Modeling the Ability of Thermal Units to Perform Load Changes in Energy Systems
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
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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The German Electricity System Model PERSEUS-NET-ESS

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
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

\[
\begin{align*}
    \text{min} & \left[ \sum_{ec \in EC} \left( \sum_{imp \in IMP} \sum_{prod \in PROD} FL_{imp, prod, ec, t} \cdot C_{fuel, imp, prod, ec, t} \right) + \sum_{prod \in PROD} \sum_{prod' \in PROD'} FL_{prod, prod', ec, t} \cdot C_{var, prod, prod', ec, t} \right] \\
    & + \sum_{proc \in PROC} \left( PL_{proc, t} \cdot C_{var, proc, t} \right) + \sum_{seas \in SEAS} C_{loadchange, proc, t, seas - 1, seas} \\
    \forall t \in T \subseteq \{2012\}
\end{align*}
\]

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

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

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

With:

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

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

Minimum time running \((\text{MinOperate}_\text{proc})\)

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

\[\forall \text{proc} \in \text{PROC}_{\text{therm}} \subset \text{PROC}; \forall t \in \text{T}; \forall \text{seas}, \text{seas}' \in \text{SEAS}\]

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

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

\[
\begin{align*}
\text{LowPS}_{\text{proc},t,\text{seas}} \cdot \text{CapRes}_{\text{unit},t} \cdot \text{MinP}_{\text{proc}} \\
+ \\
\text{HighPS}_{\text{proc},t,\text{seas}} \cdot \text{CapRes}_{\text{unit},t} \cdot (1 - \text{MinP}_{\text{proc}})
\end{align*}
\]
\[= \frac{\text{PS}_{\text{proc},t,\text{seas}}}{(h_{\text{seas}} \cdot \text{Avai}_{\text{unit},t})}\]

\[\forall \text{proc} \in \text{PROC}_{\text{unit}}; \forall \text{unit} \in \text{UNIT}_{\text{therm}}; \forall t \in T; \forall \text{seas} \in \text{SEAS}\]

Equations based on [Warland 2008]

<table>
<thead>
<tr>
<th>\text{CapRes}_{\text{unit},t}</th>
<th>\text{LowPS}_{\text{proc,seas}} = 1</th>
<th>\text{HighPS}_{\text{proc,seas}} = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{MinP}_{\text{proc}}</td>
<td>\text{LowPS}_{\text{proc,seas}} = 1</td>
<td>\text{HighPS}_{\text{proc,seas}} = 0</td>
</tr>
<tr>
<td>\text{LowPS}_{\text{proc,seas}} = 0</td>
<td>\text{HighPS}_{\text{proc,seas}} = 0</td>
<td></td>
</tr>
</tbody>
</table>

\[\text{LowPS}_{\text{proc},t,\text{seas}} \geq \text{HighPS}_{\text{proc},t,\text{seas}}\]
\[\forall \text{proc} \in \text{PROC}; \forall t \in T; \forall \text{seas} \in \text{SEAS}\]

\[\text{LowPS}_{\text{proc},t,\text{seas}} - \text{LowPS}_{\text{proc},t,\text{seas}} - 1 \]
\[\leq \text{StartUpCount}_{\text{proc},t,\text{seas}}\]
\[\forall \text{proc} \in \text{PROC}; \forall t \in T; \forall \text{seas} \in \text{SEAS}\]

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

\[
(LV_{\text{up}, \text{proc}, \text{seas} - 1, \text{seas}, t} - LV_{\text{down}, \text{proc}, \text{seas} - 1, \text{seas}, t}) = \frac{N_{\text{seas} - 1, \text{seas}, t} \cdot \left(\frac{PS_{\text{proc}, t, \text{seas}}}{h_{\text{seas}}} - \frac{PS_{\text{proc}, t, \text{seas} - 1}}{h_{\text{seas} - 1}}\right)}{\eta_{\text{proc}, t}} \\
\forall t \in T; \forall \text{seas} \in \text{SEAS}; \forall \text{proc} \in \text{PROC}
\]

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

With:

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

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

\[\forall \text{ proc } \in \text{PROC}_{\text{therm}}; \forall \text{ unit } \in \text{UNIT}_{\text{proc}}; \forall \text{ t } \in T\]

- Costs on all load changes
  - Only one literature sources with specific values could be found.
  - 1.96 $/\Delta \text{MW}$ for coal units; 0.64 $/\Delta \text{MW}$ for gas combined cycle units [Kumar et al. 2012; Lew et al. 2013]
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6. Summary and Conclusions
Start-up costs have the highest effect on the dispatch of thermal units in PERSEUS-NET-ESS.
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.

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

\[
(lV_{up}^{proc,seas-1,seas,t} + lV_{down}^{proc,seas-1,seas,t}) \cdot C_{LoadVar}^{proc,t} + StartUp\text{Count}_{proc,t,seas} \cdot C_{StartUp}^{proc,t} = C_{loadchange}^{proc,t,seas-1,seas}
\]

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

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

Energy balance equation

\[
\sum_{imp \in \text{IMP}} FL_{\text{imp,prod,ec,t}} + \sum_{\text{prod} \in \text{PROD}_{\text{prod,ec}}} FL_{\text{prod}', \text{prod,ec,t}} + \sum_{\text{proc} \in \text{GENPROC}_{\text{prod,ec}}} PL_{\text{proc,t}} \cdot \lambda_{\text{proc,ec}} 
\]

\[
= \sum_{\text{exp} \in \text{EXP}} FL_{\text{prod,exp,ec,t}} + \sum_{\text{prod} \in \text{PROD'}_{\text{prod,ec}}} FL_{\text{prod}', \text{prod,ec,t}} + \sum_{\text{proc} \in \text{DEMPROC}_{\text{prod,ec}}} PL_{\text{proc,t}} \cdot \frac{\lambda_{\text{proc,ec}}}{\eta_{\text{proc,ec}}}
\]

\( \forall t \in T; \ \forall \text{prod} \in \text{PROD}; \ \forall \text{ec} \in \text{EC}_{\text{non-seas}} \)

Process utilisation equation

\[
Cap_{\text{unit,t}} \cdot \text{Avai}_{\text{unit,t}} \cdot h_{\text{seas}} \geq \sum_{\text{proc} \in \text{PROC}_{\text{unit}}} PL_{\text{proc,seas,t}}
\]

\( \forall t \in T; \ \forall \text{unit} \in \text{UNIT}; \ \forall \text{seas} \in \text{SEAS} \)

Demand equation

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

\( \forall \text{prod} \in \text{Prod}; \ \forall \text{seas} \in \text{S}; \ \forall t \in T \)

Decision variables

- Process level
  \( PL_{p,t,seas} \in \mathbb{R}^+ \)

- Energy flow
  \( FL_{\text{prod}', \text{prod,t,seas}} \in \mathbb{R}^+ \)

- Capacity decision
  \( Cap_{\text{unit,t}, \text{NewCap}_{\text{unit,t}}} \in \mathbb{R}^+ \)
Unit Dispatch

Spring

Monday

1
2
...
23
24

... Sunday

Summer

2012

Fall

Winter

Monday

1
2
...
23
24

... Sunday