Decomposition of power system expansion planning models

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PGMO, 18 november 2025

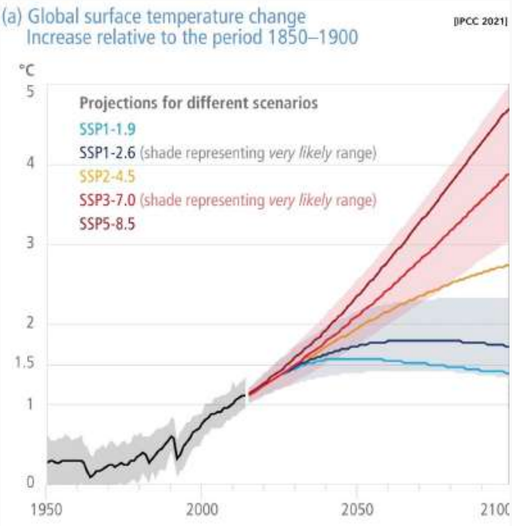
Counterintuitive policies

bad or good idea (for the environment) ?
Shorten the delay for applying new taxes/limitations on polluting vehicles.

NO if alternatives to diesel (public transportation or the market of the electrical vehicles) are not ready

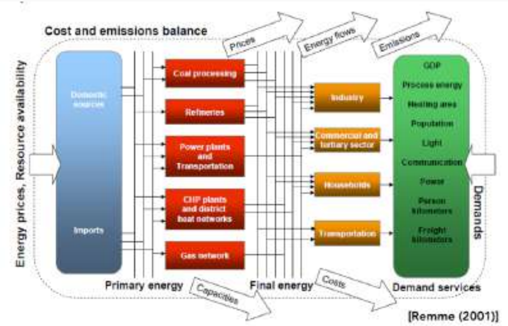
Energy models in prospective analysis

- long-term planning to evaluate policies and guide political action
- interest in the trajectory of the system in response to contrasted scenarios of the future
- integrated assessment models: large geographic, temporal, systemic scales with all the interconnections
- case of power systems: electrification is one key for decarbonization (after sobriety)



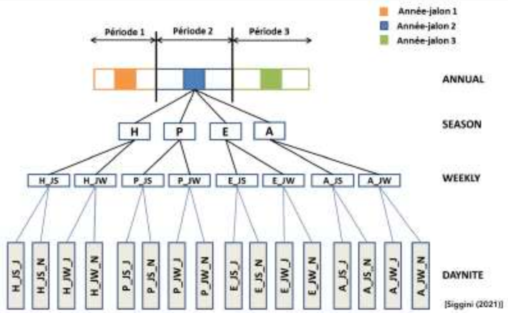
MARKAL/TIMES LP MODELS

- **T**he **I**ntegrated **M**ARKAL-**E**FOM **S**ystem by IEA-ETSAP since 80's
- bottom-up: detailed technical and economic description of the system as a multiflow
- optimization: plan investments and operations to ensure the supply/demand balance at minimal present value cost
- optimistic estimate for the potential of the system when acquiring only the most efficient technologies
- exogeneous data (demand, prices, availability, processes) as deterministic scenarios



CHALLENGES IN MODELLING POWER SYSTEMS

- huge mathematical models
- new usages, intermittent renewable sources: more **uncertainty** in supply/demand forecasts
- interconnections, storage: more flexibility with more **interdependency**



time aggregation: investment / operation scale

trade-off

system scale/model size, granularity/complexity, accuracy/knowledge

Ex: chronological constraints (e.g. ramping, storage) impact investments in flexible technologies but are relaxed in the timeslice representation

SOLVING LARGE-SCALE STRUCTURED LPs

- interior-point methods: not for heterogeneous/nonconvex models & crossover required
- soft-linking [Deane et al. 2012]: need synchronization with UCP
- bidirectional linking [Alimou 2020]: heuristic cuts, what is computed ?
- heuristic decompositions: rolling horizon, nested/hierarchical solution [Pineda&Morales 2018]

decomposition methods

- allow for (synchronized) heterogenous submodels
- iterative methods with long-tail effect but early stop is possible
- convergence, basic solutions and primal/dual certificates (for sensitivity analysis)

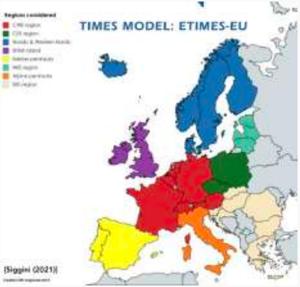
Lagrangian relaxation: relax the coupling constraints in the primal space.
Which coupling ? technological (UCP), geographical (interconnections), temporal (period/timeslices)

LAGRANGIAN RELAXATION & REGIONAL DECOMPOSITION

REGIONAL DECOMPOSITION OF THE EU ELECTRICITY SYSTEM

Gildas Siggini's 2021 PhD thesis: *Approche intégrée pour l'analyse prospective de la décarbonisation profonde du système électrique européen à l'horizon 2050 face à la variabilité climatique*

- variable geographical distribution of intermittent generation
- interconnection of the national grids for stability
- strong physical interdependency but soft model coupling



decomposition of eTimes-EU

- 29 regions, 7*64 time steps = 11M variables, 7M constraints, 42M non-zeros
- save memory and time (e.g. crossover)
- anticipate analysis/debug long before reaching optimality
- desynchronize/modulate the regional models
- non-isolated study of a national mix

LAGRANGIAN RELAXATION OF ETIMES-EU

- dualize the interconnection constraints between pairs of regions (r_1, r_2):

$$\text{import}^{r_1}(r_2, t) = \text{export}^{r_2}(r_1, t)$$

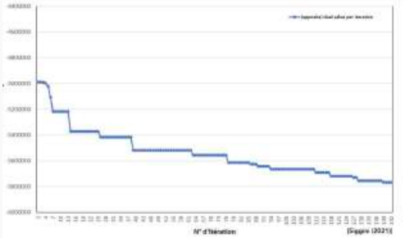
  and the global emission limits:

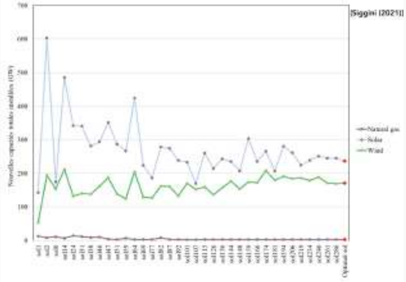
$$\sum_{t \in Period} \sum_{r \in Region} \text{ghg}^{r}(t) \leq GHG_{Period}$$

- optimize the lagrangian dual using a proximal bundle method:
  - oracle: solve the regional submodels independently for given multipliers μ
  - update the bundle/cutting-plane model $\check{\mathscr{L}}$ of the lagrangian function
  - optimize the regularized model around the current stability center: $\max \check{\mathscr{L}}(\mu) - r||\mu - \mu^*||^2$
  - update stability center μ^* if serious improvement
- heuristic: solve the global model (split in Periods) with capacities fixed as in the oracle solution

PRELIMINARY RESULTS

- decomposition=140 iterations x 2 minutes vs. direct solution=1h30
- the regional subproblems are solved 45x faster than the global model, but larger models (e.g. 262 NUTS2 regions) may benefit of decomposition
- the bundle method converges much faster than a subgradient method, but better parametrization/initialization is needed
- the heuristic solutions quickly follow the tendency of the optimal solution, still the trajectory is not stable





Temporal decomposition with variable splitting

TEMPORAL DECOMPOSITION

- time aggregation prevents to accurately describe the short-term dynamics and chronological constraints (ramping, startup costs, storage,...)
- neglecting unit commitment constraints impact the result (mix, emission and cost) [Poncelet 2023]
- soft-linking: check the capacity mix against a 1-year operation power system model [Deane 2012]
- heuristic feedback as feasibility cut: adjust the contribution of the technologies to the peak-reserve constraint [Alimou 2020]

TIMES MODEL

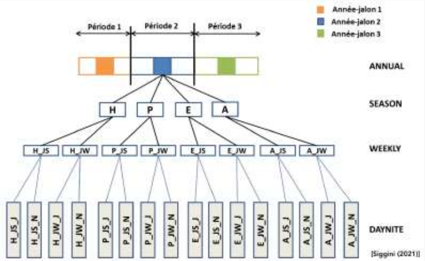
primal model

$$\min_{y,x} \sum_{p \in P} c_p^{inv}(y_p) + \sum_t c_{pt}^{ope}(x_{pt})$$

$$s.t. x_p \in X_p(L_p) \qquad \forall p \in P$$

$$x_p \leq A_p z_p \qquad \forall p \in P.$$

- y_p new investments during period p
- $z_p = \sum_{p' \leq p} y_{p'}$ available capacities for period p
- x_{pt} operation/production at time t in period p
- L_{pt} exogeneous demand at time t in period p



LR: dualize the period-coupling constraints

lagrangian subproblem

$$P(\mu) : \min_{y,x} \sum_p c_p(y_p, x_p) + \mu_p^\top (x_p - \sum_{p' \leq p} A_{p'} y_{p'})$$

$$s.t. : x_p \in X_p(L_p) \qquad \forall p \in P.$$

- separable in periods, for distributed computation
- but each operational component $x^p \in P^p(\mu)$ remains hard and poor as capacity z_p **is unknown**
- duality gap for some nonlinearities

AL: relaxation + penalization

augmented lagrangian subproblem

$$P(\mu,\rho):\min_{y,x}\sum_p c_p(y_p,x_p)+\mu_p^\top(x_p-A_pz_p)+\frac{\rho}{2}\|x_p-A_pz_p\|^2$$

$$s.t.: x_p\in X_p(L_p) \qquad \forall p\in P.$$

- add a l_2-regularization / proximal term
- additional convergence guaranties (+ smoothness and convexity)
- but no separability (remember: $z_p=\sum_{p'\le p} y_{p'}$)

ADMM: VARIABLE SPLIT AND PARTIAL UPDATE

fix investment/capacity (y, z)

$$P(\bar{y}, \bar{z}; \mu, \rho) : \min_{x} \sum_{p} c_p(\bar{y}_p, x_p) + \mu_p^\top (x_p - A_p \bar{z}_p) + \frac{\rho}{2} \|x_p - A_p \bar{z}_p\|^2$$

$$s.t. : x_p \in X_p(L_p) \qquad \forall p \in P.$$

$\downarrow$ $\uparrow$ update $\mu \mathrel{+}= \rho(\bar{x}_p - A_p \bar{z}_p)$

fix operation x

$$P(\bar{x}; \mu, \rho) : \min_{y,z} \sum_{p} c_p(y_p, \bar{x}_p) + \mu_p^\top (\bar{x}_p - A_p z_p) + \frac{\rho}{2} \|\bar{x}_p - A_p z_p\|^2.$$

- separability with easy subproblems
- theoretical convergence for linear coupling constraints
- long-tail effect can be stopped prematurely
- initialize investment with solutions of previous runs

Conclusion and perspective

- energy models for prospective analysis are getting bigger and more integrated
- decomposition methods provide primal/dual certificates for sensitivity analysis and a way to combine heteregenous models
- no benchmark set: models are long to develop, work in progress (Albin Gagnepain's PhD thesis on the nuclear representation in a world model)
- variable-splitting for scheduling and lot sizing [Demassey, Sessa, Takavoli, ISCO 2024]