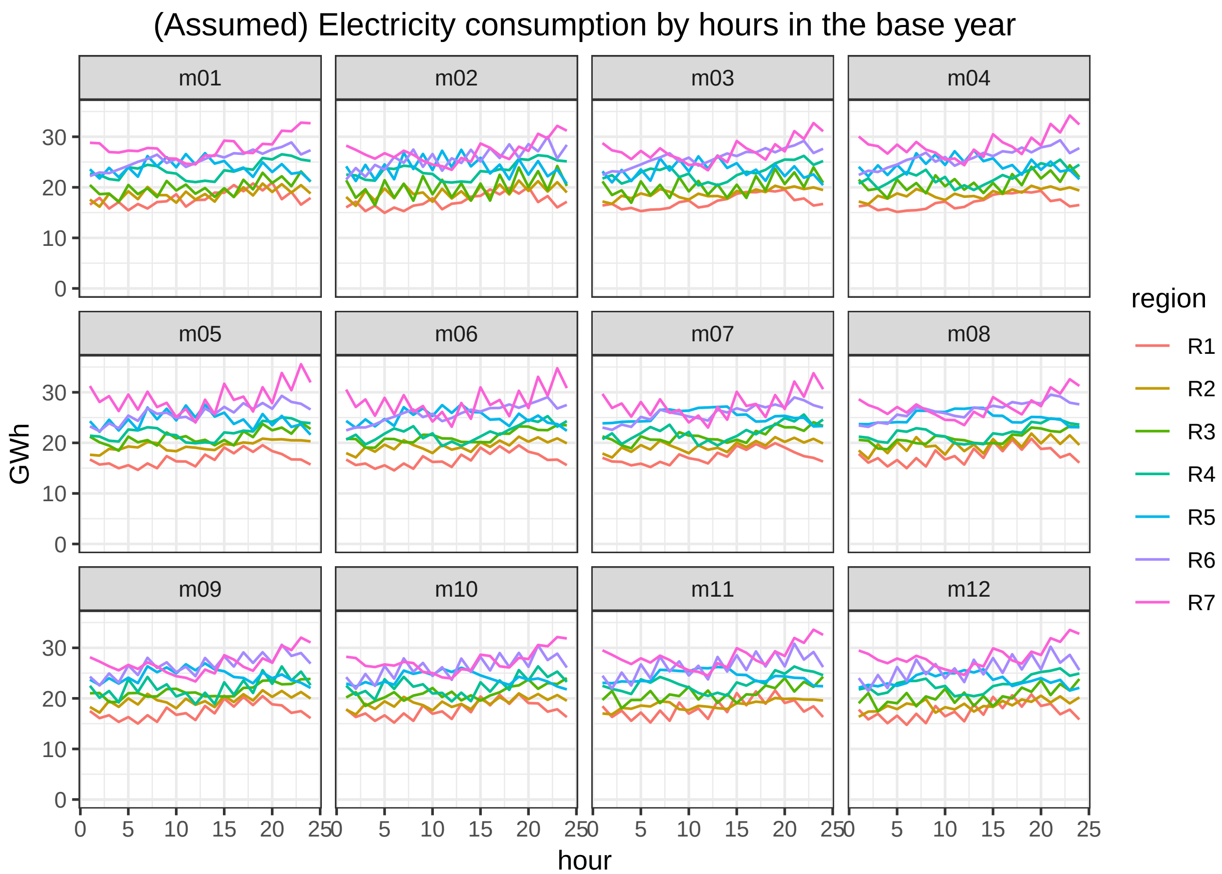
```r
CO2 <- newCommodity('CO2', description = "Carbon dioxide emissions", slice = "HOUR")
NOX <- newCommodity('NOX', description = "Nitrogen oxide emissions", slice = "HOUR")
SO2 <- newCommodity('SO2', description = "Sulfur dioxide emissions", slice = "HOUR")
HG <- newCommodity('HG', description = "Mercury emissions", slice = "HOUR")
PM <- newCommodity('PM', description = "Particulate matter emissions", slice = "HOUR")
```

The final demand

The final product in this model will be electricity (ELC), the final demand for ELC is exogenous. Since we defined *ELC* as an hour-level commodity, we specify demand for every time slice (the load curve) and every region where it is consumed. The number of hours (or groups of hours) is equal to the time-slices. In the case of the
Demand by months and hours hours Now let's specify annual, monthly, and hourly demand for electricity, assuming that every region has a different level of ELC consumptions and the loadcurve. Instead of googling and web-scrapping the Utopia's load curve, we generate it randomly for our example.

```r
# Annual demand in 2015
elc_dem_a <- tibble(region = reg_names,
                    year = 2015,
                    GWh = seq(5000, by = 500, length.out = nreg))
elc_dem_a

fLoadCurve <- function(n = 24, seed = NULL, delt = 24/n/20) {
  # a function to generate an arbitrary load curve
  if (!is.null(seed)) set.seed(seed)
  iter <- TRUE
  lc <- 1.
    for (i in 2:n) {
      # ARMA
      lc[i] <- 1 * lc[i-1] + -.1*(lc[i-1] - 1) + runif(1, -delt, delt)
    }
  (0 + lc) * n / sum(lc + 0)
}

# Hourly demand for every region
set.seed(1)
dem <- tibble(
  region = rep(reg_names, each = nslc),
  year = 2015,
  slice = rep(slc$slice, nreg),
  GWh = c(sapply(elc_dem_a$GWh, function(x) {
    (x * fLoadCurve(nmon)) %x% fLoadCurve(nhou)}))/nslc
)
head(dem)
sum(dem$GWh)

# Check by aggregating back to annual numbers
dem %>%
  group_by(region) %>%
  summarise(GWh_agg = sum(GWh)) %>%
  mutate(GWh_a = elc_dem_a$GWh)

# Add month and hour for plots
```

```r
# dem$month <- month.abb[as.numeric(substr(dem$slice, 2, 3))]
# dem$hour <- as.integer(substr(dem$slice, 6, 7))
dem <- left_join(dem, select(slc, MONTH, HOUR, slice, share), by = "slice") %>%
  rename(month = MONTH)
dem$hour <- as.numeric(as.factor(dem$HOUR))

ggplot(dem, aes(hour, GWh)) +
  geom_line(aes(color = region)) + ylim(c(0,NA)) +
  facet_wrap(.~month) +
  theme_bw() +
  labs(title = "(Assumed) Electricity consumption by hours in the base year") +
  theme(plot.title = element_text(hjust = 0.5))
```



The demand for 2015 is done, now we need to provide projections of the demand up to the last year of the model horizon, and with the same level of granularity (regions * slices) as the base year, and the commodity (ELC) itself. We can specify the demand for every (milestone) year of the model horizon, or some of them. The values between specified years will be interpolated If the model horizon goes beyond the last year, the final values will be used for interpolation forward.

```r
# Adding annual demand for 2030 and 2055
elc_dem_2030 <- dem
elc_dem_2030$year <- 2030
elc_dem_2030$GWh <- dem$GWh * 2 # assuming two-fold growth by 2030

elc_dem_2055 <- dem
elc_dem_2055$year <- 2055 # The model horizon
```

```r
elc_dem_2055$GWh <- dem$GWh * 3 # and 3-times by 2055

elc_dem <- dem %>%
  bind_rows(elc_dem_2030) %>%
  bind_rows(elc_dem_2055)

# The model units in PJ, converting...
elc_dem$PJ <- convert("GWh", "PJ", elc_dem$GWh)
elc_dem$region <- as.character(elc_dem$region)

DEM_ELC <- newDemand(
  name = "DEM_ELC",
  description = "Final demand for electricity",
  commodity = "ELC",
  dem = list(
    year = elc_dem$year,
    region = elc_dem$region,
    slice = elc_dem$slice,
    dem = elc_dem$PJ
    )
)
dim(DEM_ELC@dem)
unique(DEM_ELC@dem$year)
length(unique(DEM_ELC@dem$region))
length(unique(DEM_ELC@dem$slice))
```

Primary supply

Primary commodities, such as primary energy sources, materials, appear in the RES-model either by export from the rest of the world, or supply. Neither, supply or export from ROW has capacity per se. The main difference between them is the origin of the commodity if it is domestic or foreign Here we assume that different regions of Utopia have different resources to stimulate trade between them. Function `newSupply` creates `supply` object with declared parameters. The annual, regional, or slice-level limits, as well as costs, can be assigned with `availability` parameters.

```r
# If we assume that coal is abundunt resource, available in every region with the same price,
# we don't have to declare @region of the supply.
SUP_COA <- newSupply(
  name = "SUP_COA",
  description = "Supply of coal",
  commodity = "COA",
  unit = "PJ",
  reserve = list(res.up = 1e6), # total limit of the resource (i.e. deposits)
  region = reg_names[1],
  availability = list(
    year = c(2015, 2030, 2050),
    ava.up = c(1000, 2000, 1000), # the upper bound on availability of the commodity
    cost = c(convert("USD/tce", "MUSD/PJ", c(50, 60, 70) * .7)) # assumed price per 1PJ
  ),
  slice = "ANNUAL"
)
```

The saved parameter can be checked in `SUP_COA@availability` slot:

region	year	slice	ava.lo	ava.up	ava.fx	cost
NA	2015	NA	NA	1000	NA	1.194213
NA	2030	NA	NA	2000	NA	1.433056
NA	2050	NA	NA	1000	NA	1.671898

The `NA` values mean "for all" by default in columns with sets (`region`, `year`, `slice`) or "no constraint" in columns with numeric parameters. The values between the specified years will be linearly interpolated by default.
Similarly, for other primary commodities:

```
set.seed(100)
SUP_GAS <- newSupply(
  name = "SUP_GAS",
  description = "Supply of natural gas",
  commodity = "GAS",
  unit = "PJ",
  reserve = list(res.up = runif(1, 1e3, 1e6)), #
  region = reg_names[min(2, nreg)], # only those regions will have the supply
  availability = list(
    year = c(2015, 2030, 2050),
    ava.up = c(1000, 2000, 1000),
    cost = c(convert("USD/tce", "MUSD/PJ", c(60, 70, 80) * .7))
  ),
  slice = "ANNUAL"
)

SUP_NUC <- newSupply(
  name = "SUP_NUC",
  commodity = "NUC",
  availability = list(
    cost = convert("USD/MWh", "MUSD/PJ", 4) # assumed
  ),
  slice = "ANNUAL"
)

RES_HYD <- newSupply(
  name = "RES_HYD",
  commodity = "HYD",
  availability = data.frame(
    ava.up = 1e3,
    cost = 0 # no price to the resource, can be dropped
  )
)

RES_SOL <- newSupply(
  name = "RES_SOL",
  commodity = "SOL",
  # availability will be defined by weather factors (see below)
)

RES_WIN <- newSupply(
  name = "RES_WIN",
  commodity = "WIN"
```

```
  # availability will be defined by weather factors (see below)
)
```

Technologies

Technologies (techs) are the key part of the RES-modeling. This topic is broad and deserves a separate tutorial (in progress). By now, the main ideas to keep in mind:
– techs take some commodities as input and generate other as output;
– there are several levels of transformation of input into output, with two main intermediate steps: `use` and `activity`;
– `use` can be seen as an aggregation of all inputs with various weights into one level, then all the comm…

Coal power plant

```
# Coal-fired power plants ####
ECOA <- newTechnology(
  name = "ECOA",
  description = "Generic Coal Power Plant",
  input = list(
    comm = "COA",
    unit = "PJ",
    combustion = 1
  ),
  output = list(
    comm = "ELC",
    unit = "PJ"
  ),
  aux = list(
    acomm = c("HG", "NOX", "PM", "SO2"),
    unit = c("t", "kt", "kt", "kt")
  ),
  cap2act = 31.536,
  ceff = list(
    #region = "R1",
    # year = c(2015),
    comm = c("COA"),
    cinp2use = c(.4)
  ),
  aeff = list(
    acomm = c("HG", "NOX", "SO2", "PM"),
    use2aout = c(0.1, 1.0, 2.0, .2)
  ),
  afs = list(
    slice = "ANNUAL",
    afs.up = .6
  ),
  fixom = list(
    fixom = 100
  ),
  invcost = list(
    invcost = 1500
```

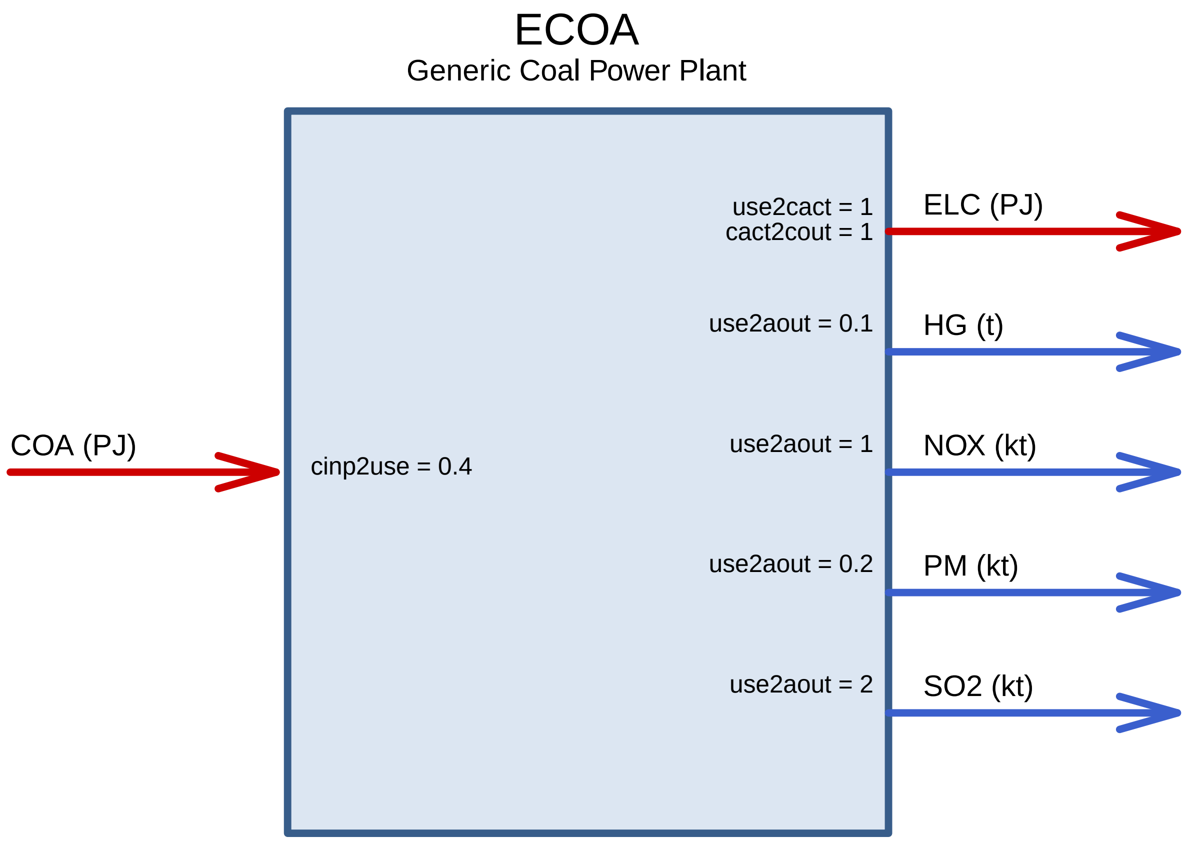


Figure 3: Coal-fired power plant.

```
  ),
  stock = data.frame(
    region = c(reg_names, reg_names),
    year = c(rep(2015, nreg), rep(2045, nreg)),
    stock = c(runif(nreg, 0, 10), rep(0, nreg))
  ),
  start = list(
    start = 2010
  ),
  olife = list(
    olife = 30
  ),
  slice = 'HOUR'
)
draw(ECOA)
```

Gas power plant

```r
# Gas-fired power plant ####
set.seed(1e3)
EGAS <- newTechnology(
  name = "EGAS",
  description = "Generic gas Power Plant",
  input = list(
    comm = "GAS",
    unit = "PJ",
    combustion = 1
  ),
  output = list(
    comm = "ELC",
    unit = "PJ"
  ),
  aux = list(
    acomm = c("NOX", "CH4"),
    unit = c("kt", "kt")
  ),
  cap2act = 31.536,
  ceff = list(
    #region = "R1",
    # year = c(2015),
    comm = c("GAS"),
    cinp2use = c(.5)
  ),
  aeff = list(
    acomm = c("NOX", "CH4"),
    use2aout = c(1.5, .1) # arbitrary
  ),
  afs = list(
    slice = "ANNUAL",
    afs.up = .8
  ),
  fixom = list(
    fixom = 100
  ),
  invcost = list(
    invcost = 1200
  ),
  stock = data.frame(
    region = c(reg_names, reg_names),
    year = c(rep(2015, nreg), rep(2040, nreg)),
    stock = c(runif(nreg, .2, 5), rep(0, nreg)) # phasing out
  ),
  start = list(
    start = 2010
  ),
  olife = list(
    olife = 30
  ),
  slice = 'HOUR'
)
draw(EGAS)
```

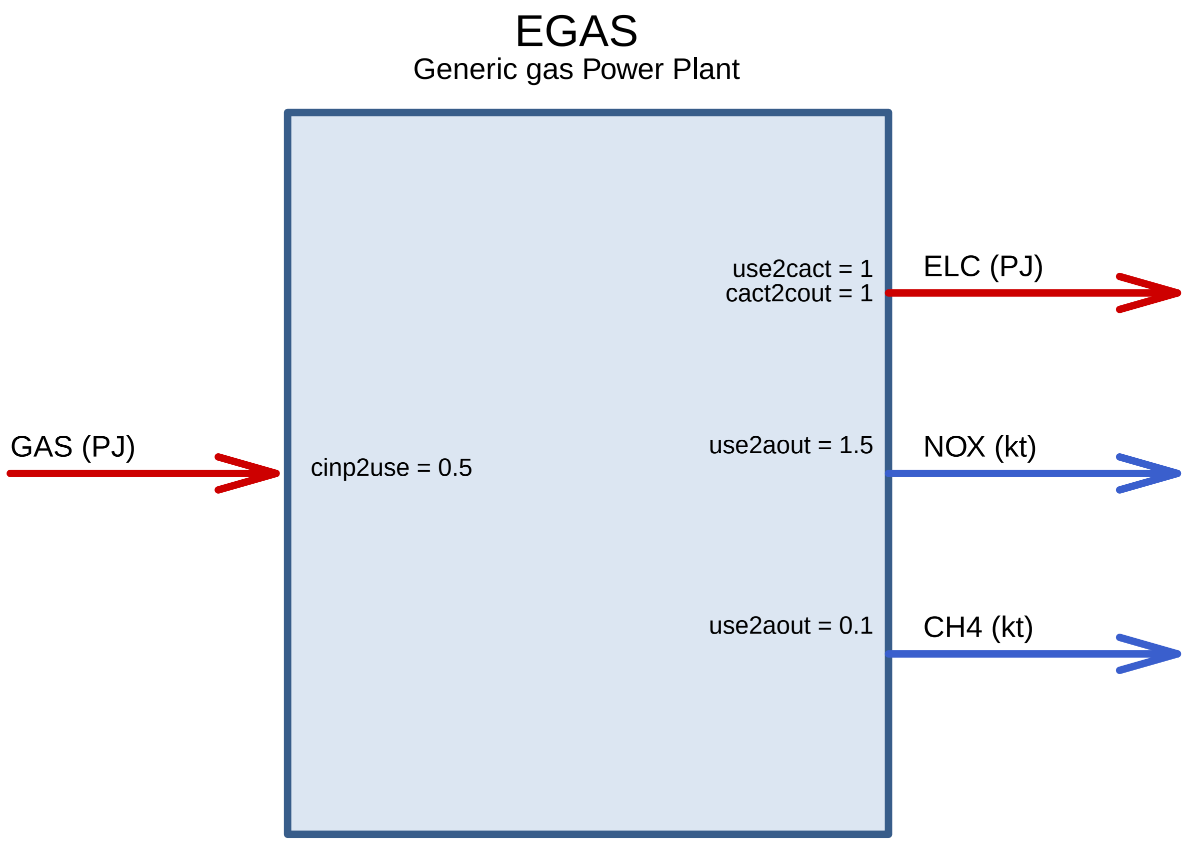


Figure 4: Gas-fired power plant.

Biomass-to-power plant

```
# Biomass-cofired power plants ####
EBIO <- newTechnology(
  name = "EBIO",
  description = "Generic Biomass-fired power plant",
  region = reg_names[min(7, nreg)],
  input = list(
    comm = "BIO",
    unit = "PJ",
    combustion = 1
  ),
  output = list(
    comm = "ELC",
    unit = "PJ"
  ),
  aux = list(
    acomm = c("NOX", "PM", "CH4"),
    unit = c("kt", "kt", "kt")
  ),
  cap2act = 31.536,
  ceff = list(
    comm = c("BIO"),
    cinp2use = c(.3)
  ),
  aeff = list(
    acomm = c("NOX", "PM", "CH4"),
    use2aout = c(0.1, 1, .01)
  ),
  afs = list(
    # activity level bounds per sum of listed slices ('ANNUAL')
    slice = "ANNUAL",
    afs.up = .5
  ),
  fixom = list(
    fixom = 50
  ),
  varom = list(
    varom = convert("USD/MWh", "MUSD/PJ", .5) # Assumption
  ),
  invcost = list(
    # year = 2015,
    invcost = 2000
  ),
  # # stock = data.frame(
  #   region = ,
  #   year = ,
  #   stock = )
  # ),
  start = list(
    start = 2010
  ),
  olife = list(
```

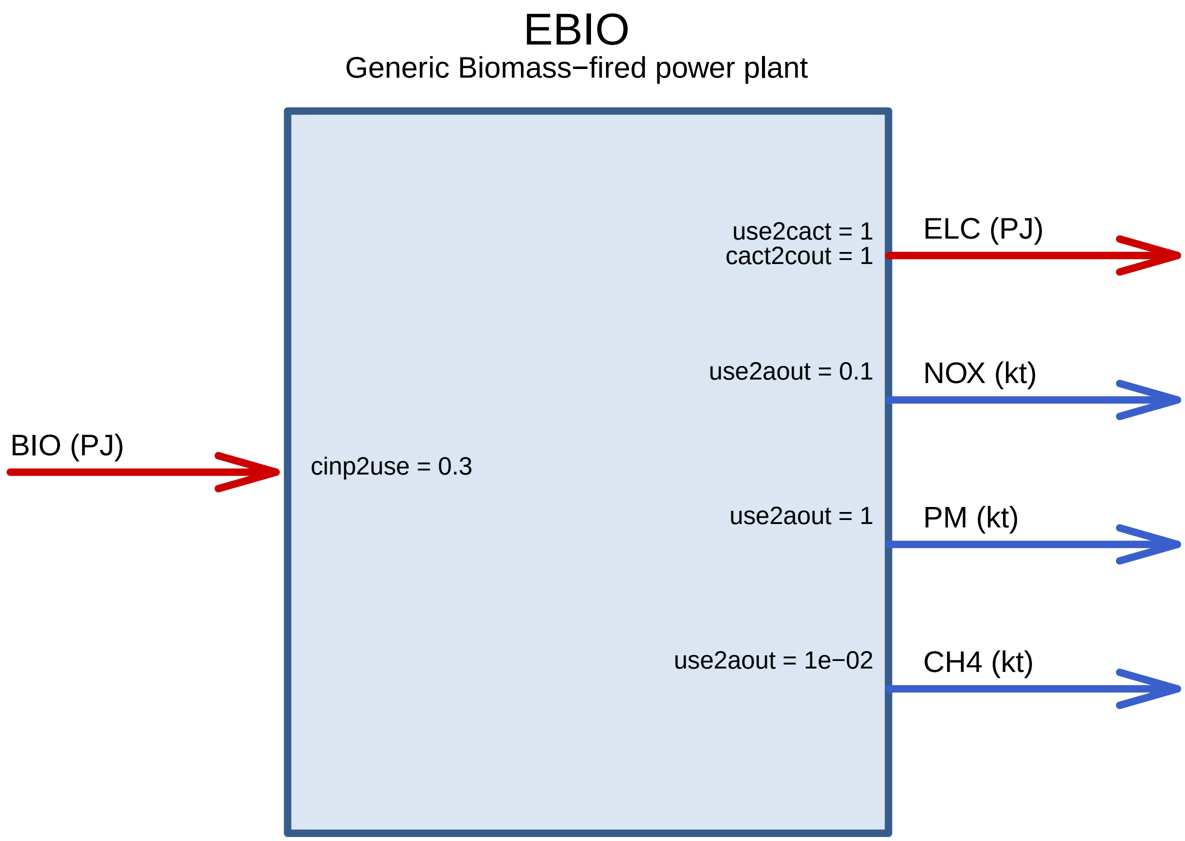


Figure 5: Biomass-to-power technology.

```
    olife = 30
  ),
  slice = 'HOUR'
)
draw(EBIO)
```

Nuclear power

```
# Nuclear power plant #
ENUC <- newTechnology(
  name = "ENUC",
  description = "Nuclear power plants",
  region = reg_names[1],
  input = list(
    comm = "NUC",
    unit = "PJ"
  ),
  output = list(
    comm = "ELC",
    unit = "PJ"
```

```r
  ),
  cap2act = 31.536,
  ceff = list(
    comm = c("NUC"),
    cinp2use = c(.35)
  ),
  af = list(
    af.lo = .8
 ),
  fixom = list(
    fixom = 30
  ),
  invcost = list(
    invcost = convert("USD/kW", "MUSD/GW", 3500)
  ),
  stock = data.frame(
    region = reg_names[1],
    year = c(2015, 2060),
    stock = 2
  ),
  start = list(
    start = 2010
  ),
  end = list(
    end = 2030
  ),
  olife = list(
    olife = 60
  ),
  slice = 'HOUR'
)
draw(ENUC)
```

Hydro power

```r
EHYD <- newTechnology(
  name = "EHYD",
  description = "Hydro power plants",
  input = list(
    comm = "HYD",
    unit = "PJ",
    combustion = 0
  ),
  region = reg_names[min(3, nreg)],
  output = list(
    comm = "ELC",
    unit = "PJ"
  ),
  cap2act = 31.536,
  ceff = list(
    comm = c("HYD"),
    cinp2use = c(1)
```

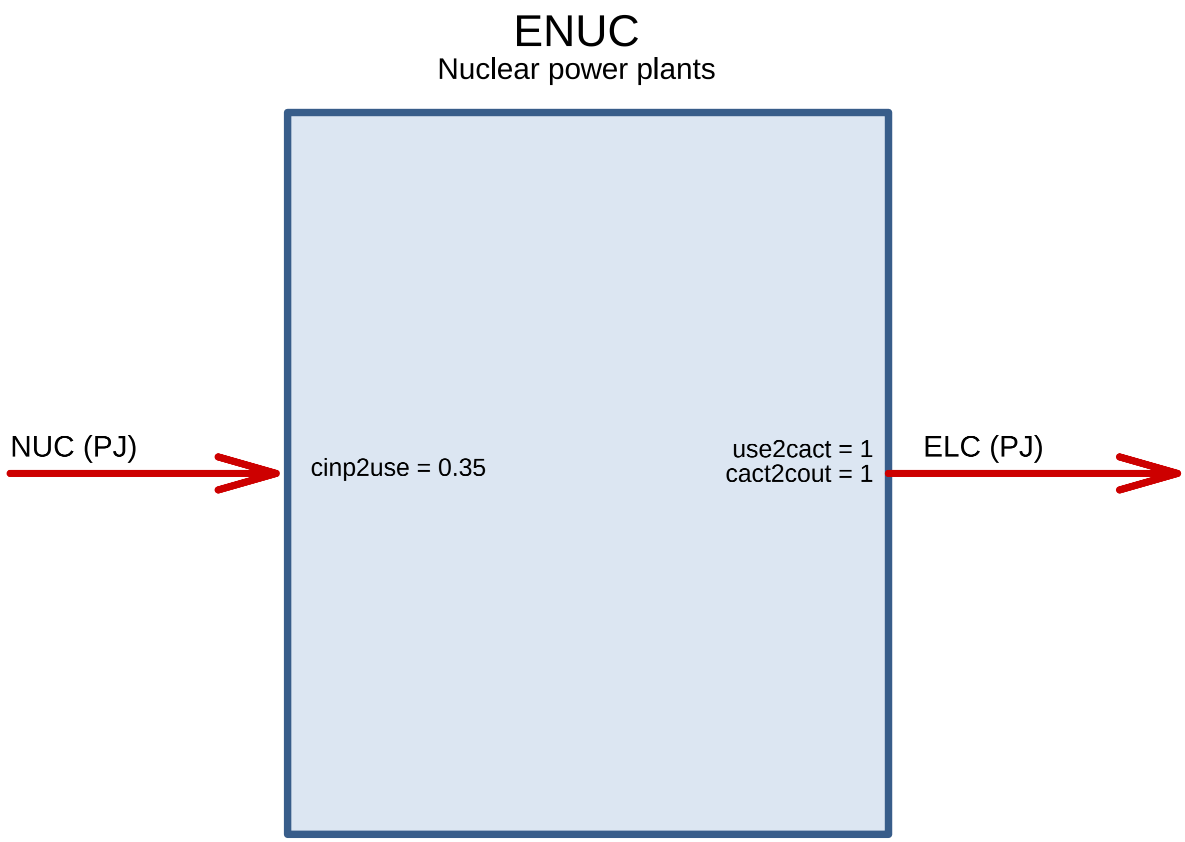


Figure 6: Nuclear power technology.

```r
  ),
  af = list(
    af.lo = 0.15
  ),
  afs = data.frame(
    slice = "ANNUAL",
    afs.up = .4,
    afs.lo = .3
  ),
  fixom = list(
    fixom = 61.4
  ),
  invcost = list(
    invcost = 5000
  ),
  stock = data.frame(
    region = reg_names[min(3, nreg)],
    year = c(2015, 2060),
    stock = 5
  ),
  start = list(
    start = 2060
  ),
  olife = list(
    olife = 80
  ),
  slice = 'HOUR'
)
draw(EHYD)
```

RBAU: Adding renewables

Weather factors

```r
# The weather information can be obtained from Utopia'a weather agency.
# Here we just randomly generate solar and wind availability factors (AF).
# For wind we can target, say, 25% annual AF, which can be achieved with
# around 35% of the time when the wind is available, and the mean speed of wind
# tending to 80% of maximum output capacity of wind plants.
# For simplicity, let's disregard seasonal components, spatial
# and temporal autocorrelation.
#

# Wind availability function
rwind <- function(n, sh1 = 5, sh2 = 2, pwind = .35) {
  # pwind - probability of wind
  rbeta(n, sh1, sh2) * sample(0:1, n, TRUE, c(1 - pwind, pwind))
}
# Check
mean(rwind(1e5))

# We can use similar approach for clouds, assuming that expected value for
```

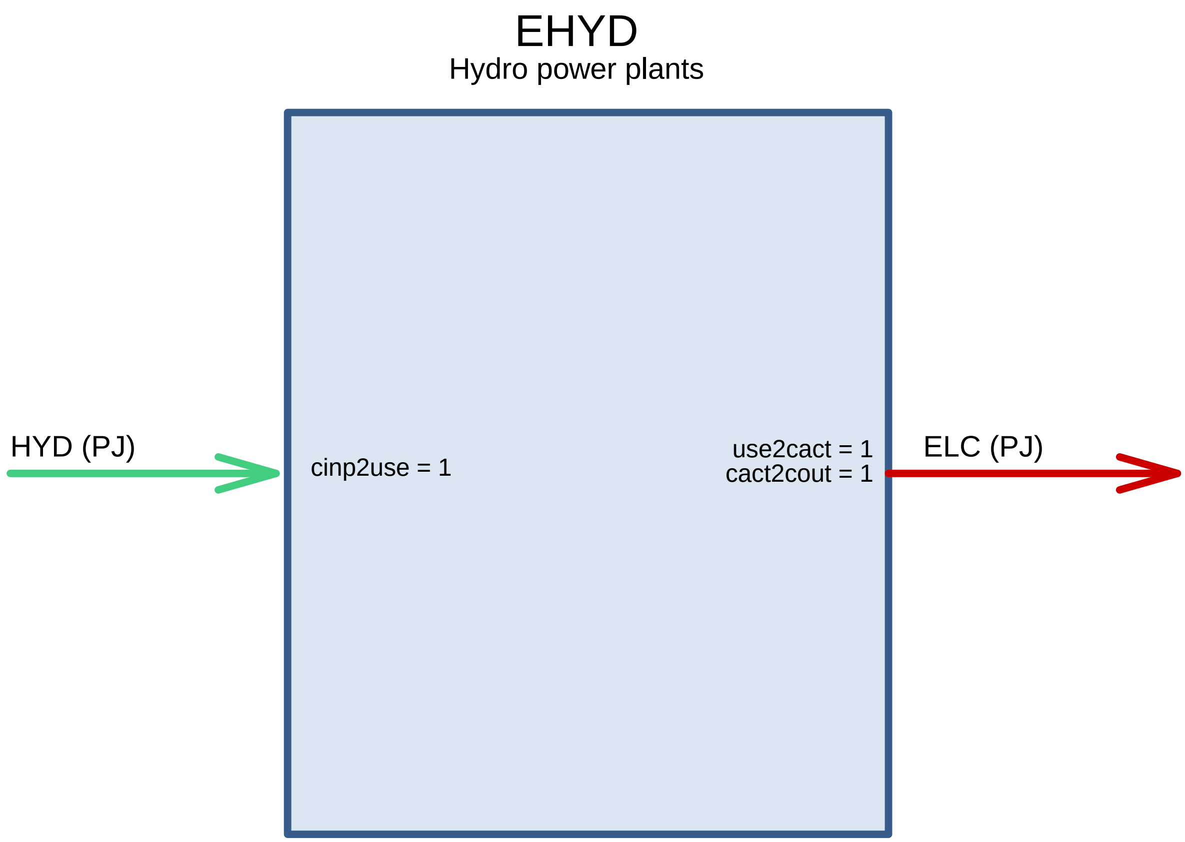
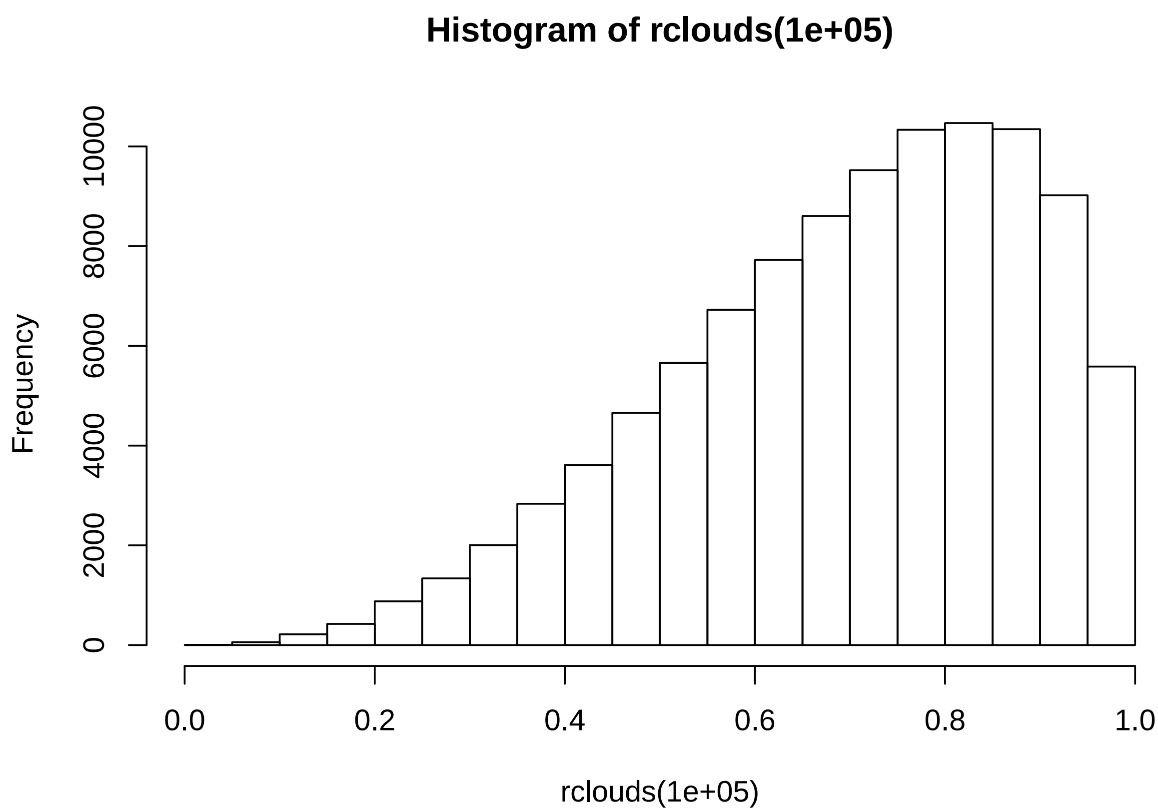


Figure 7: Hydro power technology.

```r
# sky transparency is 70%, applying it to solar radiation profile by hours.
rclouds <- function(n, sh1 = 3.5, sh2 = 1.5) rbeta(n, sh1, sh2)
mean(rclouds(1e5))
hist(rclouds(1e5))
```



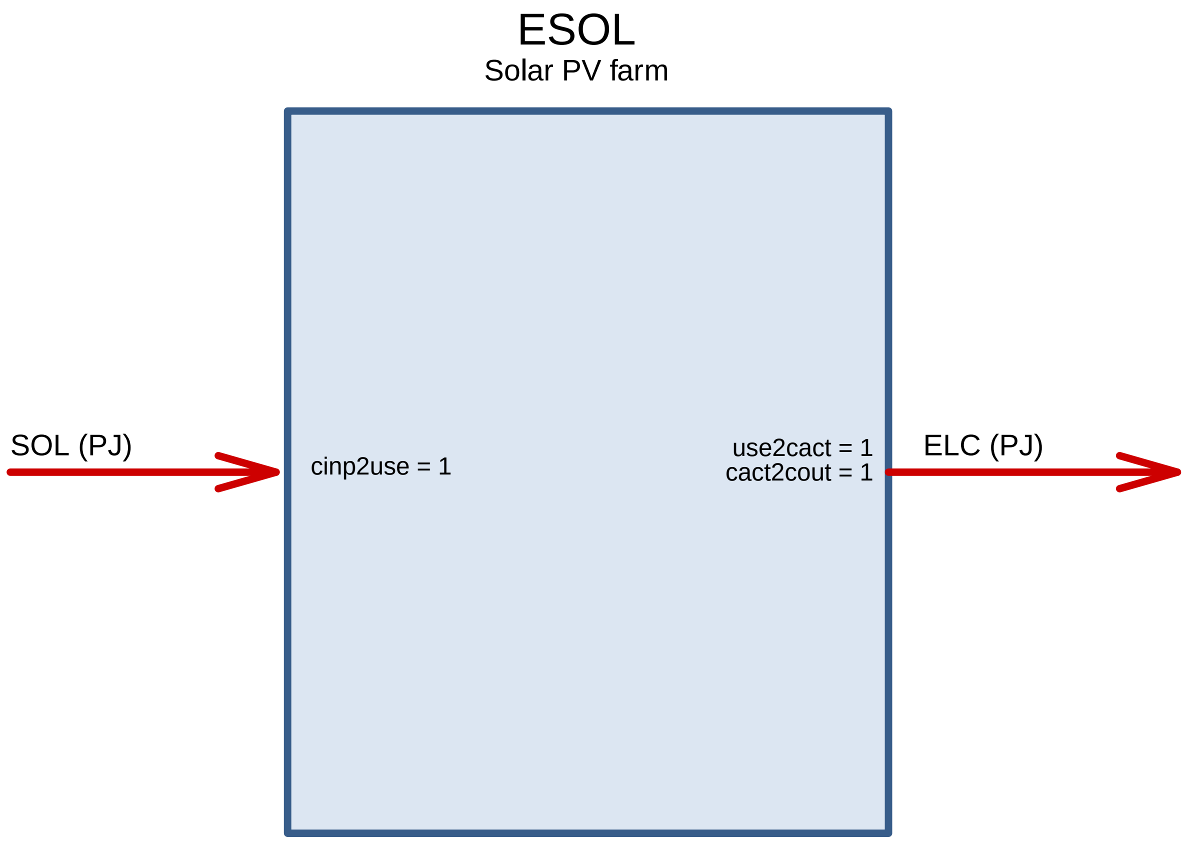

```r
# Solar radiation as function of time slice
solrad <- function(slice) {
  if (!is.character(slice)) slice <- as.character(slice)
  idx <- rep(0, length(slice))
  # assuming no difference between months/seasons for sunlight
  if_h <- grepl("_h", slice)
  if_D <- grepl("_D$", slice)
  # browser()
  if (any(if_h)) {
    # propose function of solar radiation by hours
    fsun <- function(h) {
      rad <- -cos(2 * pi * (h)/23)
      rad[rad < 0] <- 0
      rad
      }
    # extract hours as numbers from slices of type "m**_h**"
    h <- as.integer(substr(slice[if_h], 6, 7))
    idx[if_h] <- fsun(h)
  } else if (any(if_D)) {
    idx[if_D] <- 1
```

```r
    # assign some sun for Peak hours
    if_P <- grepl("_P$", slice)
    idx[if_P] <- .5
  } else {
    stop("unknown slices: ", head(paste(slice, collapse = ", ")))
  }
  idx
}

if(F) { # test
  rad <- rbind(slc$slice, solrad(slc$slice))
  plot(rad[2,], type = "l", col = "red")
}

set.seed(1111)
WWIN <- newWeather("WWIN",
                    description = "Wind availability factor",
                    slice = "HOUR",
                    weather = data.frame(
                      region = rep(reg_names, each = nslc),
                      year = 2015,
                      slice = rep(slc$slice, nreg),
                      wval = rwind(nreg * nslc)
                    ))


WSOL <- newWeather("WSOL",
                    description = "Solar radiation index",
                    slice = "HOUR",
                    weather = data.frame(
                      region = rep(reg_names, each = nslc),
                      year = 2015,
                      slice = rep(slc$slice, nreg),
                      wval = 0 # assign later
                    ))
WSOL@weather$wval <- rclouds(nreg*nslc) * solrad(WSOL@weather$slice)
sum(WSOL@weather$wval) / length(WSOL@weather$wval)

if (F) {
  plot(WSOL@weather$wval, type = "l", col = "red")
}
```

Solar farms

```r
ESOL <- newTechnology(
  name = "ESOL",
  description = "Solar PV farm",
  input = list(
    comm = "SOL",
    unit = "PJ"
  ),
  output = list(
```

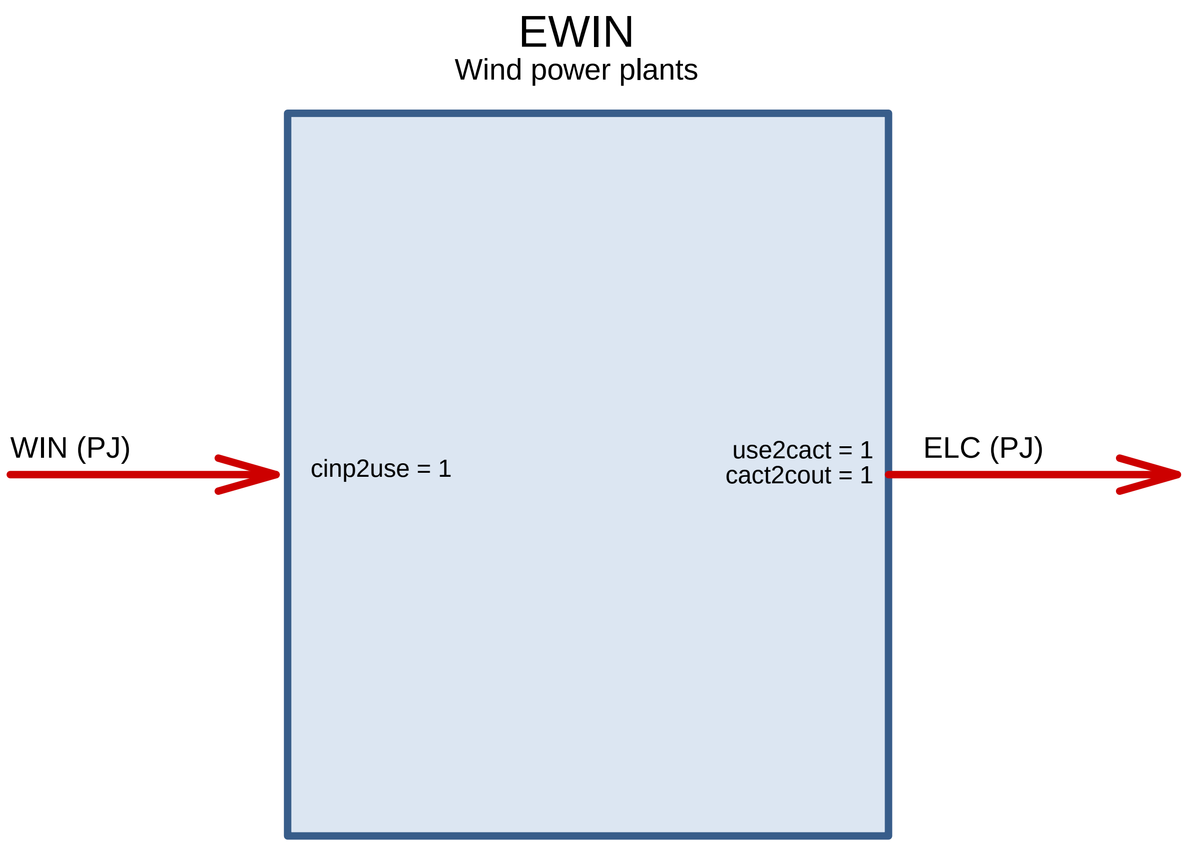
```r
    comm = "ELC",
    unit = "PJ"
  ),
  cap2act = 31.536,
  weather = list(
    weather = c("WSOL"),
    waf.up = c(1) # * af.s * WSOL@weather$wval
  ),
  fixom = list(
    fixom = 1
  ),
  invcost = list(
    invcost = convert("USD/W", "MUSD/GW", 1)
  ),
  stock = data.frame(
    region = c(reg_names, reg_names),
    year = c(rep(2015, nreg), rep(2035, nreg)),
    stock = c(runif(nreg, 0, 3), rep(0, nreg))
  ),
  start = list(
    start = 2015
  ),
  olife = list(
    olife = 25
  )
)
draw(ESOL)
```



Wind farms

```
EWIN <- newTechnology(
  name = "EWIN",
  description = "Wind power plants",
  input = list(
    comm = "WIN",
    unit = "PJ"
  ),
  output = list(
    comm = "ELC",
    unit = "PJ"
  ),
  cap2act = 31.536,
  ceff = list(
    comm = c("WIN"),
    cinp2use = 1,
    afc.up = 1
  ),
  weather = list(
    weather = "WWIN",
    comm = "WIN",
    waf.up = 1 #
  ),
```

```
  fixom = list(
    fixom = 3
  ),
  invcost = list(
    invcost = 1500
  ),
  stock = data.frame(
    region = c(reg_names, reg_names),
    year = c(rep(2015, nreg), rep(2035, nreg)),
    stock = c(runif(nreg, 0, 3), rep(0, nreg))
  ),
  start = list(
    start = 2015
  ),
  olife = list(
    olife = 25
  )
)
draw(EWIN)
```



Energy storage systems

```
STGELC <- newStorage(
```

```
  name = 'STGELC',
  commodity = 'ELC',
  description = "Energy storage systems",
  slice = 'HOUR',
  cap2stg = 1,
  olife = list(olife = 10),
  invcost = list(
    invcost = convert("USD/kWh", "MUSD/PJ", 200)
    ),
  seff = data.frame(
    stgeff = .99,
    inpeff = .9,
    outeff = .95
    )
)
```

Interregional trade

The trade is basically a definition of trade routes between regions for each commodity and each direction. There are many ways to arrange the trade routes, which is growing with the number of regions. Here we define trade between neihbor regions, which opens flows between all uninsulated regions. The neighbor regions can be obtained based on the GIS info.

```
# Neighbor regions
nbr <- spdep::poly2nb(gis, snap = .001)
names(nbr) <- gis@data$region

# Trade matrix
trd_nbr <- matrix(rep(NA, nreg*nreg),
                  nrow = nreg,
                  dimnames = list(reg_names, reg_names))

for (i in 1:length(reg_names)) {
  trd_nbr[i, nbr[[i]]] <- 1
  trd_nbr[nbr[[i]], i] <- 1
}
dim(trd_nbr)
head(trd_nbr)
```

Table 2: Trade routes matrix.

	R1	R2	R3	R4	R5	R6	R7
R1	NA	1	1	NA	NA	NA	NA
R2	1	NA	1	1	NA	NA	NA
R3	1	1	NA	1	NA	NA	1
R4	NA	1	1	NA	1	NA	NA
R5	NA	NA	NA	1	NA	NA	NA
R6	NA	NA	NA	NA	NA	NA	1
R7	NA	NA	1	NA	NA	1	NA

We can visualize the open trade routes over the map.

```r
# Data frame of trade routes
trd_dt <- as.data.frame.table(trd_nbr, stringsAsFactors = F)
trd_dt <- trd_dt[!is.na(trd_dt$Freq),] # drop NAs
head(trd_dt)
dim(trd_dt)
trd_dt <- dplyr::distinct(trd_dt) # drop duplicates
dim(trd_dt)
names(trd_dt) <- c("src", "dst", "trd")
head(trd_dt)

# Map inter-region trade routes
trd_rou <- left_join(trd_dt, reg_centers[,1:3], by = c("src" = "region"))
trd_rou <- left_join(trd_rou, reg_centers[,1:3], by = c("dst" = "region"))
trd_rou <- trd_rou %>%
  rename(xsrc = x.x, ysrc = y.x,
         xdst = x.y, ydst = y.y)
trd_rou <- as_tibble(trd_rou)

# a <- value
trd_flows_map <-
  ggplot(data = ggis) +
    geom_polygon(aes(x = long, y = lat, group = group), fill = "wheat",
                 colour = "white", alpha = 1, size = .5) + # aes fill = id,
    coord_fixed(1.) +
    guides(fill=FALSE) +  # do this to leave off the color legend
    theme_void() +
    labs(title = "Open interregional electricity trade routes")  +
    theme(plot.title = element_text(hjust = 0.5),
          plot.subtitle = element_text(hjust = 0.5)) +
    geom_segment(aes(x=xsrc, y=ysrc, xend=xdst, yend=ydst),
                 data = trd_rou, inherit.aes = FALSE, size = 5,
                 alpha = 1, colour = "dodgerblue", lineend = "round", show.legend = T) +
    geom_point(data = reg_centers, aes(x, y), colour = "red") +
    geom_segment(aes(x=xsrc, y=ysrc, xend=xdst, yend=ydst),
                 data = trd_rou, inherit.aes = FALSE, size = .1,
             arrow = arrow(type = "closed", angle = 15,
                           length = unit(0.15, "inches")),
             colour = "white", alpha = 0.75,
             lineend = "butt", linejoin = "mitre", show.legend = T) # , name = "Trade, PJ"
trd_flows_map
```

For every trade-route, direction, and every traded commodity we have to define an object of class `trade` to open the trades in the model. To simplify the process, we can group the trades by source regions. Therefore we will have up to 7 trade objects.

Trade

For electric power sector model, we can potentially consider trades as dispatch, adding various levels of voltages, or we may want to add an option for primary commodities trade between regions. In this simplified demonstration we define trade for electricity itself, without consideration of different levels of voltages, as well as investments in grid. It can be done adding into the model more technologies, such as transformers, and the grid-lines. Though this type of models don't have such details as grid simulation models have. ...

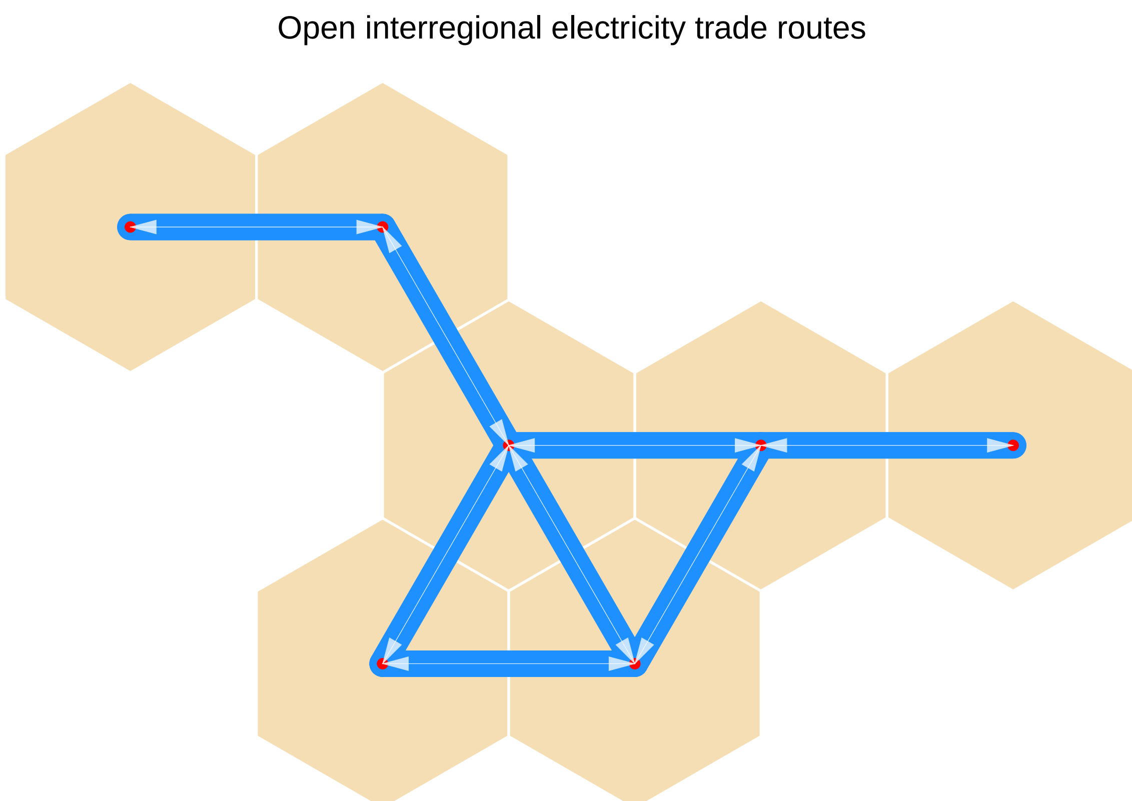


Figure 8: Trade routes.

```r
# Define trade losses
trd_dt$distance_km <- 0.
for (i in 1:dim(trd_dt)[1]) {
  rg_dst <- trd_dt$dst[i]
  rg_src <- trd_dt$src[i]
  lab_dst <- reg_centers[rg_dst, 2:3]
  lab_src <- reg_centers[rg_src, 2:3]
  trd_dt$distance_km[i] <- raster::pointDistance(
    lab_src, lab_dst, T)/1e3
}

# Assume losses 1% per 1000 km
trd_dt$losses <- round(trd_dt$distance_km / 1e3 * 0.01, 4)
trd_dt$teff <- 1 - trd_dt$losses
# Assuming 0.1 US cents per kWh per 1000 km for the transmission
trd_dt$cost <- round(trd_dt$distance_km / 1e3 *
                       convert("USD/kWh", "MUSD/GWh", .001), 5)
trd_dt <- as_tibble(trd_dt)

# A repository for trades, related technologies and commodities
TRD_ELC_ALL <- newRepository(name = "TRD_ELC_ALL")
# Define trade object for each route
for (src_nm in unique(trd_dt$src)) {
# The loop creates trade-objects for every region with neighbors,
  ii <- trd_dt$src %in% src_nm # select routes for the source region
  dst_nms <- trd_dt$dst[ii] # all destinations from the region
  trd_nm <- paste0("TRD_ELC_", src_nm)  # Trade object name
  cmd_nm <- "ELC"
  cmd_nm_nbr <- "ELC"

  # Trade class for every route
  trd <- newTrade(trd_nm,
                  commodity = cmd_nm,
                  source = src_nm,
                  destination = dst_nms,
                  trade = data.frame(
                    src = src_nm,
                    dst = dst_nms,
                    ava.up = convert("GWh", "PJ", 10), # Maximum capacity per route in GW
                    teff = trd_dt$teff[ii], # trade losses
                    cost = trd_dt$cost[ii]  # trade costs
                    )
                  )
  TRD_ELC_ALL <- add(TRD_ELC_ALL, trd)
}

names(TRD_ELC_ALL@data)
```

Global trade

```r
COAIMP <- newImport(
  name = "COAIMP",
```

```r
  description = "Coal import from ROW",
  commodity = "COA",
  imp = list(
    # Let's make it a bit more expensive than domestic coal
    year = SUP_COA@availability$year,
    price = SUP_COA@availability$cost * 1.2
  )
)

GASIMP <- newImport(
  name = "GASIMP",
  description = "Natural gas import from ROW",
  commodity = "GAS",
  imp = list(
    # Let's make it a bit more expensive than domestic coal
    year = SUP_GAS@availability$year,
    price = SUP_GAS@availability$cost * 1.2
  )
)

# OILIMP <- newImport(
#   name = "OILIMP",
#   description = "Oil import from ROW",
#   commodity = "OIL",
#   imp = list(
#     # Let's make it a bit more expensive than domestic coal
#     year = SUP_OIL@availability$year,
#     price = SUP_OIL@availability$cost * 1.2
#   )
# )
```

The model

```r
reps <- add(newRepository('utopia_repository'),
            # Commodities
            ELC, # electricity
            COA, GAS, NUC, HYD, BIO, # energy
            WIN, SOL, # renewables
            CO2, PM, NOX, SO2, HG, CH4, # emissions
            # Supply
            SUP_NUC, SUP_COA, SUP_GAS, RES_HYD,
            RES_SOL, RES_WIN,
            # Import from ROW
            COAIMP, GASIMP,
            # Technologies
            ECOA, EGAS, ENUC, EHYD,
            # EWIN, ESOL,
            # Electricity trade
            # TRD_ELC_ALL, # repository with electricity trade routes
            DEM_ELC # ELC demand with load curve (24 hours x 12 months)
            )
```

```
length(reps@data)
names(reps@data)

mdl <- newModel('UTOPIA',
                debug = data.frame(#comm = "ELC",
                                   dummyImport = 1e6,
                                   dummyExport = 1e6),
                region = reg_names,
                discount = 0.05,
                slice = timeslices,
                # slice = unlist(timeslices2),
                repository = reps,
                GIS = gis,
                early.retirement = F)
```

We can check the shares of the time-slices which are auto-calculated assuming that all slices have the same weights. This works for 24 hours, but the weights for every month can be specified to take the difference in months length.

	ANNUAL	MONTH	HOUR	share
1	ANNUAL	m01	h00	0.0034722
2	ANNUAL	m02	h00	0.0034722
3	ANNUAL	m03	h00	0.0034722
4	ANNUAL	m04	h00	0.0034722
5	ANNUAL	m05	h00	0.0034722
6	ANNUAL	m06	h00	0.0034722
283	ANNUAL	m07	h23	0.0034722
284	ANNUAL	m08	h23	0.0034722
285	ANNUAL	m09	h23	0.0034722
286	ANNUAL	m10	h23	0.0034722
287	ANNUAL	m11	h23	0.0034722
288	ANNUAL	m12	h23	0.0034722

The model horizon and annual time-steps (`milesone years`)

If we don't need year-by-year steps, milestone years (MSY) can be specifyed to reduce the model dimention. The function `setMilestoneYears` takes as arguments the model start year and the intervals between MSYs, and calculates the interval years (start and end) for each milestone year.

```
mdl <- setMilestoneYears(mdl, start = 2015, interval = c(1, 2, rep(5, 8)))
mdl@sysInfo@milestone
```

Scenarios

"BASE": traditional techs, no trade

```

scen_BASE <- solve(mdl, name = "BASE",
                   # tmp.path = "C:/solwork",
                   solver = mysolver,
```

```
                   tmp.name = "UTOPIA_BASE",
                   tmp.del = F
                   )
summary(scen_BASE)
```

"GRID": traditional techs and interregional trade

```
scen_GRID <- solve(add(mdl, TRD_ELC_ALL), # Adding trade routes
                   name = "GRID",
                  # tmp.path = "C:/solwork",
                   solver = mysolver,
                   tmp.name = "UTOPIA_GRID",
                   tmp.del = F
                  )
summary(scen_GRID)
```

"RBAU": traditional techs and interregional trade

```
scen_RBAU <- solve(add(mdl, TRD_ELC_ALL, WWIN, WSOL, EWIN, ESOL, STGELC),
                   name = "RBAU",
                   description = "Adding renewables",
                  # tmp.path = "C:/solwork",
                   solver = mysolver,
                  # solver = "GLPK",
                  # solver = "GAMS",
                   tmp.name = "UTOPIA_REN",
                   tmp.del = F
                  )
summary(scen_RBAU)
```

Quick look at the results

```
# scen <- scen_BASE
scen <- scen_RBAU

# Quick check
scen@modOut@solutionStatus
scen@modOut@variables$vObjective
```

getData function

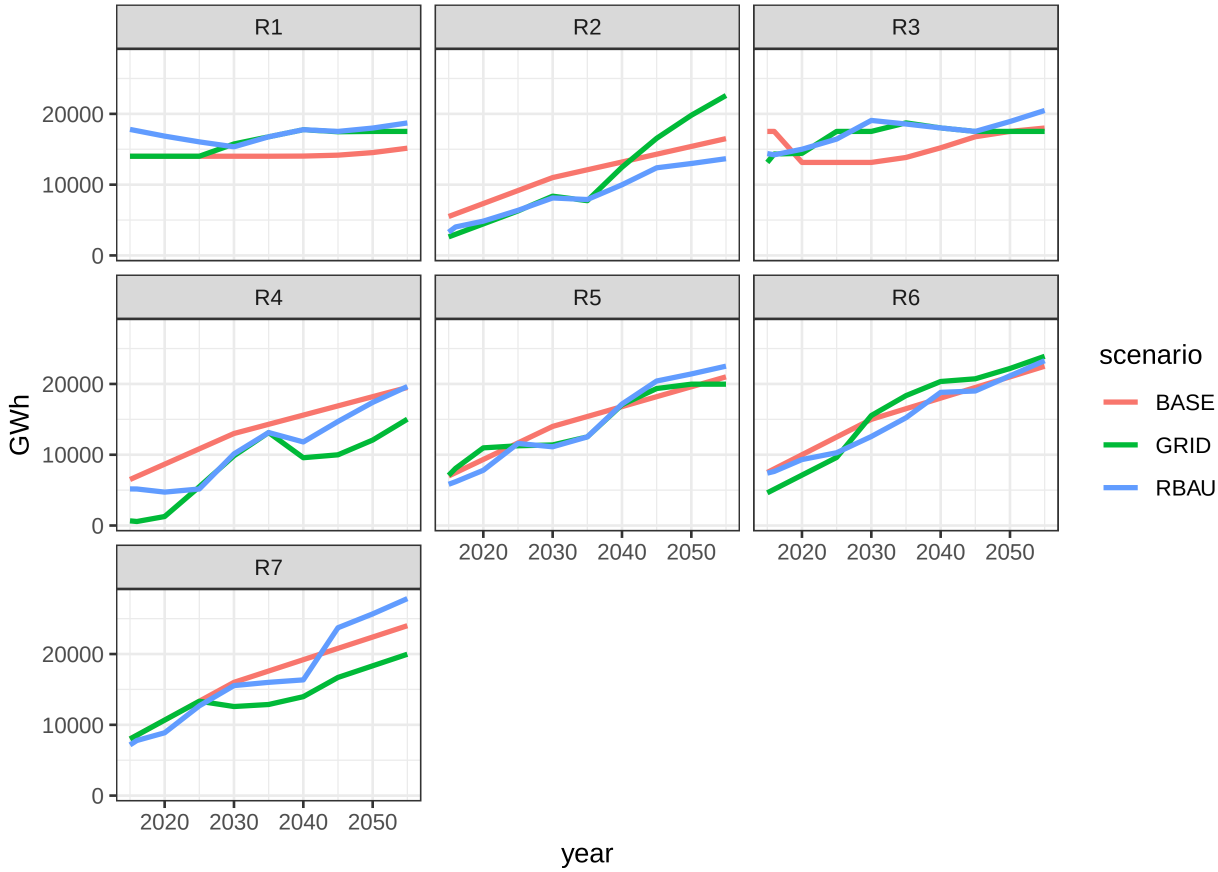
```
sns <- list(scen_BASE, scen_GRID, scen_RBAU)

getData(sns, name = "vObjective", merge = T)
getData(scen_BASE, name = "vTechOutTot", comm = "ELC", merge = F)
getData(sns, name = "vTechOutTot", comm = "ELC", merge = F)
```

Pivot tables

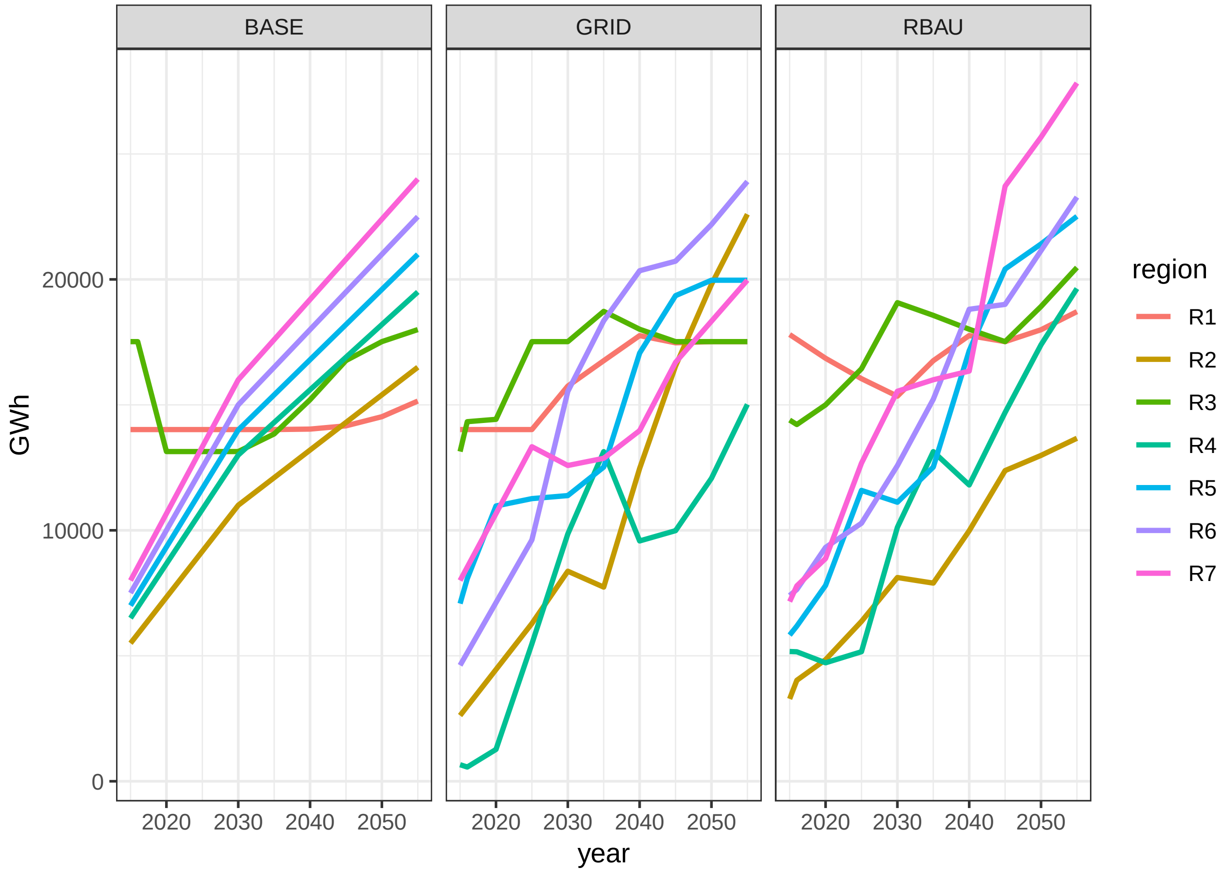
```r
# getData format
pivot(sns, comm = "ELC", name = "vTechOut")
```

Some figures

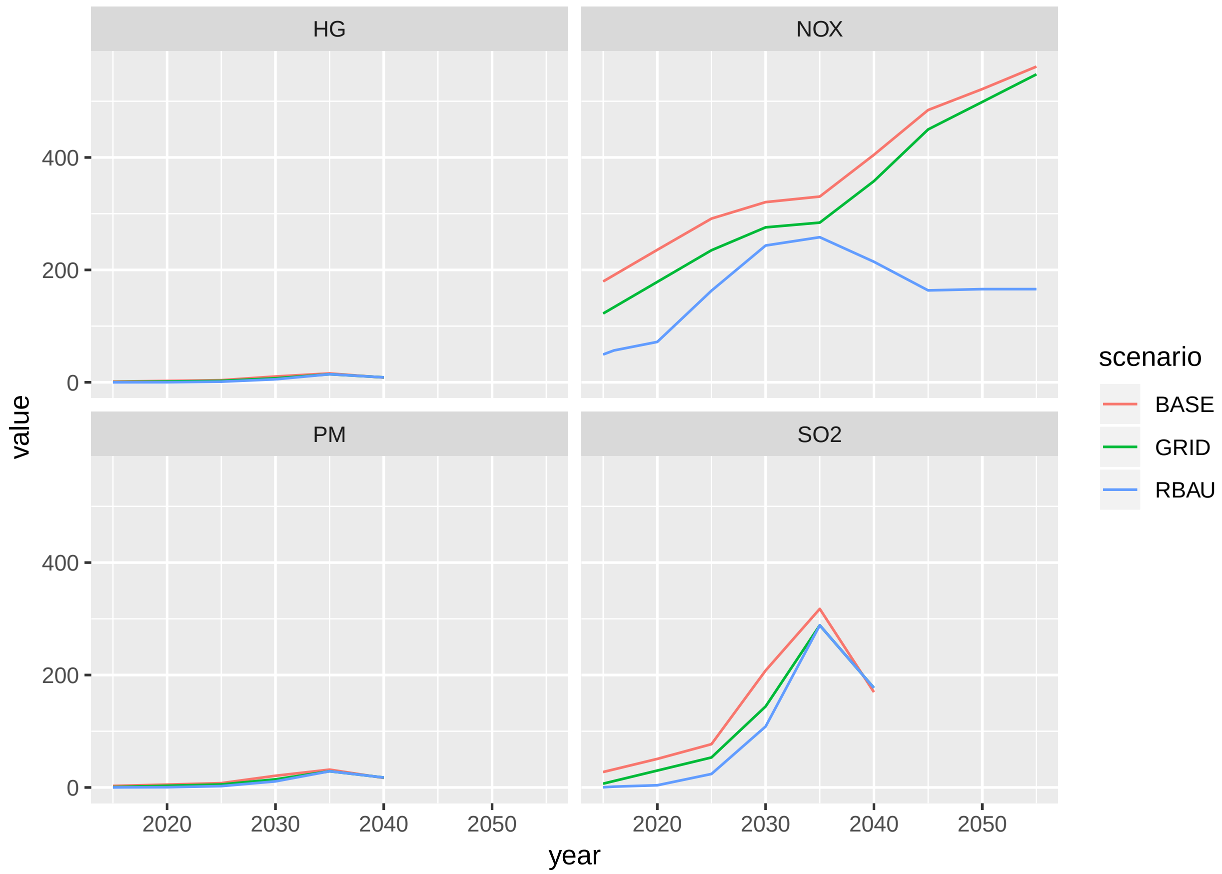
```r
elc_out <- getData(sns, name = "vTechOutTot", comm = "ELC", merge = T)
elc_out
#> # A tibble: 59,632 x 7
#>    scenario name        comm  region  year slice   value
#>    <chr>    <chr>       <chr> <chr>  <int> <chr>   <dbl>
#>  1 BASE     vTechOutTot ELC   R1      2015 m01_h00 0.175
#>  2 BASE     vTechOutTot ELC   R1      2015 m01_h01 0.175
#>  3 BASE     vTechOutTot ELC   R1      2015 m01_h02 0.175
#>  4 BASE     vTechOutTot ELC   R1      2015 m01_h03 0.175
#>  5 BASE     vTechOutTot ELC   R1      2015 m01_h04 0.175
#>  6 BASE     vTechOutTot ELC   R1      2015 m01_h05 0.175
#>  7 BASE     vTechOutTot ELC   R1      2015 m01_h06 0.175
#>  8 BASE     vTechOutTot ELC   R1      2015 m01_h07 0.175
#>  9 BASE     vTechOutTot ELC   R1      2015 m01_h08 0.175
#> 10 BASE     vTechOutTot ELC   R1      2015 m01_h09 0.175
#> # ... with 59,622 more rows
elc_out <- elc_out %>%
  group_by(comm, year, region, scenario) %>%
  summarise(GWh = sum(convert("PJ", "GWh", value)))

ggplot(elc_out, aes(year, GWh, colour = scenario)) + geom_line(size = 1) +
  theme_bw() +
  facet_wrap(.~region)
```




```r
ggplot(elc_out, aes(year, GWh, colour = region)) + geom_line(size = 1) +
  theme_bw() +
  facet_wrap(.~scenario)
```

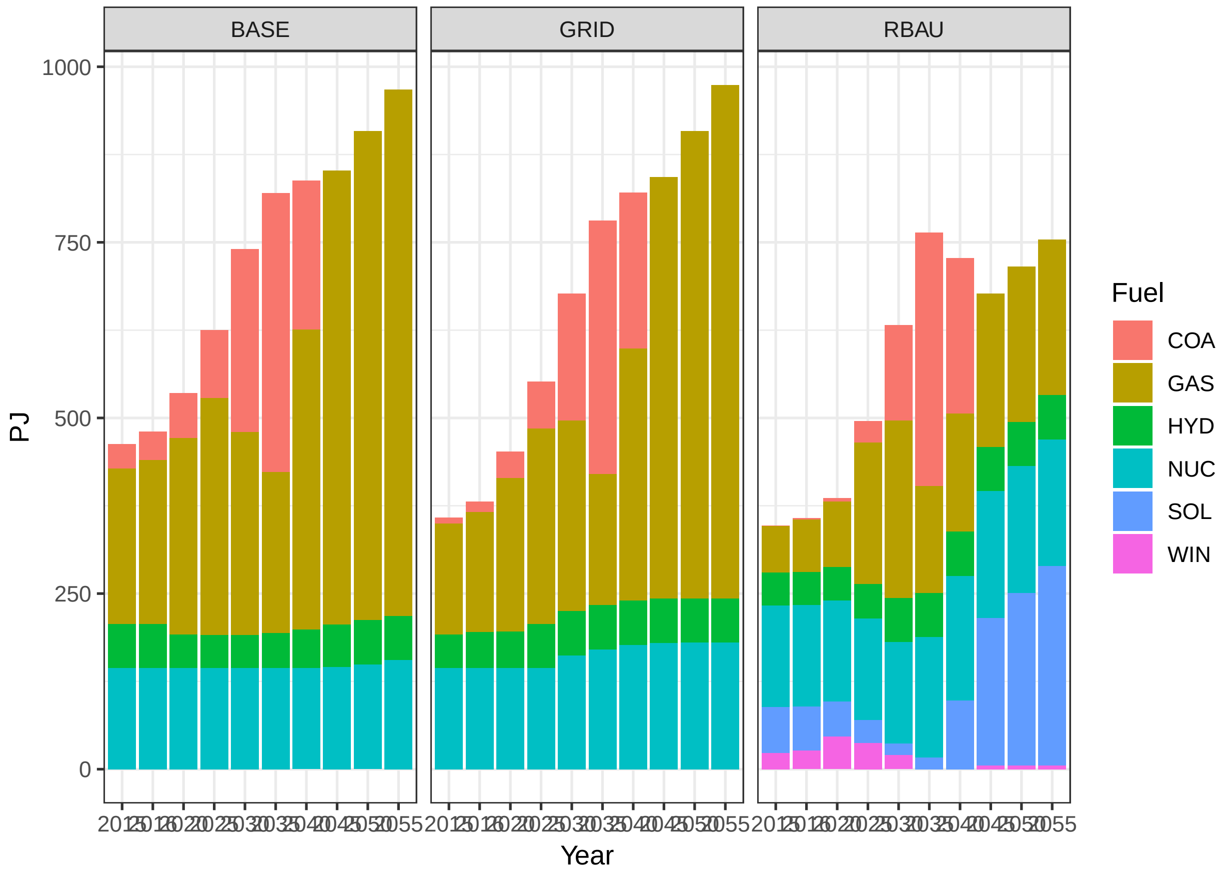



```r
emis <-
  getData(sns, name = "vBalance", merge = T, comm = c("NOX", "SO2", "PM", "HG")) %>%
    group_by(scenario, comm, year) %>%
    summarise(value = sum(value))
ggplot(emis, aes(year, value, colour = scenario)) + geom_line() + facet_wrap(.~comm)
```




```
# Fuel Mix

vTechInp <- getData(sns, name = "vTechInp", tech_ = "^E", merge = T, yearsAsFactors = T)
unique(vTechInp$tech)
#> [1] "ECOA" "EGAS" "ENUC" "EHYD" "EWIN" "ESOL"
unique(vTechInp$comm)
#> [1] "COA" "GAS" "NUC" "HYD" "WIN" "SOL"
unique(vTechInp$scenario)
#> [1] "BASE" "GRID" "RBAU"

fumx <- vTechInp %>%
  group_by(scenario, comm, year) %>%
  summarise(PJ = sum(value))
fumx
#> # A tibble: 129 x 4
#> # Groups:   scenario, comm [14]
#>    scenario comm  year    PJ
#>    <chr>    <chr> <int> <dbl>
#>  1 BASE     COA    2015  34.4
#>  2 BASE     COA    2016  40.2
#>  3 BASE     COA    2020  63.5
#>  4 BASE     COA    2025  96.3
#>  5 BASE     COA    2030 260.
#>  6 BASE     COA    2035 397.
```

```
#>   7 BASE      COA     2040 212.
#>   8 BASE      GAS     2015 221.
#>   9 BASE      GAS     2016 233.
#>  10 BASE      GAS     2020 280.
#> # ... with 119 more rows

ggplot(fumx, aes(as.factor(year), PJ, fill = comm)) +
  geom_bar(stat = "identity") +
  theme_bw() +
  labs(x = "Year", fill = "Fuel") +
  facet_wrap(.~scenario)
```




```
# The same by regions
fumxr <- vTechInp %>%
  group_by(scenario, region, comm, year) %>%
  summarise(PJ = sum(value))
head(fumxr)
#> # A tibble: 6 x 5
#> # Groups:   scenario, region, comm [2]
#>   scenario region comm   year      PJ
#>   <chr>    <chr>  <chr> <int>   <dbl>
#> 1 BASE     R1     GAS    2055   0.166
#> 2 BASE     R1     NUC    2015 144.
#> 3 BASE     R1     NUC    2016 144.
#> 4 BASE     R1     NUC    2020 144.
```

```
#> 5 BASE     R1     NUC    2025 144.
#> 6 BASE     R1     NUC    2030 144.

ggplot(fumxr, aes(as.factor(year), PJ, fill = comm)) +
  geom_bar(stat = "identity") +
  theme_bw() +
  labs(x = "Year", fill = "Fuel") +
  facet_grid(region ~ scenario)
```

Trade

```
trd <- getData(scen, name = "vTradeIr", comm = "ELC", merge = T)
head(trd)
# There are two sets with names of regions: `src` and `dst`
# to plot the flows we will need to ...

trd <- getData(scen, name = "vTradeIr", comm = "ELC", merge = T)

trd_flo <- trd %>%
  left_join(reg_centers[,1:3], by = c("src" = "region")) %>%
  left_join(reg_centers[,1:3], by = c("dst" = "region")) %>%
  rename(xsrc = x.x, ysrc = y.x, xdst = x.y, ydst = y.y) %>%
  mutate(GWh = convert("PJ", "GWh", value))
```

```r
trd_flo
dim(trd_rou)
dim(trd_flo)
summary(trd_flo$GWh)

# ss <- unique(trd_flo$slice)[1]

ftrd_flo_map <- function(slice = sample(unique(trd_flo$slice), 1),
                         year = sample(unique(trd_flo$year), 1)) {
  ii <- trd_flo$slice == slice
  ii <- ii & trd_flo$year
  trd_flo_map <-
    ggplot(data = ggis) +
      geom_polygon(aes(x = long, y = lat, group = group), fill = "wheat",
                   colour = "white", alpha = 1, size = .5) + # aes fill = id,
      coord_fixed(1.) +
      guides(fill=FALSE) +  # do this to leave off the color legend
      theme_void() +
      labs(title = paste0("Interregional electricity trade flows, year = ", year, ", slice = ", slice))
      theme(plot.title = element_text(hjust = 0.5),
            plot.subtitle = element_text(hjust = 0.5)) +
      geom_segment(aes(x=xsrc, y=ysrc, xend=xdst, yend=ydst, size = GWh),
                   data = trd_flo[ii,], inherit.aes = FALSE,
                   alpha = 1, colour = "dodgerblue", lineend = "round", show.legend = T) +
      scale_size_area(limits = range(trd_flo$GWh), max_size = 8) +
      geom_point(data = reg_centers, aes(x, y), colour = "red") +
      geom_segment(aes(x=xsrc, y=ysrc, xend=xdst, yend=ydst),
                   data = trd_flo[ii,], inherit.aes = FALSE, size = .1,
              arrow = arrow(type = "closed", angle = 15,
                            length = unit(0.15, "inches")),
              colour = "white", alpha = 0.75,
              lineend = "butt", linejoin = "mitre", show.legend = T) # , name = "Trade, PJ"
  trd_flo_map
}
ftrd_flo_map()
ftrd_flo_map()

if (!dir.exists("/tmp/fig")) dir.create("/tmp/fig", recursive = T, showWarnings = F)
library(animation)
saveLatex({
  n <- 1
  for (s in slc$slice) {
    pp <- ftrd_flo_map(s, year = 2015)
    ggsave(paste0("Rplot", n, ".pdf"), device = "pdf")
    n <- n + 1
  }},
  use.dev = FALSE,
  caption = "Electricity generation and inter-regional trade.",
  # label = "blablabla",
  ani.dev = "pdf", ani.type = "pdf", img.fmt = "Rplot%d.pdf",
  ani.width = 8, ani.height = 10.5,
  # documentclass = docclass,
  verbose = T
```

```
  # latex.filename = fname #label = h,
  # pdflatex = NULL
  #caption = tsdh2datetime(h)
)
```

Scenarios with constraints

tbc...

NXSX: NOX and SO2 control

GHG50: Cap and trade

Comparative figures

Costs

Output

tbc...

Emissions

tbc...

Average electricity price

References

...

Appendix: energyRt variables and parameters.

Table 4: List of ‘energyRt‘ model variables.

name	description	dimension (sets)
vTechInv	Overnight investment costs	(tech,region,year)
vTechEac	Annualized investment costs	(tech,region,year)
vTechSalv	Salvage value (on the end of the model horizon, to substract from costs)	(tech,region)
vTechOMCost	Sum of all operational costs is equal vTechFixom + vTechVarom (AVarom + CVarom + ActVarom)	(tech,region,year)
vSupCost	Supply costs	(sup,region,year)
vEmsFuelTot	Total fuel emissions	(comm,region,year,slice)
vTechEmsFuel	Emissions from commodity input to tech (like fuel combustion)	(tech,comm,region,year,slice)
vBalance	Net commodity balance	(comm,region,year,slice)
vCost	Total costs	(region,year)
vObjective	Objective costs	()
vTaxCost	Total tax levies (tax costs)	(comm,region,year)
vSubsCost	Total subsidies (for substraction from costs)	(comm,region,year)
vAggOut	Aggregated commodity output	(comm,region,year,slice)
vStorageSalv	Storage salvage costs	(stg,region)
vStorageOMCost	Storage O&M costs	(stg,region,year)
vTradeCost	Total trade costs	(region,year)
vTradeRowCost	Trade with ROW costs	(region,year)
vTradeIrCost	Interregional trade costs	(region,year)
vTechUse	Use level in technology	(tech,region,year,slice)
vTechNewCap	New capacity	(tech,region,year)
vTechRetiredCap	Early retired capacity	(tech,region,year)
vTechCap	Total capacity of the technology	(tech,region,year)
vTechAct	Activity level of technology	(tech,region,year,slice)
vTechInp	Input level	(tech,comm,region,year,slice)
vTechOut	Output level	(tech,comm,region,year,slice)
vTechAInp	Auxiliary commodity input	(tech,comm,region,year,slice)
vTechAOut	Auxiliary commodity output	(tech,comm,region,year,slice)
vSupOut	Output of supply	(sup,comm,region,year,slice)
vSupReserve	Total supply reserve	(sup,comm,region)
vDemInp	Input to demand	(comm,region,year,slice)
vOutTot	Total commodity output (consumption is not counted)	(comm,region,year,slice)
vInpTot	Total commodity input	(comm,region,year,slice)
vInp2Lo	Desagregation of slices for input parent to (grand)child	(comm,region,year,slice)
vOut2Lo	Desagregation of slices for output parent to (grand)child	(comm,region,year,slice)
vSupOutTot	Total commodity supply	(comm,region,year,slice)

Table 4: List of ‘energyRt‘ model variables. *(continued)*

name	description	dimension (sets)
vTechInpTot	Total commodity input to technologies	(comm,region,year,slice)
vTechOutTot	Total commodity output from technologies	(comm,region,year,slice)
vStorageInpTot	Total commodity input to storages	(comm,region,year,slice)
vStorageOutTot	Total commodity output from storages	(comm,region,year,slice)
vStorageAInp	Aux-commodity input to storage	(stg,comm,region,year,slice)
vStorageAOut	Aux-commodity input from storage	(stg,comm,region,year,slice)
vDummyImport	Dummy import (for debugging)	(comm,region,year,slice)
vDummyExport	Dummy export (for debugging)	(comm,region,year,slice)
vDummyCost	Dummy import & export costs (for debugging)	(comm,region,year)
vStorageInp	Storage input	(stg,comm,region,year,slice)
vStorageOut	Storage output	(stg,comm,region,year,slice)
vStorageStore	Storage accumulated level	(stg,comm,region,year,slice)
vStorageInv	Storage technology investments	(stg,region,year)
vStorageCap	Storage capacity	(stg,region,year)
vStorageNewCap	Storage new capacity	(stg,region,year)
vImport	Total regional import (Ir + ROW)	(comm,region,year,slice)
vExport	Total regional export (Ir + ROW)	(comm,region,year,slice)
vTradeIr	Total physical trade flows between regions	(trade,comm,region,year,slice)
vTradeIrAInp	Trade auxilari input	(trade,comm,region,year,slice)
vTradeIrAInpTot	Trade total auxilari input	(comm,region,year,slice)
vTradeIrAOut	Trade auxilari output	(trade,comm,region,year,slice)
vTradeIrAOutTot	Trade auxilari output	(comm,region,year,slice)
vExportRowAccumulated	Accumulated export to ROW	(expp,comm)
vExportRow	Export to ROW	(expp,comm,region,year,slice)
vImportRowAccumulated	Accumulated import from ROW	(imp,comm)
vImportRow	Import from ROW	(imp,comm,region,year,slice)

Table 5: List of ‘energyRt‘ model parameters.

name	description	type	dimension (sets)
ordYear	ord year for GLPK	parameter	(year)
cardYear	card year for GLPK	parameter	(year)
pPeriodLen	Length of perios for milestone year	parameter	(year)
pSliceShare	Share of slice	parameter	(slice)
pAggregateFactor	Aggregation factor of commodities	parameter	(comm)

Table 5: List of ‘energyRt‘ model parameters. *(continued)*

name	description	type	dimension (sets)
pTechOlife	Operational life of technologies	parameter	(tech,region)
pTechCinp2ginp	Multiplier that transforms commodity input into group input	parameter	(tech,comm,region,year,slice)
pTechGinp2use	Multiplier that transforms group input into use	parameter	(tech,group,region,year,slice)
pTechCinp2use	Multiplier that transforms commodity input to use	parameter	(tech,comm,region,year,slice)
pTechUse2cact	Multiplier that transforms use to commodity activity	parameter	(tech,comm,region,year,slice)
pTechCact2cout	Multiplier that transforms commodity activity to commodity output	parameter	(tech,comm,region,year,slice)
pTechEmisComm	Combustion factor for input commodity (from 0 to 1)	parameter	(tech,comm)
pTechUse2AInp	Multiplier to use to get aux-commodity input	parameter	(tech,comm,region,year,slice)
pTechAct2AInp	Multiplier to activity to calculate aux-commodity input	parameter	(tech,comm,region,year,slice)
pTechCap2AInp	Multiplier to capacity to calculate aux-commodity input	parameter	(tech,comm,region,year,slice)
pTechNCap2AInp	Multiplier to new-capacity to calculate aux-commodity input	parameter	(tech,comm,region,year,slice)
pTechCinp2AInp	Multiplier to commodity-input to calculate aux-commodity input	parameter	(tech,comm,region,year,slice)
pTechCout2AInp	Multiplier to commodity-output to calculate aux-commodity input	parameter	(tech,comm,region,year,slice)
pTechUse2AOut	Multiplier to use to calculate aux-commodity output	parameter	(tech,comm,region,year,slice)
pTechAct2AOut	Multiplier to activity to calculate aux-commodity output	parameter	(tech,comm,region,year,slice)
pTechCap2AOut	Multiplier to capacity to calculate aux-commodity output	parameter	(tech,comm,region,year,slice)
pTechNCap2AOut	Multiplier to new capacity to calculate aux-commodity output	parameter	(tech,comm,region,year,slice)
pTechCinp2AOut	Multiplier to commodity to calculate aux-commodity output	parameter	(tech,comm,region,year,slice)
pTechCout2AOut	Multiplier to commodity-output to calculate aux-commodity input	parameter	(tech,comm,region,year,slice)
pTechFixom	Fixed Operating and maintenance (O&M) costs (per unit of capacity)	parameter	(tech,region,year)
pTechVarom	Variable O&M costs (per unit of acticity)	parameter	(tech,region,year,slice)

Table 5: List of ‘energyRt‘ model parameters. *(continued)*

name	description	type	dimension (sets)
pTechInvcost	Investment costs (per unit of capacity)	parameter	(tech,region,year)
pTechShareLo	Lower bound for share of the commodity in total group input or output	parameter	(tech,comm,region,year,slice)
pTechShareUp	Upper bound for share of the commodity in total group input or output	parameter	(tech,comm,region,year,slice)
pTechAfLo	Lower bound for activity for each slice	parameter	(tech,region,year,slice)
pTechAfUp	Upper bound for activity for each slice	parameter	(tech,region,year,slice)
pTechAfsLo	Lower bound for activity for sum over slices	parameter	(tech,region,year,slice)
pTechAfsUp	Upper bound for activity for sum over slices	parameter	(tech,region,year,slice)
pTechAfcLo	Lower bound for commodity output	parameter	(tech,comm,region,year,slice)
pTechAfcUp	Upper bound for commodity output	parameter	(tech,comm,region,year,slice)
pTechStock	Technology capacity stock	parameter	(tech,region,year)
pTechCap2act	Technology capacity units to activity units conversion factor	parameter	(tech)
pTechCvarom	Commodity-specific variable costs (per unit of commodity input or output)	parameter	(tech,comm,region,year,slice)
pTechAvarom	Auxilary Commodity-specific variable costs (per unit of commodity input or output)	parameter	(tech,comm,region,year,slice)
pDiscount	Discount rate (can be region and year specific)	parameter	(region,year)
pDiscountFactor	Discount factor (cumulative)	parameter	(region,year)
pSupCost	Costs of supply (price per unit)	parameter	(sup,comm,region,year,slice)
pSupAvaUp	Upper bound for supply	parameter	(sup,comm,region,year,slice)
pSupAvaLo	Lower bound for supply	parameter	(sup,comm,region,year,slice)
pSupReserveUp	Total supply reserve by region Up	parameter	(sup,comm,region)
pSupReserveLo	Total supply reserve by region Lo	parameter	(sup,comm,region)
pDemand	Exogenous demand	parameter	(dem,comm,region,year,slice)
pEmissionFactor	Emission factor	parameter	(comm)
pDummyImportCost	Dummy costs parameters (for debugging)	parameter	(comm,region,year,slice)
pDummyExportCost	Dummy costs parameters (for debuging)	parameter	(comm,region,year,slice)
pTaxCost	Commodity taxes	parameter	(comm,region,year,slice)
pSubsCost	Commodity subsidies	parameter	(comm,region,year,slice)
pWeather	Weather factor (class weather)	parameter	(region,year,slice,weather)

Table 5: List of ‘energyRt‘ model parameters. *(continued)*

name	description	type	dimension (sets)
pSupWeatherLo	Weather multiplier for supply ava.lo	parameter	(sup,weather)
pSupWeatherUp	Weather multiplier for supply ava.up	parameter	(sup,weather)
pTechWeatherAfLo	Weather multiplier for tech af.lo	parameter	(tech,weather)
pTechWeatherAfUp	Weather multiplier for tech af.up	parameter	(tech,weather)
pTechWeatherAfsLo	Weather multiplier for tech afs.lo	parameter	(tech,weather)
pTechWeatherAfsUp	Weather multiplier for tech afs.up	parameter	(tech,weather)
pTechWeatherAfcLo	Weather multiplier for tech afc.lo	parameter	(tech,comm,weather)
pTechWeatherAfcUp	Weather multiplier for tech afc.up	parameter	(tech,comm,weather)
pStorageWeatherAfUp	Weather multiplier for storages af.up	parameter	(stg,weather)
pStorageWeatherAfLo	Weather multiplier for storages af.lo	parameter	(stg,weather)
pStorageWeatherCinpUp	Weather multiplier for storages cinp.up	parameter	(stg,weather)
pStorageWeatherCinpLo	Weather multiplier for storages cinp.lo	parameter	(stg,weather)
pStorageWeatherCoutUp	Weather multiplier for storages cout.up	parameter	(stg,weather)
pStorageWeatherCoutLo	Weather multiplier for storages cout.lo	parameter	(stg,weather)
pStorageInpEff	Storage input efficiency	parameter	(stg,comm,region,year,slice)
pStorageOutEff	Storage output efficiency	parameter	(stg,comm,region,year,slice)
pStorageStgEff	Storage time-efficiency (annual)	parameter	(stg,comm,region,year,slice)
pStorageStock	Storage capacity stock	parameter	(stg,region,year)
pStorageOlife	Storage operational life	parameter	(stg,region)
pStorageCostStore	Storing costs per stored amount (annual)	parameter	(stg,region,year,slice)
pStorageCostInp	Storage input costs	parameter	(stg,region,year,slice)
pStorageCostOut	Storage output costs	parameter	(stg,region,year,slice)
pStorageFixom	Storage fixed O&M costs	parameter	(stg,region,year)
pStorageInvcost	Storage investment costs	parameter	(stg,region,year)
pStorageCap2stg	Storage capacity units to activity units conversion factor	parameter	(stg)
pStorageAfLo	Storage capacity lower bound (minimum charge level)	parameter	(stg,region,year,slice)
pStorageAfUp	Storage capacity upper bound (maximum charge level)	parameter	(stg,region,year,slice)
pStorageCinpUp	Storage input upper bound	parameter	(stg,comm,region,year,slice)
pStorageCinpLo	Storage input lower bound	parameter	(stg,comm,region,year,slice)
pStorageCoutUp	Storage output upper bound	parameter	(stg,comm,region,year,slice)
pStorageCoutLo	Storage output lower bound	parameter	(stg,comm,region,year,slice)
pStorageStg2AInp	Storage accumulated volume to auxilary input	parameter	(stg,comm,region,year,slice)

Table 5: List of ‘energyRt‘ model parameters. *(continued)*

name	description	type	dimension (sets)
pStorageStg2AOut	Storage accumulated volume output	parameter	(stg,comm,region,year,slice)
pStorageInp2AInp	Storage input to auxilary input coefficient	parameter	(stg,comm,region,year,slice)
pStorageInp2AOut	Storage input to auxilary output coefficient	parameter	(stg,comm,region,year,slice)
pStorageOut2AInp	Storage output to auxilary input coefficient	parameter	(stg,comm,region,year,slice)
pStorageOut2AOut	Storage output to auxilary output coefficient	parameter	(stg,comm,region,year,slice)
pStorageCap2AInp	Storage capacity to auxilary input coefficient	parameter	(stg,comm,region,year,slice)
pStorageCap2AOut	Storage capacity to auxilary output coefficient	parameter	(stg,comm,region,year,slice)
pStorageNCap2AInp	Storage new capacity to auxilary input coefficient	parameter	(stg,comm,region,year,slice)
pStorageNCap2AOut	Storage new capacity to auxilary output coefficient	parameter	(stg,comm,region,year,slice)
pTradeIrEff	Inter-regional trade efficiency	parameter	(trade,region,year,slice)
pTradeIrUp	Upper bound on trade flow	parameter	(trade,region,year,slice)
pTradeIrLo	Lower bound on trade flow	parameter	(trade,region,year,slice)
pTradeIrCost	Costs of trade flow	parameter	(trade,region,year,slice)
pTradeIrMarkup	Markup of trade flow	parameter	(trade,region,year,slice)
pTradeIrCsrc2Ainp	Auxiliary input commodity in source region	parameter	(trade,comm,region,year,slice)
pTradeIrCsrc2Aout	Auxiliary output commodity in source region	parameter	(trade,comm,region,year,slice)
pTradeIrCdst2Ainp	Auxiliary input commodity in destination region	parameter	(trade,comm,region,year,slice)
pTradeIrCdst2Aout	Auxiliary output commodity in destination region	parameter	(trade,comm,region,year,slice)
pExportRowRes	Upper bound on accumulated export to ROW	parameter	(expp)
pExportRowUp	Upper bound on export to ROW	parameter	(expp,region,year,slice)
pExportRowLo	Lower bound on export to ROW	parameter	(expp,region,year,slice)
pExportRowPrice	Export prices to ROW	parameter	(expp,region,year,slice)
pImportRowRes	Upper bound on accumulated import to ROW	parameter	(imp)
pImportRowUp	Upper bount on import from ROW	parameter	(imp,region,year,slice)
pImportRowLo	Lower bound on import from ROW	parameter	(imp,region,year,slice)
pImportRowPrice	Import prices from ROW	parameter	(imp,region,year,slice)
pLECLoACT		parameter	(region)