1 Overview

medea is a simple, stylized and parsimonious power system model. It simulates investment in intermittent and conventional electricity and heat generation technologies as well as in cross-border electricity transmission capacities. At the same time, the model determines the system-cost minimizing hourly dispatch of electricity and heat generators to meet price-inelastic demand. Model results include hourly energy generation by technology and the associated fuel use and CO2 emissions, investment in and decommissioning of conventional and renewable generators and energy storages, hourly cross-border flows of electricity and potentially required transmission capacity expansion, as well as producer and consumer surplus.

A detailed description of the model is provided in the following. Section 2 gives an overview of the sets and set elements used in *medea*. Sections 3 and 4 introduce the model's parameters and variables, while section 5 gives a detailed description of the model's mathematical formulation.

2 Sets

name	math symbol	GAMS symbol	elements
market zones	$z \in Z$	`r`	`AT, DE`
time periods (hours)	$t \in T$	`t`	`t1, t2, ..., t8760`
power generating technologies	$i \in I$	`tec`	`nuc, lig_stm, lig_stm_chp, lig_boa, lig_boa_chp, coal_sub, coal_sub_chp, coal_sc, coal_sc_chp, coal_usc, coal_usc_chp, coal_igcc, ng_stm, ng_stm_chp, ng_ctb_lo, ng_ctb_lo_chp, ng_ctb_hi, ng_ctb_hi_chp, ng_cc_lo, ng_cc_lo_chp, ng_cc_hi, ng_cc_hi_chp, ng_mtr, ng_mtr_chp, ng_boiler_chp, oil_stm, oil_stm_chp, oil_ctb, oil_ctb_chp, oil_cc, oil_cc_chp, bio, bio_chp, heatpump_pth`
CHP technologies	$j \in I$	`tec_chp`	`lig_stm_chp, lig_boa_chp, coal_sub_chp, coal_sc_chp, coal_usc_chp, ng_stm_chp, ng_ctb_lo_chp, ng_ctb_hi_chp, ng_cc_lo_chp, ng_cc_hi_chp, ng_mtr_chp, ng_boiler_chp, oil_stm_chp, oil_ctb_chp, oil_cc_chp, bio_chp`
power to heat technologies	$h \in I$	`tec_pth`	`heatpump_pth`
storage technologies	$k \in K$	`tec_strg`	`res_day, res_week, res_season, psp_day, psp_week, psp_season, battery`
intermittent generators	$n \in N$	`tec_itm`	`wind_on, wind_off, pv, ror`
fuels	$f \in F$	`f`	`nuclear, lignite, coal, gas, oil, biomass, power`
feasible operation region limits	$l \in L$	`l`	`l1, l2, l3, l4`
energy products	$p \in P$	`prd`	`power, heat`

3 Parameters

name	math symbol	GAMS symbol	Unit
minimal conventional generation	μ_z	`ANCIL_SERVICE_LVL(r)`	GW
energy demand	$D_{z,t,p}$	`CONSUMPTION(r,t,prd)`	GW
power plant efficiency	$\eta_{i,p,f}$	`EFFICIENCY(tec,prd,f)`	MW/MW_{th}
fuel emission intensity	ε_f	`EMISSION_INTENSITY(f)`	$t\mathrm{CO}_2/MWh_{th}$
feasible operating region	$\chi_{i,l,f}$	`FEASIBLE_INPUT(tec,l,f)`	MWh ?
feasible operating region	$\psi_{i,l,p}$	`FEASIBLE_OUTPUT(tec,l,prd)`	MWh ?
intermittent generation profile	$\phi_{z,t,n}$	`GEN_PROFILE(r,t,tec_itm)`	%
installed capacity of intermittent generators	$r^0_{z,n}$	`INSTALLED_CAP_ITM(r,tec_itm)`	GW
installed capacity of thermal generators	$g^0_{z,i}$	`INSTALLED_CAP_THERM(r,tec)`	GW
capital cost of intermittent generators (specific, annuity)	$\kappa_{z,n}$	`INVESTCOST_ITM(r,tec_itm)`	$\frac{mnEUR}{GW}$
capital cost of thermal generators (specific, annuity)	$\kappa_{z,i}$	`INVESTCOST_THERMAL(r,tec)`	$\frac{mnEUR}{GW}$
capital cost of storages - power (specific, annuity)	$\kappa^P_{z,k}$	`STORAGE_PROPERTIES(r,tec_strg,'cost_power')`	$\frac{mnEUR}{GW}$
capital cost of storages - energy (specific, annuity)	$\kappa^E_{z,k}$	`STORAGE_PROPERTIES(r,tec_strg,'cost_energy')`	$\frac{mnEUR}{GW}$
net transfer capacity	$\tau_{z,zz}$	`NTC(r,rr)`	GW
count of power plants of same technology	$\|i_z\|$	`NUM(r,tec)`	.
fixed O&M cost	κ^o_i	`OM_FIXED_COST(tec)`	EUR
variable O&M cost	κ^o_i	`OM_VAR_COST(tec)`	EUR / MWh
CO_2 price	$p^e_{t,z}$	`PRICE_EUA(t,r)`	EUR / t CO2
fuel price	$p_{t,z,f}$	`PRICE_FUEL(t,r,f)`	EUR / MWh
reservoir inflows	$\rho_{z,t,k}$	`RESERVOIR_INFLOWS(r,t,tec_strg)`	MW
max power out	$\bar{s}^{out}_{z,k}$	`STORAGE_PROPERTIES(r,tec_strg,'power_out')`	GW
max power in	$\bar{s}^{in}_{z,k}$	`STORAGE_PROPERTIES(r,tec_strg,'power_in')`	GW
max energy stored	$\bar{v}_{z,k}$	`STORAGE_PROPERTIES(r,tec_strg,'energy_max')`	.
efficiency power out	$\eta^{out}_{z,k}$	`STORAGE_PROPERTIES(r,tec_strg,'efficiency_out')`	.
efficiency power in	$\eta^{in}_{z,k}$	`STORAGE_PROPERTIES(r,tec_strg,'efficiency_in')`	.

4 Variables

name	math symbol	GAMS symbol	Unit
system cost	C_z	`cost(r)`	EUR
emission cost	$C^e_{z,t,i}$	`cost_emission(r,t,tec)`	EUR
fuel cost	$C^f_{z,t,i}$	`cost_fuel(r,t,tec)`	EUR
total o&m cost	$C^{om}_{z,i}$	`cost_om(r,tec)`	EUR
capital cost of generators	$C^{inv,i}_z$	`cost_invgen(r)`	EUR
capital cost of storages	$C^{inv,k}_z$	`cost_invstrg(r)`	EUR
capital cost of interconnectors	$C^{inv,ic}_z$	`cost_gridexpansion(r)`	EUR
added capacity of intermittents	$r^+_{z,n}$	`invest_res(r,tec_itm)`	GW
added capacity of conventionals	$g^+_{z,i}$	`invest_thermal(r,tec)`	GW
added storage capacity (power)	$v^+_{z,k}$	`invest_storage_power(r,tec_strg)`	EUR
added in storage capacity (energy)	$s^+_{z,k}$	`invest_storage_energy(r,tec_strg)`	EUR
added transmission capacity	$x^+_{z,zz}$	`invest_ntc(r,rr)`	EUR
decommissioned capacity of conventionals	$g^-_{z,i}$	`decommission(r,tec)`	GW
energy generated by conventionals	$g_{z,t,i,p}$	`q_gen(r,t,tec,prd)`	GW
electricity generated by intermittents	$r_{z,t,n}$	`q_itm(r,t,tec_itm)`	GW
operating region weight	$w_{z,t,i,l}$	`cc_weights(r,t,tec,l)`	.
fuel burn for energy generation	$b_{z,t,i,f}$	`q_fueluse(r,t,tec,f)`	GW
energy stored in	$s^{in}_{z,t,k}$	`q_store_in(r,t,tec_strg)`	GW
energy stored out	$s^{out}_{z,t,k}$	`q_store_out(r,t,tec_strg)`	GW
storage energy content	$v_{z,t,k}$	`storage_level(r,t,tec_strg)`	GWh
electricity net export	$x_{z,zz,t}$	`flow(r,rr,t)`	GW
curtailed energy	$\Omega^-_{z,t,p}$	`q_curtail(r,t,prd)`	GW
non-served energy	$\Omega^+_{z,t,p}$	`q_nonserved(r,t,prd)`	GW
CO_2 emissions	e_z	`emissions(r)`	t CO_2

5 Mathematical description

Objective function: total system cost, minimization

$$\min C = \sum_z (C_z) \tag{1}$$

System cost consist of fuel cost $C^f_{z,t,i}$, emission cost $C^e_{z,t,i}$, operation and maintenance cost $C^{om}_{z,i}$, and capital costs of investment in generation, storage and transmission equipment plus the cost of non-served load that accrues when demand is not met, i.e. when there is a black out.

$$\begin{aligned} C_z = \sum_{t,i} C^f_{z,t,i} + \sum_{t,i} C^e_{z,t,i} + \sum_i C^{om}_{z,i} + C^{inv,i}_z + \\ C^{inv,n}_z + C^{inv,k}_z + C^{inv,ic}_z + \sum_{t,p} C^{nse}_{z,t,p} \qquad \forall z \end{aligned} \tag{2}$$

Our power system model uses a linear programming formulation of the economic dispatch problem for thermal units within the Austro-German bidding zone. Operation of pumped storage plants is also formulated as a linear problem. The model's objective is to minimize total system cost, the sum of fuel, emission and operation and maintenance cost along with the cost associated with curtailment of renewable energies and loss of load.

$$\min \left(\sum_{t,g,f} \left(\left(P_{t,f} + em_f P_{t,eua} + om_g \right) qf_{t,g,f} + qns_{t,p} M + qct_t N \right) \right) \tag{3}$$

In each hour the market has to clear, such that electricity supply from thermal and net generation from hydro storage plants plus power generation from non-dispatchable sources (wind energy, photovoltaics, and run-of-river hydro plants) equals electricity demand less net imports of electricity.

$$\begin{aligned} D_{t,pwr} - Q_{t,nip} = \sum_g \left(qp_{t,g,pwr} \right) + \sum_{g \in PSP} \left(qpsp_{t,g} - ppsp_{t,g} \right) \\ + Q_{t,we} + Q_{t,pv} + Q_{t,ror}, \forall t \end{aligned} \tag{4}$$

In linear (economic dispatch) models, the marginals ('shadow prices') on equation (4) can be interpreted as power prices in an energy-only market. We use these marginals to derive the pass-through from emission prices to power prices. As we also consider co-generation of heat and power in our model, we introduce the heat balance equation (5). Heat supply from CHP units and heat boilers must be adequate to meet district heating demand $D_{t,ht}$.

$$D_{t,ht} \leq \sum_{g \in CHP} \left(qp_{t,g,ht} \right) + qns_{t,p}, \forall t \tag{5}$$

Hourly generation of power and heat is constrained by installed capacity.

$$qp_{t,g,p} \leq \bar{C}_{g,p}, \forall t \tag{6}$$

Coproduction of heat and power in CHP-plants is governed by

$$\sum_{l} sconv_{t,g,l} = 1, \forall g \in CHP \tag{7}$$

$$\sum_{l} sconv_{t,g,l} ORP_{g,l,p} = qp_{t,g,p}, \forall g \in CHP \tag{8}$$

$$\sum_{l} sconv_{t,g,l} ORF_{g,l,f} \leq qfuel_{t,g,f} \tag{9}$$

Power production by power-only generators is modelled as a linear function of plant efficiency

$$qp_{t,g,pwr} \leq \sum_{f} \eta_{g,f,pwr} qf_{t,g,f}, \forall t, g \notin CHP \tag{10}$$

Ancillary services must be provided by operating thermal generation units or active hydro storage plants (regardless of whether they are pumping or turbining).

$$\underline{a} \leq qp_{t,g,pwr} + qpsp_{h,g} + qstor_{t,g}, \forall t \tag{11}$$

Operation of pumped storage plants is subject to the equations

$$qpsp_{h,g} \eta_g \leq \overline{C}_g, \forall t, g \in PSP \tag{12}$$

$$ppsp_{t,g} \leq \overline{C}_g, \forall t, g \in PSP \tag{13}$$

$$qstor_{t,g} - qstor_{t-1,g} = ppsp_{h,g} \eta_g - qpsp_{h,g} \tag{14}$$

$$qstor_{t,g} \leq \overline{STOR}_g, \forall t, g \in PSP \tag{15}$$

6 Data

Information regarding the power plant stock (generation capacities, technology, locations) in Germany are based on data provided by the Open Power System Data (OPSD) project (**?**). Data on Austrian power plants was collected through own research and includes information from the regulatory body (**?**), sector associations (**?**), operating companies, and water registers of federal authorities (**??**). Hourly electricity generation from intermittent sources (solar PV, wind) and load in Austria and Germany is also sourced from **?**. Further time series on international commercial electricity exchanges, the aggregate filling rate of hydro reservoirs and storage plants, and the actual electricity generation and consumption of hydro power plants (including run-of-river plants) are obtained from ENTSO-E's transparency platform (**?**). We approximate inflows of water to reservoirs in Austria by combining downsampled data on weekly water reservoir levels with hourly electricity generation and pumping from hydro reservoirs and pumped storage plants.[1] Hourly district heating demand is estimated based on synthetic load profiles for natural gas demand (**?**). These load profile make use of daily average temperatures from MERRA-2 satellite data (**?**) and are scaled to total final consumption of district heat in Germany and Austria.[2] Realized prices of hard coal, natural gas and EU emission allowances for the year

[1] In Germany, 98% of the installed hydro storage capacity is pumped hydro power so that we abstract from inflows to German hydro storage plants.

[2] As final data for the consumption of district heat in 2017 was not published at the time of writing, we scale 2016 district heat consumption by the relative change in heating degree days from 2016 to 2017 (**??**).

Table 1: Descriptive statistics

	Unit	Min	Max	Mean	Std. Dev	Source
Wind	GW	0.279	41.72	12.49	9.03	OPSD
Solar PV	GW	0	28.33	4.23	6.49	OPSD
Run-of-river	GW	2.08	7.13	4.78	1.13	ENTSO-E
Reservoir inflows	GW	0	2.14	0.79	0.59	own calculations
Electricity consumption	GW	38.52	96.77	69.09	12.59	ENTSO-E
District heat consumption	GW	1.54	42.04	13.49	9.60	own calculations
Net imports (commercial exchange)	GW	-13.74	7.07	-4.87	2.93	ENTSO-E
Coal price (API2)	€$/MWh_{th}$	8.32	11.36	9.65	0.72	eex
Natural gas price (NCG)	€$/MWh_{th}$	15.91	19.02	17.27	0.87	eex
Mineral oil price	€$/MWh_{th}$	23.18	32.93	28.25	2.57	EIA
EU Emission Allowance price	€$/MWh_{th}$	4.41	8.21	5.89	1.11	eex

2017 are taken from the **?**. Prices for mineral oil are approximated on the basis of prices for Brent crude oil as published by the **?**. As there are no market prices for nuclear fuel and lignite, we estimate lignite cost at 5.50 €/MWh (including mining, but excluding emission cost) and 3.50 €/MWh for nuclear fuel. Descriptive Statistics for all used time series are displayed in Table 1.