Modeling the Ability of Thermal Units to Perform Load Changes in Energy Systems

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Agenda

1. Motivation

2. The Electricity System Model PERSEUS-NET-ESS

3. Modeling the Load Changing Ability of Thermal Units
   - I. Minimum power, minimum times stopped and running
   - II. Start-up costs on positive load changes below the minimum power
   - III. Costs on all load changes

4. Data Availability

5. Test Calculations to Analyze the Different Modelling Technics

6. Summary and Conclusions
1 Motivation

Increasing share of electricity generation from volatile renewable sources (wind, solar) in Germany

- The electricity generation in thermal units has to become increasingly flexible
- Increasing relevance of cycling costs
- Growing importance to model the load changing ability of thermal units in energy system models
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6. Summary and Conclusions
Modeling of the transmission grid
- 441 grid nodes (locations of power plants and electricity demand processes)
- 560 power lines as grid node connections

Modeling of power generating capacities
- ~ 270 plants > 100 MW modeled individually at specific nodes
- Smaller plants < 100 MW modeled cumulated and assigned to NUTS3-regions

Specific electricity demand assigned to each grid node
- Forecast based on population and GDP of the NUTS3-region

Source: Eßer-Frey 2012
PERSEUS-NET-ESS: Model specifications

Model type and methodology
- Myopic linear (mixed-integer) programming approach
- Technology oriented bottom-up energy and material flow model combined with nodal pricing

Objective function and constraints
- Objective function: minimisation of decision-relevant expenditures (net present value)
- Variables: plant commissioning, unit dispatch, operation modes, electricity flows on the grid
- Constraints: generation capacity, plant availability, transmission capacity…
- Driving force: electricity demand has to be satisfied

Market understanding
- Perfect markets with complete information

Modelling timeframe and time structure
- Consideration of three days of a type per season (weekday, Saturday and Sunday) for the year 2012

Main results
- Optimal system dispatch
**PERSEUS-NET-ESS: Objective function**

\[
\begin{align*}
\min & \sum_{ec \in EC} \left( \sum_{imp \in IMP} \sum_{prod \in PROD} FL_{imp,prod,ec,t} \cdot C_{fuel,imp,prod,ec,t} \right) \\
& + \sum_{prod \in PROD} \sum_{prod' \in PROD'} FL_{prod,prod',ec,t} \cdot C_{var,prod,prod',ec,t} \\
& + \sum_{proc \in PROC} P_{L,proc,t} \cdot C_{var,proc,t} \\
& + \sum_{seas \in SBAS} C_{loadchange,proc,t,seas-1,seas}
\end{align*}
\]

\[\forall t \in T \subset \{2012\}\]

**Minimization of the system relevant expenditures. These consist of**

- Energy carrier costs (EC),
- Costs of electricity generation processes (PROC)
- Costs related to electricity generation units (UNIT)
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3 1 Minimum power

The process level is either “0” or above the minimum power

\[
\text{CapRes}_{\text{unit},t} \cdot h_{\text{seas}} \cdot \text{Avai}_{\text{unit},t} \cdot \text{GEN01}_{\text{proc},t,\text{seas}} \geq P_{\text{S}_{\text{proc},t,\text{seas}}}
\]

\[
\geq \text{CapRes}_{\text{unit},t} \cdot h_{\text{seas}} \cdot \text{MinP}_{\text{proc}} \cdot \text{GEN01}_{\text{proc},t,\text{seas}}
\]

\( \forall \text{proc} \in \text{PROC}_{\text{unit}}; \forall \text{unit} \in \text{UNIT}_{\text{thrm}}; \forall t \in T; \forall \text{seas} \in \text{SEAS} \)

Equation based on [Díaz 2008]

With:

- \( \text{GEN01}_{\text{proc},t,\text{seas}} \): Binary variable stating if the generation process \( \text{proc} \) is on or off (0/1) in hour \( \text{seas} \) of year \( t \)
- \( P_{\text{S}_{\text{proc},t,\text{seas}}} \): Process level of the generation process \( \text{proc} \) in the hour \( \text{seas} \)
- \( \text{CapRes}_{\text{unit},t} \): Installed capacity of the generation unit \( \text{unit} \) in year \( t \)
- \( h_{\text{seas}} \): Weighting of the considered hour \( \text{seas} \)
- \( \text{Avai}_{\text{unit},t} \): Availability factor of unit \( \text{unit} \)
- \( \text{MinP}_{\text{proc}} \): Minimum power of the generation process \( \text{proc} \) as a share of the installed capacity
Minimum times stopped & running

Minimum time stopped \((MinStopped_{\text{proc}})\)

\[
\sum_{\text{seas} = \text{seas}' - \text{MinStopped}_{\text{proc}}}^{\text{seas}' - 1} (1 - GEN01_{\text{proc},t,\text{seas}}) \geq MinStopped_{\text{proc}} \cdot (\text{GEN01}_{\text{proc},t,\text{seas}' - 1} - \text{GEN01}_{\text{proc},t,\text{seas}' - 1})
\]

Minimum time running \((MinOperate_{\text{proc}})\)

\[
\sum_{\text{seas} = \text{seas}' - \text{MinOperate}_{\text{proc}}}^{\text{seas}' - 1} \text{GEN01}_{\text{proc},t,\text{seas}} \geq MinOperate_{\text{proc}} \cdot (\text{GEN01}_{\text{proc},t,\text{seas}' - 1} - \text{GEN01}_{\text{proc},t,\text{seas}'})
\]

\(\forall \text{proc} \in \text{PROC}_{\text{therm}} \subset \text{PROC}; \quad \forall t \in T; \quad \forall \text{seas}, \text{seas}' \in \text{SEAS}\)

Example: If \(\text{seas}' = 4\) p.m., \(MinOperate_{\text{proc}} = 3\) and \(\text{GEN01}_{\text{proc},t,3\text{p.m.}} = 1\) than

\[
\text{GEN01}_{\text{proc},t,1\text{p.m.}} + \text{GEN01}_{\text{proc},t,2\text{p.m.}} + 1 \geq 3 \cdot (1 - \text{GEN01}_{\text{proc},t,4\text{p.m.}})
\]

\[
\text{GEN01}_{\text{proc},t,4\text{p.m.}} \geq 1 - 1/3 \cdot (\text{GEN01}_{\text{proc},t,1\text{p.m.}} + \text{GEN01}_{\text{proc},t,2\text{p.m.}} + 1)
\]
Costs on positive load changes below the minimum power (start-up costs)

\[
\begin{align*}
\text{LowPS}_{\text{proc}, t, \text{seas}} & \cdot \text{CapRes}_{\text{unit}, t} \cdot \text{MinP}_{\text{proc}} \\
+ \quad \text{HighPS}_{\text{proc}, t, \text{seas}} & \cdot \text{CapRes}_{\text{unit}, t} \cdot (1 - \text{MinP}_{\text{proc}}) \\
\quad \text{PS}_{\text{proc}, t, \text{seas}} &= \text{CapRes}_{\text{unit}, t} \\
(h_{\text{seas}} \cdot \text{Avai}_{\text{unit}, t}) & \\
\forall \text{proc} \in \text{PROC}_{\text{unit}}; \forall \text{unit} \in \text{UNIT}_{\text{therm}}; \forall t \in T; \forall \text{seas} \in \text{SEAS}
\end{align*}
\]

Equations based on [Warland 2008]

\[
\begin{align*}
\text{LowPS}_{\text{proc}, t, \text{seas}} & \leq \text{HighPS}_{\text{proc}, t, \text{seas}} \\
\forall \text{proc} \in \text{PROC}; \forall t \in T; \forall \text{seas} \in \text{SEAS}
\end{align*}
\]

With:

- \(\text{LowPS}_{\text{proc}, t, \text{seas}}\): Positive variable between “0” and “1” to indicate process levels of process \text{proc} below the minimum power.
- \(\text{HighPS}_{\text{proc}, t, \text{seas}}\): Positive variable between “0” and “1” to indicate process levels of process \text{proc} above the minimum power.
- \(\text{StartUpCount}_{\text{proc}, t, \text{seas}}\): Positive variable that accounts for the load changes levels of process \text{proc} below the minimum power.
Costs on all load changes

\[
(LV_{up}^{proc,seas-1,seas,t} - LV_{down}^{proc,seas-1,seas,t}) = N_{0}^{seas-1,seas,t} \cdot \left( \frac{PS_{proc,t,seas}}{h_{seas}} - \frac{PS_{proc,t,seas-1}}{h_{seas-1}} \right) \cdot \frac{1}{\eta_{proc,t}}
\]

\forall t \in T; \forall seas \in SEAS; \forall proc \in PROC

Equation based on [Rosen 2008, Eßer-Frey 2012]

With:

- \(LV_{up}^{proc,seas-1,seas,t}\) Positive variable to account for positive load changes between the hours \(seas - 1\) and \(seas\) in [MW]
- \(LV_{down}^{proc,seas-1,seas,t}\) Positive variable to account for negative load changes between the hours \(seas - 1\) and \(seas\) in [MW]
- \(N_{0}^{seas-1,seas}\) Number of occurrences of the change from one hour \(seas - 1\) to the next one \(seas\) within the considered year \(t\)
- \(\eta_{proc,t}\) Efficiency of the generation process \(proc\) in year \(t\)
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4 Data Availability

Data about a realistic power plant dispatch and specific cycling costs are hard to determine (and confidential)

- Minimum times stopped and running
  - No real technical limitation, rather a “fictive” limitation for energy system modelling to prevent a unit dispatch with high cycling costs [Schröder et al. 2013; Hundt et al. 2009].
  - Values for minimum times stopped and running can be found in literature. However, these differ [Schröder et al. 2013].

- Start-up costs
  - Very few literature sources with specific values could be found [Kumar et al. 2012; Lew et al. 2013; Maiborn 2008; DENA 2005].
  - Values differ and do not consider specific generation units’ characteristics. Subsequently values for start-up costs for PERSEUS-NET-ESS are estimated by the following equation:

\[
\text{StartUpCosts}_{proc,t} = \text{MinP}_{proc} \cdot \text{CapRes}_{unit,t} \cdot \text{MinStopped}_{proc} \cdot \left( \frac{C_{\text{var}}_{proc,t}}{\eta_{proc,t}} + \frac{C_{\text{fuel}}_{proc,t}}{\eta_{proc,t}} \right)
\]

\(\forall \ proc \in \text{PROC}_{\text{therm}}; \ \forall \ unit \in \text{UNIT}_{proc}; \ \forall \ t \in T\)

- Costs on all load changes
  - Only one literature sources with specific values could be found.
  - 1.96 $/\Delta MW for coal units; 0.64 $/\Delta MW for gas combined cycle units [Kumar et al. 2012; Lew et al. 2013]
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Average derivation to the dispatch without consideration of the load changing behavior [GW]

Min. power and times 0.05
Cost on all load changes 0.02
Start-up costs 0.1

Min. power and times 0.46
Cost on all load changes 0.71
Start-up costs 0.82

Min. power and times 0.36
Cost on all load changes 0.24
Start-up costs 0.66

Start-up costs have the highest effect on the dispatch of thermal units in PERSEUS-NET-ESS
### 5 Computation Time of Test Calculations

<table>
<thead>
<tr>
<th></th>
<th>Minimum power, time stopped &amp; running</th>
<th>Start-up costs</th>
<th>Costs on all load changes</th>
<th>No consideration of load changing behavior</th>
<th>Start-up costs and costs on all load changes</th>
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</thead>
<tbody>
<tr>
<td>Equations</td>
<td>1.82 Mio</td>
<td>1.79 Mio</td>
<td>1.72 Mio</td>
<td>1.68 Mio</td>
<td>1.83 Mio</td>
</tr>
<tr>
<td>Variables</td>
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<td>1.48 Mio</td>
<td>1.45 Mio</td>
<td>1.36 Mio</td>
<td>1.59 Mio</td>
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<tr>
<td>Non-zero Elements</td>
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<td>7.33 Mio</td>
<td>7.18 Mio</td>
<td>6.93 Mio</td>
<td>7.66 Mio</td>
</tr>
<tr>
<td>Binary variables</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total computation time*</td>
<td>12 min 57</td>
<td>5 min 57 sec</td>
<td>5 min 41 sec</td>
<td>5 min 35 sec</td>
<td>6 min 14 sec</td>
</tr>
</tbody>
</table>

*with Cplex 12.4 on 12 threads on a computer with Windows Server 2008 R2 Enterprise, Intel(R) Xeon(R) CPU E5-1650@ 3.20 GHz 3.20 GHz; 96 GB RAM; 64 Bit

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As of the mixed-integer calculation the modelling approach with minimum power and minimum times stopped & running has a significantly higher computation time than the linear approaches.

A combination of start-up costs and costs on all load changes has a comparably “short” computation time and is therefore usable for PERSEUS-NET-ESS calculations.
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Summary and Conclusion

Minimum power in combination with minimum times running and stopped
- Widely used in energy systems modelling; Data available
- Disadvantage of needing binary variables
- No “real” technical restriction (?)

Costs on positive load changes below the minimum power (start-up costs)
- Very few literature sources with specific data; Data that is found differs
- Assignment of specific start-up costs to generation units in PERSEUS-NET-ESS through the developed approach
- Comparably high effect on the dispatch of thermal generation units in the PERSEUS-NET-ESS model

Costs on all load changes
- Easy to apply
- Very few literature sources with specific data
- Applicable in energy system models with endogenous linear commissioning of generation units
- No consideration of the minimum power

For the energy system model PERSEUS-NET-ESS a combination of costs on all load changes and start-up costs seems to be advantageous
We are grateful to the German Federal Ministry for Economic Affairs and Energy for funding this work in the framework of the EVREST project.

Supported by:

on the basis of a decision by the German Bundestag

THANK YOU FOR YOUR ATTENTION!
BACK-UP
Consideration of Costs in the Objective Function

\[
(l V_{\text{up}, \text{proc}, \text{seas} - 1, \text{seas}, t} + l V_{\text{down}, \text{proc}, \text{seas} - 1, \text{seas}, t}) \cdot \text{C}_\text{LoadVar}_{\text{proc}, t} + \\
\text{StartUpCount}_{\text{proc}, t, \text{seas}} \cdot \text{C}_\text{StartUp}_{\text{proc}, t} = \\
\text{C}_{\text{loadchange}}_{\text{proc}, t, \text{seas} - 1, \text{seas}}
\]

\( \forall t \in T; \forall \text{seas} \in \text{SEAS}; \forall \text{proc} \in \text{PROC} \)

- With:
  - \( \text{C}_\text{LoadVar}_{\text{proc}, t} \): Costs on load changes of process \( \text{proc} \) in year \( t \) [$/\text{MW}]
  - \( \text{C}_\text{StartUp}_{\text{proc}, t} \): Costs for starting-up the process \( \text{proc} \) in year \( t \) [$/\text{start-up to the minimum power}]
  - \( \text{C}_{\text{loadchange}}_{\text{proc}, t, \text{seas} - 1, \text{seas}} \): Costs for the load changes of process \( \text{proc} \) in year \( t \) between the hours \( \text{seas} - 1 \) and \( \text{seas} \) to be considered in the objective function [$]
PERSEUS-NET-TS: Selected Constraints

Energy balance equation

\[
\sum_{imp \in IMP} FL_{imp, prod, ec, t} + \sum_{prod \in PROD_{prod, ec}} FL_{prod, prod, ec, t} + \sum_{proc \in GENPROC_{prod, ec}} PL_{proc, t} \cdot \lambda_{proc, ec} = \sum_{exp \in EXP} FL_{prod, exp, ec, t} + \sum_{prod' \in PROD_{prod, ec}} FL_{prod', prod, ec, t} + \sum_{proc \in DEMPROC_{prod, ec}} PL_{proc, t} \cdot \frac{\lambda_{proc, ec}}{\eta_{proc, ec}}
\]

\forall t \in T; \ \forall prod \in PROD; \ \forall ec \in EC_{non-seas}

Process utilisation equation

\[
Cap_{unit, t} \cdot Avai_{unit, t} \cdot h_{seas} \geq \sum_{proc \in PROC_{unit}} PL_{proc, seas, t}
\]

\forall t \in T; \ \forall unit \in UNIT; \ \forall seas \in SEAS

Demand equation

\[
\sum_{prod \in Prod} \sum_{exp \in Exp} FL_{prod, exp, t, seas} \geq D_{t, seas}
\]

\forall prod \in Prod; \ \forall seas \in S; \ \forall t \in T