PRIMES-IEM

PRIMES MODEL FOR THE INTERNAL ELECTRICITY MARKET OF THE EU

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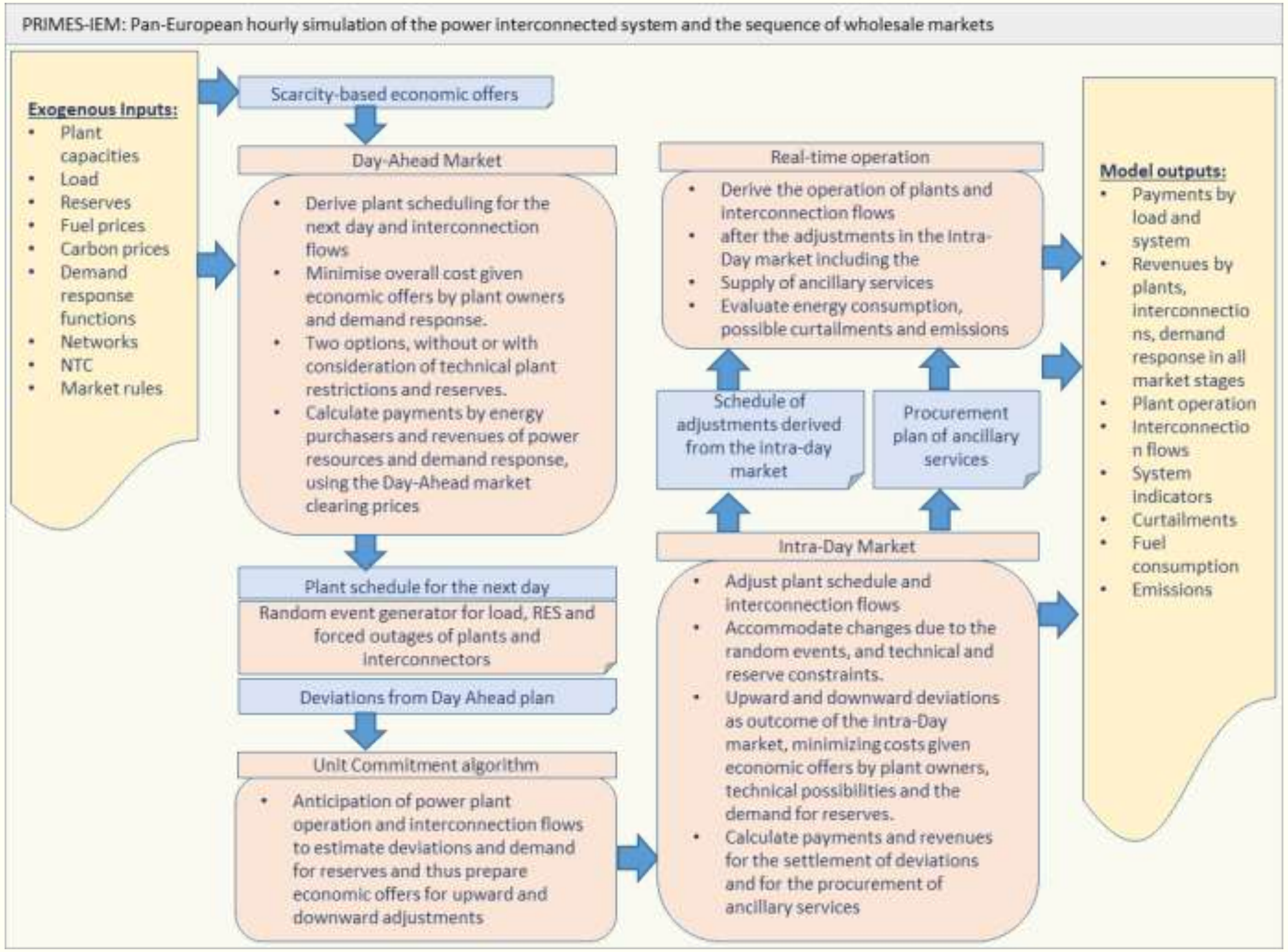
As used for the assessment of the EU Electricity Directive in 2019

Schematic representation of PRIMES-IEM (Internal Electricity Market) model

- PRIMES-IEM is a special version of the power sector model that simulates the sequence of wholesale markets at a pan-European scale, together with power exchange flows. The model simulates the target model for the internal electricity market, and support impact assessment studies for market design options
- The sequence is:
  - Day-Ahead Market (DAM)
  - Random events changing conditions
  - Intra-Day and balancing Market (IDM)
  - Reserves and ancillary services market or procurement
- The model cover all 28 EU MS individually and neighboring countries to account for the cross-border trade
- The model uses as inputs capacities, fuel availability and costs as projected into the future by the standard PRIMES model



Scarcity bidding by generators

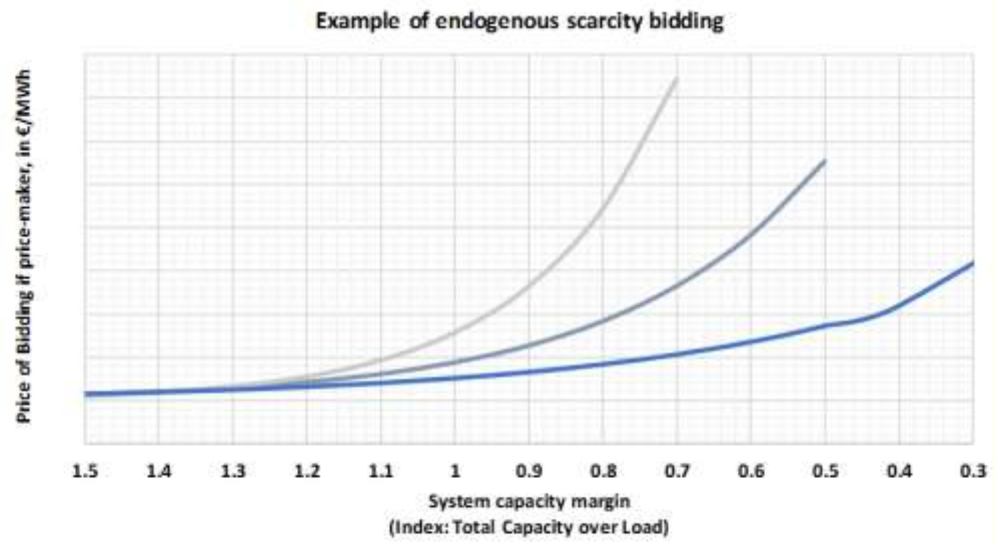
- Bidding by power plants in the various stages of the wholesale markets is endogenous, deriving from a scarcity bidding function, which is a simplified representation of supply function equilibrium
- The scarcity bidding function $B_{p,v,h,t}$ of each power plant p, built in year v, at each time segment h has an ascending slope as a function of scarcity of capacities in relation to load
- $mc_{p,v,t}$ represents the marginal cost of the power plant, considered as the floor of the bidding price
- The ratio $^{sup_{h,t}}/_{dem_{h,t}}$ represents capacity scarcity
- Parameter $ceil_{h,t}$ acts as a ceiling of bid prices, irrespective of scarcity
- the coefficient t$rate_p$ reflects the steepness of the influence of scarcity on bidding behaviours
- The steepness parameter may represent various factors that a bidder considers in his behaviour, including the degree of risk-prone behaviour, whether the plant is a peaking one or not (in the sense of taking the risk of price making), and the intensity of competition by other plants in the merit order of dispatching

Mathematical formulation

Endogenous scarcity bidding:

$$B_{p,v,h,t} = mc_{p,v,t} + ceil_{h,t} e^{-rate_p \left(^{sup_{h,t}}/_{dem_{h,t}} - 1 \right)} \quad \forall i,p,h \quad v \le t, t$$

Illustrative example:



Modelling a Pure Energy Market for the Day-Ahead Market

Day-Ahead Market:

- The modelling of the day-ahead market (DAM) builds on the EUPHEMIA algorithm
- The main addition is the modelling of bidding behaviour endogenously
- The model includes user-defined options to control the bidding, for which at least two contrasting views are available
  - A. Bidders submit only for energy injection and consumption without any other consideration
  - B. The participants submit bids which are adjusted optimally after pre-empting technical limitation plant and system-related
- For B the mathematical formulation used includes the equations of the unit commitment algorithm

Mathematical formulation for Case A	
Hourly balance of electricity demand and supply $$D^{E}_{i,h,t} = N_{i,h,t} + \sum_{p,v\le t} G_{i,p,v,h,t} + \overline{G}_{i,p,v,h,t}$$	$\forall i,h,t$
Maximum generation limit $$G_{i,p,v,h,t} \le k_{i,p,v,t} \cdot af_{i,p,v,h}$$	$\forall i,p,v \le t,h,t$
Maximum flow over an interconnector limit $$\left|FL_{k,h,t}\right| \le t^{max}_{k,t}$$	$\forall k,h,t$
NTC restriction on cross-border flows $$\left|\sum_{k} n_{i,k} \cdot FL_{k,h,t} \cdot n^{\top}_{k,ii}\right| \le NTC_{i,ii,t}$$	$\forall i,ii,t$
DC power flow equation $$FL_{k,h,t} = \sum_{i} \Theta_{i,h,t} \cdot \sum_{kk} n_{i,k} \cdot b_{k,kk}$$	$\forall k,h,t$
The sum of all nodal injections equals zero $$\sum_{k} FL_{k,h,t} = 0$$	$\forall h,t$
Net imports $$N_{i,h,t} = \sum_{k} n_{i,k} \cdot FL_{k,h,t}$$	$\forall i,h,t$
Phase angle is zero in the swing (reference) node $$\Theta_{i,h,t} = 0$$	$\forall i \in sw,t$

Objective function of the DA market and market-clearing price

- The DAM optimises the objective function, subject to constraints, to determine:
  - the optimal schedule of the plants (having requested remuneration equal or below the market-clearing price),
  - The flows over interconnections
  - The part of the demand to meet
- Maximisation of social surplus is equivalent to a market equilibrium where the consumers minimise costs and producers maximise profits
- After solving for the optimisation, the model determines the marginal price of the system ($P_{i,h}$), from the demand curve

Mathematical formulation for Case A:

Objective function:

$$\underset{G,D,FL}{\text{Max}}\ Social\ Surplus = \sum_{i,t}\sum_{h}\left(\int_{0}^{D_{i,h,t}} d_{i,h}(x_{i,h,t})\,\mathrm{d}x_{i,h,t} - \sum_{p,v\le t} B_{i,p,v,h,t}(G_{i,p,v,h})\cdot G_{i,p,v,h}\right)$$

Hourly market-clearing price is the marginal price of the system

$$P_{i,h,t} = d_{i,h,t}(D_{i,h,t}) \qquad \forall i,h,t$$

Generation of Random Events after the Day-Ahead Market

- To mimic the occurrence of deviations between the plant scheduling derived by the DAM and the operation of the system, the PRIMES-IEM generates random events
- The random events include:
  - Unexpected variation of the hourly demand $\Delta d_{i,h,t}$
  - Forecast errors for the availability of variable renewable sources $\Delta af_{i,p,h,t}$
  - Forced outages of large power plants $\Delta af_{i,p,h,t}$
  - Unplanned loss of transmission lines $\Delta t_{k,t}$
- These random events imply either upward or downward deviations
- The random variables follow a normal distribution with a given variance-covariance matrix
- Monte-Carlo sampling generates a few scenarios to run the models for the markets after the Day-Ahead.
- For every scenario retained, the model performs a simulation of the intra-day market and the balancing and reserves market or procurement procedures. Then weighted sums provide the final results

Intra-day and balancing market

- Intra-day market
  - Manages upwards and downwards deviations and settles revenues and payments for deviations
  - The market participants anticipate deviations to form their volume and price offers
  - The model mimics anticipation by running the unit commitment algorithm, after the occurrence of random events
  - The unit commitment run includes demand for ancillary services and the technical constraints of plant operation, and thus deviations from DAM are also due to the non-inclusion of technical constraints and ancillary services in the DAM (depending on the rules of the DAM)
  - The unit commitment is constrained to adjust the plant scheduling without deviating too much from the scheduling derived from the DAM and thus minimise the financial burden of the deviations for market participants
- The intra-day market involves bidding by participants separately for upward and downward adjustments
- Before bidding, the market participants consider the status of their portfolio as included in the scheduling derived from the DAM and after considering possible alterations due to the random events
- The simulation of the intra-day market has the form of an optimisation problem with an objective function expressing the minimisation of total costs for meeting the deviations (or maximisation of consumer surplus in case demand response participates in the market)

Objective function of the ID market and market-clearing prices

- The objective of the intra-day market is to ensure the adequacy of system operation in real-time and remunerate the participants for the adjustments of the power levels of their portfolio and includes
  - Bidding of plant for covering deviations (different bidding for upward $b^{up}_{i,p,v,h,t}$ and downward $b^{dn}_{i,n,h}$ adjustments)
  - the shut-down ($C^{sd}_{i,p,v}$) and start-up ($C^{sd}_{i,p,v}$) costs only for the plants performing start-up or shut-down specifically in the intra-day.
- The marginal system prices for upward and downward deviations derive as dual variables of constraints by the demand for deviations after solving the relaxed problem.
- The relaxed problem of a mixed-integer optimisation problem (MIP) is the linear equivalent problem, after replacing the integer (or binary) variables with parameters, which take values from the solution of the MIP problem

Mathematical formulation of the objective function:

Objective function z is the total cost of deviations:

$$\underset{G^{up},G^{dn},G^{open},G^{shut},FL^{IDM}}{Min} z=$$

$$\sum_{h}\sum_{i}\sum_{p,v\leq t}\left[b^{up}_{i,p,v,h,t}\left(G^{up}_{i,p,v,h,t}\right)\cdot G^{up}_{i,p,v,h,t}+b^{up}_{i,n,h}\left(G^{open}_{i,p,v,h,t}\right)\cdot G^{open}_{i,p,v,h,t}+b^{dn}_{i,n,h}\left(G^{dn}_{i,p,v,h,t}\right)\cdot G^{dn}_{i,p,v,h,t}+SU^{open}_{i,p,v,h,t}C^{su}_{i,p,v}+SD^{shut}_{i,p,v,h,t}C^{sd}_{i,p,v}\right],\forall t$$

Mathematical formulation of the Intra-day Market - 1

The mixed-integer programming formulation includes the binary variables representing

- the operating status of the plants ($U^{IDM}_{i,p,v,h,t}$,$SU^{IDM}_{i,p,v,h,t}$,$SD^{IDM}_{i,p,v,h,t}$), as in the model for the DAM
- $B^{open}_{i,p,v,h,t}$ and $B^{shut}_{i,p,v,h,t}$, which represent the deviation of the plant commitment status between the day-ahead and the intra-day
- $SU^{open}_{i,p,v,h,t}$ and $SD^{shut}_{i,p,v,h,t}$, representing the choice of starting-up an offline in DAM plant or shutting down a committed in the DAM plant
- The capacity constraints restricting depend on the operating status ($\bar{u}_{i,p,v,h,t}$) and the power level of the plant in the DAM-derived schedule ($\bar{g}_{i,p,v,h,t}$), the withheld capacity for reserve purposes ($\bar{r}^{up}_{i,p,v,h,t}$,$\bar{r}^{dn}_{i,p,v,h,t}$)

Mathematical formulation
$G^{up}_{i,p,v,h,t} + \bar{g}_{i,p,v,h,t} + \bar{r}^{up}_{i,p,v,h,t} \leq k_{i,p,v,t} \cdot \left(af_{i,p,v,h,t} + \Delta af_{i,p,v,h,t}\right) \cdot \left(\bar{u}_{i,p,v,h,t} - B^{shut}_{i,p,v,h,t}\right)$
$G^{dn}_{i,p,v,h,t} \leq \left(\bar{g}_{i,p,v,h,t} - \bar{r}^{dn}_{i,p,v,h,t} - m_{i,p,v}\right) \cdot \left(\bar{u}_{i,n,h} - B^{shut}_{i,p,v,h,t}\right)$
$G^{open}_{i,p,v,h,t} \leq k_{i,p,v,t} \cdot \left(af_{i,p,v,h,t} + \Delta af_{i,p,v,h,t}\right) \cdot B^{open}_{i,p,v,h,t}$
$G^{open}_{i,p,v,h,t} \geq m_{i,p,v} \cdot B^{open}_{i,p,v,h,t}$
$G^{shut}_{i,p,v,h,t} = \bar{g}_{i,p,v,h,t} \cdot B^{shut}_{i,p,v,h,t}$
$\left\lvert G^{up}_{i,p,v,h,t} + \bar{g}_{i,p,v,h,t} - \left(G^{up}_{i,p,v,h-1,t} + \bar{g}_{i,p,v,h-1,t}\right)\right\rvert \leq r_{i,p,v}$
$\left\lvert G^{open}_{i,p,v,h,t} - G^{open}_{i,p,v,h-1,t}\right\rvert \leq R_{i,p,v}$
$\left\lvert \bar{g}_{i,p,v,h,t} - G^{dn}_{i,p,v,h,t} - \left(\bar{g}_{i,p,v,h-1,t} - G^{dn}_{i,p,v,h-1,t}\right)\right\rvert \leq r_{i,p,v}$
$U^{IDM}_{i,p,v,h,t} = \bar{u}_{i,p,v,h,t} + B^{open}_{i,p,v,h,t} - B^{shut}_{i,p,v,h,t}$
$U^{IDM}_{i,p,v,h,t} - U^{IDM}_{i,p,v,h-1,t} = SU^{IDM}_{i,p,v,h,t} - SD^{IDM}_{i,p,v,h,t}$
$SU^{IDM}_{i,p,v,h,t} + SD^{IDM}_{i,p,v,h,t} \leq 1$
$B^{open}_{i,p,v,h,t} - B^{open}_{i,p,v,h-1,t} \leq SU^{open}_{i,p,v,h,t}$
$B^{shut}_{i,p,v,h,t} - B^{shut}_{i,p,v,h-1,t} \leq SD^{shut}_{i,p,v,h,t}$

Mathematical formulation of the Intra-day Market - 2

- The capacity constraints for the flows over interconnectors as in the DAM ($\bar{f}_{k,h,t}$) and the inflows minus outflows per node considered as adjustments relative to the DAM ($\bar{N}_{i,h,t}$)

Mathematical formulation
$SU^{open}_{i,p,v,h,t} + SD^{shut}_{i,p,v,h,t} \leq 1$
$\sum_{hh \in [(h - mdn_{i,n,h} - 1 \leq hh) \cap (hh \leq h)]} SD^{IDM}_{i,p,v,h,t} \leq 1 - U^{IDM}_{i,p,v,h,t},$
$\sum_{hh \in [(h - mup_{i,n,h} + 1 \leq hh) \cap (hh \leq h)]} SU^{IDM}_{i,p,v,h,t} \leq U^{IDM}_{i,p,v,h,t},$
$\left\lvert FL^{IDM}_{k,h,t} + \bar{f}_{k,h,t} \right\rvert \leq t_{k,t} + \Delta t_{k,t},$
$\left\lvert \sum_k n_{i,k} \cdot \left(FL^{IDM}_{k,h,t} + \bar{f}_{k,h}, t\right) \cdot n^{\intercal}_{k,ii} \right\rvert \leq ntc_{i,ii,t}$
$N^{IDM}_{i,h,t} + \bar{N}_{i,h,t} = \sum_k n_{i,k} \cdot (FL^{IDM}_{k,h,t} + \bar{f}_{k,h})$
$FL^{IDM}_{k,h,t} + \bar{f}_{k,h} = \sum_i \Theta_{i,h,t} \sum_{kk} n_{i,k} \cdot b_{k,kk}$
$\sum_k FL^{IDM}_{k,h,t} + \bar{f}_{k,h} = 0\,,$
$d^{up}_{i,h,t} - d^{dn}_{i,h,t} = \sum_n \left(G^{up}_{i,p,v,h,t} + G^{open}_{i,p,v,h,t} - G^{dn}_{i,p,v,h,t} - G^{shut}_{i,p,v,h,t}\right) + N^{IDM}_{i,h,t}$

Simulation of the Balancing/Reserves Market

Description:

- The model minimises the cost of procurement of the services and accordingly selects the power resources that are eligible for provision of ancillary services, following submission of financial offers
- The optimisation determines the commitment of capacity of resources to be ready to adjust upwards $R^{up}_{i,p,v,a,h,t}$ or downwards $R^{dn}_{i,p,v,a,h,t}$
- The plants submit price-quantity bids based on the bidding functions $br^{up}_{i,p,v,a,h,t}$ and $br^{dn}_{i,p,v,a,h}$, which reflect opportunity costs (compared to using the plant for energy rather than for reserve) plus a mark-up, depending on scarcity conditions in the market for reserves. Only eligible resources can bid
- Optionally, the interconnectors can contribute $C_{i,h,t}$ to certain types of ancillary services up to a certain limit $c^{up}_{i,h,t}$
- The optimisation takes into account the dispatching schedule resulting from the intra-day market

Mathematical formulation

$Min_{R^{up},R^{dn},C}\ z = \sum_i \sum_a \sum_{p,v\leq t} br^{up}_{i,p,v,a,h,t} \cdot R^{up}_{i,p,v,a,h,t} + br^{dn}_{i,p,v,a,h,t} \cdot R^{dn}_{i,p,v,a,h,t}$	$\forall t$
$g^{IDM}_{i,p,v,h,t} + \sum_a R^{up}_{i,p,v,a,h,t} \leq u^{IDM}_{i,p,v,h,t} \cdot K_{i,p,v,h,t} \cdot (af_{i,p,v,h} + \Delta af_{i,p,v,h})$	$\forall i,p,$ $v \leq t,t$
$g^{IDM}_{i,p,v,h,t} - \sum_a R^{dn}_{i,p,v,a,h,t} \geq u^{IDM}_{i,p,v,h,t} \cdot m_{i,p,v,h,t}$	$\forall i,p,$ $v \leq t,t$
$\lvert C_{i,h,t} \rvert \leq c^{up}_{i,h,t}$	$\forall i,p,$ $v \leq t,t$
$\sum_{p,v\leq t} R^{up}_{i,p,v,a,h,t} \geq srr^{up}_{i,a,h,t} + C_{i,h,t} \cdot n^{IDM}_{i,h,t}$	$\forall i,a,h,t$
$\sum_{p,v\leq t} R^{dn}_{i,p,v,a,h,t} \geq srr^{dn}_{i,a,h,t}$	$\forall i,a,h,t$