Karlsruhe Institute of Technology

Institute for Industrial Production

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

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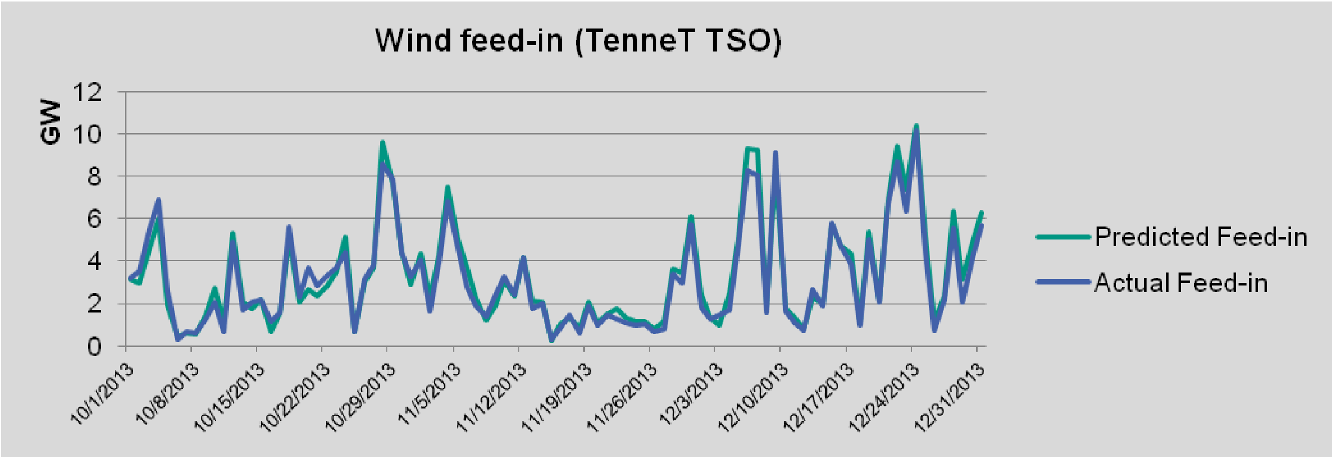
Agenda

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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2 The German Electricity System Model PERSEUS-NET-ESS

Modeling of the transmission grid

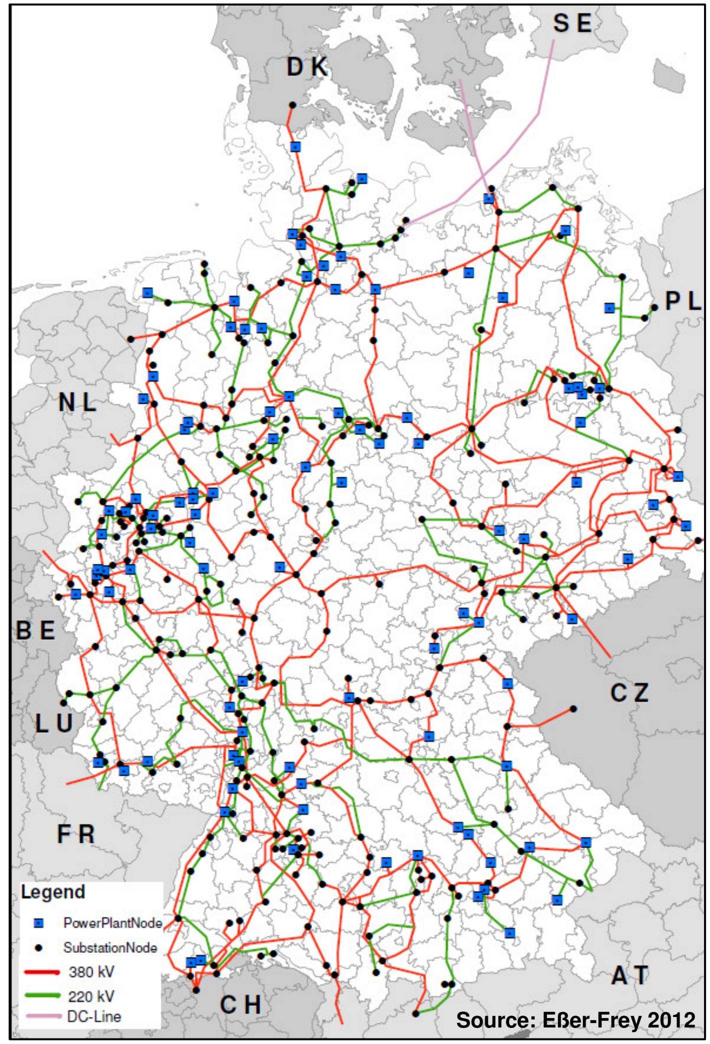
- 441 grid nodes
(locations of power plants and electricity demand processes)
- 560 power lines as grid node connections

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



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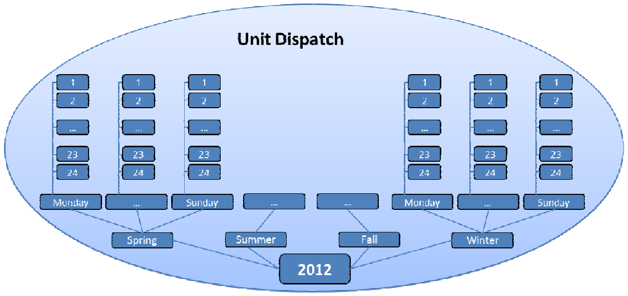
2 PERSEUS-NET-ESS: Model specifications

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

2 PERSEUS-NET-ESS: Objective function

$$\min \left[\sum_{ec \in EC} \left(\begin{array}{l} \sum_{imp \in IMP} \sum_{prod \in PROD} FL_{imp,prod,ec,t} \cdot Cfuel_{imp,prod,ec,t} \\ + \sum_{prod \in PROD} \sum_{prod' \in PROD'} FL_{prod,prod',ec,t} \cdot Cvar_{prod,prod',ec,t} \end{array} \right) + \sum_{proc \in PROC} \left(\begin{array}{l} PL_{proc,t} \cdot Cvar_{proc,t} \\ + \sum_{seas \in SEAS} Cloadchange_{proc,t,seas-1,seas} \end{array} \right) \right]$$

$$\forall t \in T \subset \{2012\}$$

Fuel costs

Transport, system usage charge

Variable costs

Load changing costs

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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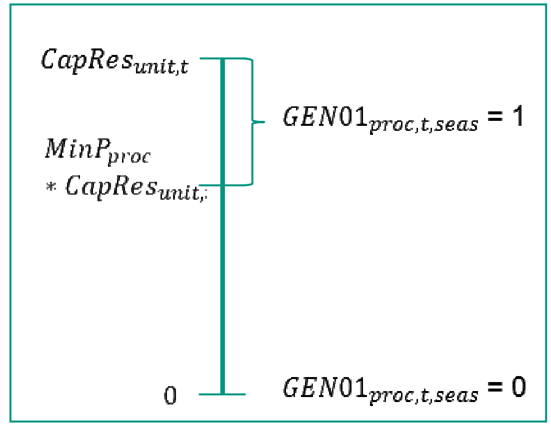
3 | Minimum power

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

$$CapRes_{unit,t} \cdot h_{seas} \cdot Avai_{unit,t} \cdot GEN01_{proc,t,seas}$$
$$\geq$$
$$PS_{proc,t,seas}$$
$$\geq$$
$$CapRes_{unit,t} \cdot h_{seas} \cdot MinP_{proc} \cdot GEN01_{proc,t,seas}$$
$$\forall proc \in PROC_{unit};\ \forall unit \in UNIT_{therm};\ \forall t \in T;\ \forall seas \in SEAS$$

Equation based on [Díaz 2008]



With:

$GEN01_{proc,t,seas}$	Binary variable stating if the generation process $proc$ is on or off (0/1) in hour $seas$ of year t
$PS_{proc,t,seas}$	Process level of the generation process $proc$ in the hour $seas$
$CapRes_{unit,t}$	Installed capacity of the generation unit $unit$ in year t
h_{seas}	Weighting of the considered hour $seas$
$Avai_{unit,t}$	Availability factor of unit $unit$
$MinP_{proc}$	Minimum power of the generation process $proc$ as a share of the installed capacity

3 | Minimum times stopped & running

Minimum time stopped ($MinStopped_{proc}$)

$$\sum_{seas\,=\,seas'-MinStopp_{proc}}^{seas'-1} \left(1 - GEN01_{proc,t,seas}\right) \geq MinStopped_{proc} \cdot \left(GEN01_{proc,t,seas'} - GEN01_{proc,t,seas'-1}\right)$$

Equations based on [Díaz 2008]

Minimum time running ($MinOperate_{proc}$)

$$\sum_{seas\,=\,seas'-MinOperate_{proc}}^{seas'-1} GEN01_{proc,t,seas} \geq MinOperate_{proc} \cdot \left(GEN01_{proc,t,seas'-1} - GEN01_{proc,t,seas'}\right)$$

$$\forall proc \in PROC_{therm} \subset PROC;\ \forall t \in T;\ \forall seas, seas' \in SEAS$$

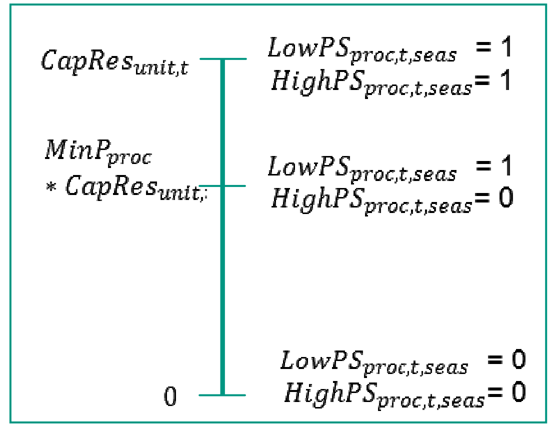
Example: If $seas'$= 4 p.m. ,$MinOperate_{proc}$ = 3 and $GEN01_{proc,t,3p.m.}$ = 1 than
$GEN01_{proc,t,1p.m.}$+ $GEN01_{proc,t,2p.m.}$+1 ≥ 3 · (1 − $GEN01_{proc,t,4p.m.}$)
$GEN01_{proc,t,4p.m.} \geq 1 - 1/3 \cdot (GEN01_{proc,t,1p.m.} + GEN01_{proc,t,2p.m.} + 1)$

3 II Costs on positive load changes below the minimum power (start-up costs)

$$LowPS_{proc,t,seas} \cdot CapRes_{unit,t} \cdot MinP_{proc} + HighPS_{proc,t,seas} \cdot CapRes_{unit,t} \cdot (1 - MinP_{proc}) = \frac{PS_{proc,t,seas}}{(h_{seas} \cdot Avai_{unit,t})}$$

$$\forall proc \in PROC_{unit};\ \forall unit \in UNIT_{therm};\ \forall t \in T;\ \forall seas \in SEAS$$

Equations based on [Warland 2008]



$$LowPS_{proc,t,seas} \geq HighPS_{proc,t,seas}$$

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

$$LowPS_{proc,t,seas} - LowPS_{proc,t,seas-1} \leq StartUpCount_{proc,t,seas}$$

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

With:

$LowPS_{proc,t,seas}$	Positive variable between “0” and “1” to indicate process levels of process $proc$ below the minimum power
$HighPS_{proc,t,seas}$	Positive variable between “0” and “1” to indicate process levels of process $proc$ above the minimum power
$StartUpCount_{proc,t,seas}$	Positive variable that accounts for the load changes levels of process $proc$ below the minimum power

3 III Costs on all load changes

$$(LVup_{proc,seas-1,seas,t} - LVdown_{proc,seas-1,seas,t}) = No_{seas-1,seas,t} \cdot \left(\frac{PS_{proc,t,seas}}{h_{seas}} - \frac{PS_{proc,t,seas-1}}{h_{seas-1}}\right) \cdot \frac{1}{\eta_{proc,t}}$$

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

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

With:

$LVup_{proc,seas-1,seas,t}$	Positive variable to account for positive load changes between the hours $seas-1$ and $seas$ in [MW]
$LVdown_{proc,seas-1,seas,t}$	Positive variable to account for negative load changes between the hours $seas-1$ and $seas$ in [MW]
$No_{seas-1,seas}$	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

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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:

$$StartUpCosts_{proc,t} = MinP_{proc} \cdot CapRes_{unit,t} \cdot MinStopped_{proc} \cdot \left(Cvar_{proc,t} + \frac{Cfuel_{proc,t}}{\eta_{proc,t}} \right)$$

$$\forall\, proc \in PROC_{therm};\ \forall\, unit \in UNIT_{proc};\ \forall\, t \in T$$

- Costs on all load changes
  - Only one literature sources with specific values could be found.
  - 1.96 $/ΔMW for coal units; 0.64 $/ΔMW for gas combined cycle units [Kumar et al. 2012; Lew et al. 2013]

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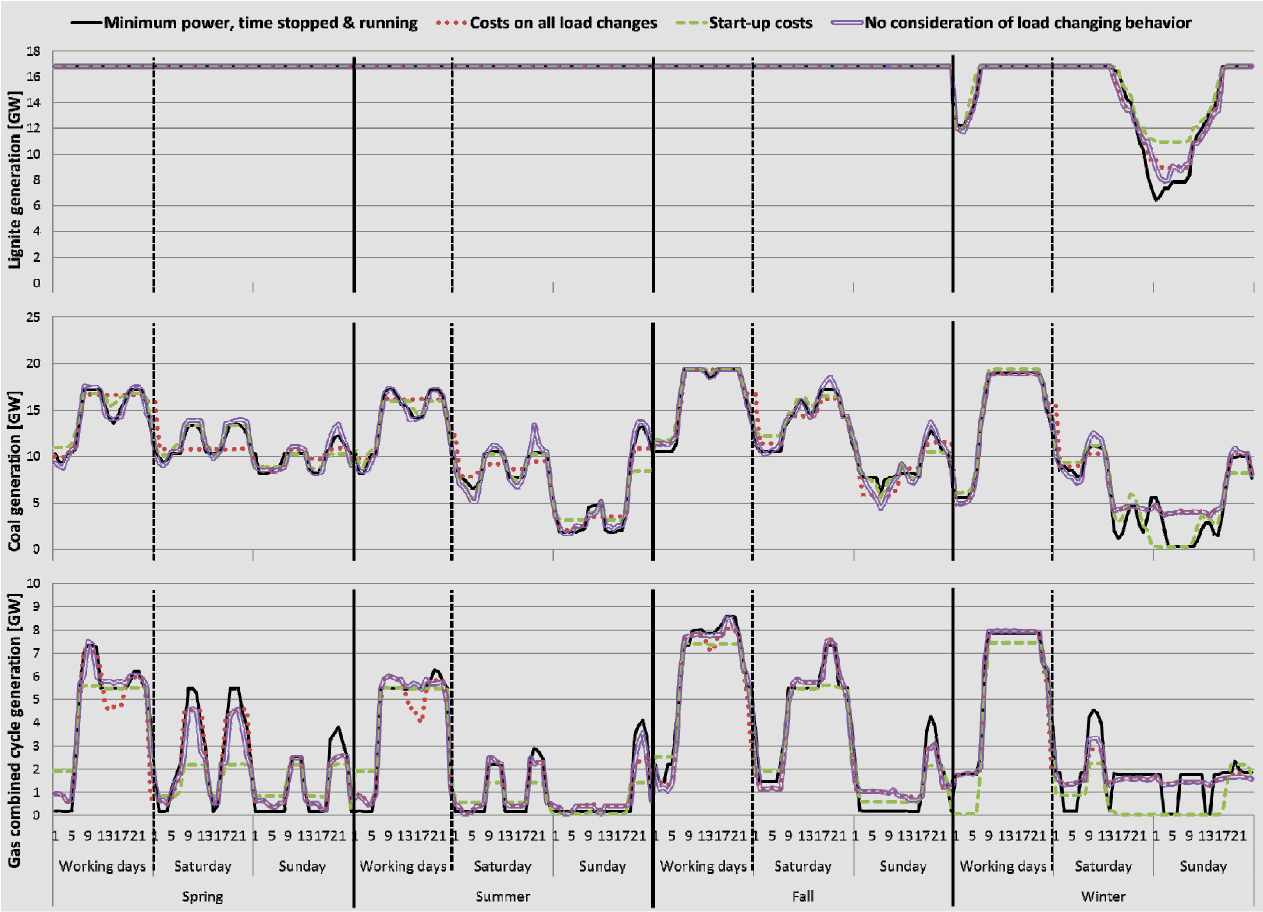
5 Thermal Unit Dispatch



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

	Minimum power, time stopped & running	Start-up costs	Costs on all load changes	No consideration of load changing behavior	Start-up costs and costs on all load changes
Equations	1.82 Mio	1.79 Mio	1.72 Mio	1.68 Mio	1.83 Mio
Variables	1.44 Mio	1.48 Mio	1.45 Mio	1.36 Mio	1.59 Mio
Non-zero Elements	7.45 Mio	7.33 Mio	7.18 Mio	6.93 Mio	7.66 Mio
Binary variables	35,090	-	-	-	-
Total computation time*	12 min 57	5 min 57 sec	5 min 41 sec	5 min 35 sec	6 min 14 sec

*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

- 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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5 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

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SEVENTH FRAMEWORK
PROGRAMME

THANK YOU FOR YOUR ATTENTION!

BACK-UP

3 | II & III

Consideration of Costs in the Objective Function

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$$(LVup_{proc,seas-1,seas,t} + LVdown_{proc,seas-1,seas,t}) \cdot CLoadVar_{proc,t}$$
$$+$$
$$StartUpCount_{proc,t,seas} \cdot CStartUp_{proc,t}$$
$$=$$
$$Cloadchange_{proc,t,seas-1,seas}$$

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

- With:

$CLoadVar_{proc,t}$	Costs on load changes of process $proc$ in year t [$/MW]
$CStartUp_{proc,t}$	Costs for starting-up the process $proc$ in year t [$/start-up to the minimum power]
$Cloadchange_{proc,t,seas-1,seas}$	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 [$]

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PERSEUS-NET-TS: Selected Constraints

Energy balance equation

$$\sum_{imp \in IMP} FL_{imp,prod,ec,t} + \sum_{prod' \in PROD_{prod,ec}} FL_{prod',prod,ec,t} + \sum_{proc \in GENPROC_{prod,ec}} PL_{proc,t} \cdot \lambda_{proc,ec}$$

$$= \sum_{exp \in EXP} FL_{prod,exp,ec,t} + \sum_{prod' \in PROD'_{prod,ec}} FL_{prod,prod',ec,t} + \sum_{proc \in DEMPROC_{prod,ec}} PL_{proc,t} \cdot \frac{\lambda_{proc,ec}}{\eta_{proc,ec}}$$

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

Process utilisation equation

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

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

Demand equation

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

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

Decision variables

Process level

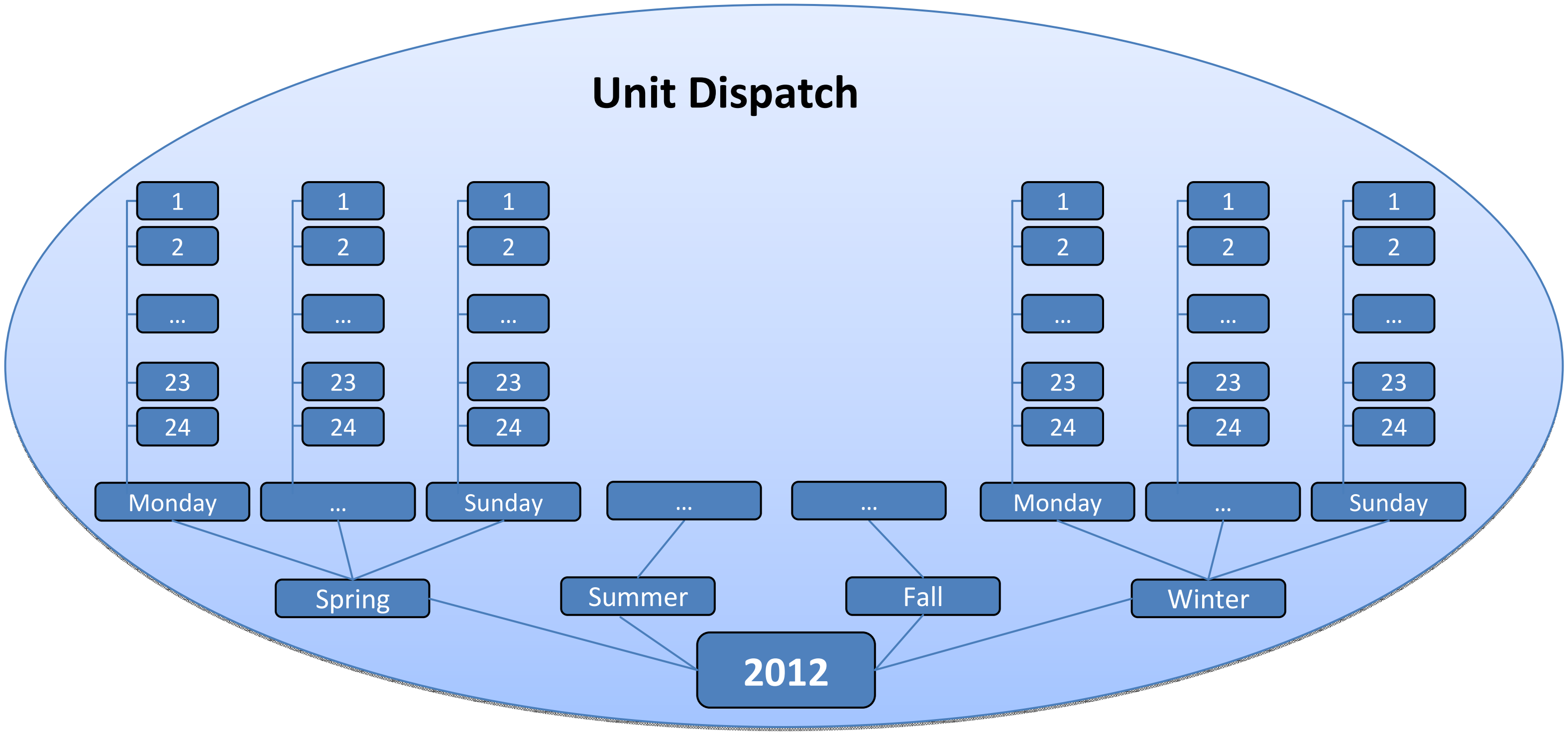
$$PL_{p,t,seas} \in \text{¡}^{+}$$

Energy flow

$$FL_{prod',prod,t,seas} \in \text{¡}^{+}$$

Capacity decision

$$Cap_{unit,t}, NewCap_{unit,t} \in \text{¢}^{+}$$


Unit Dispatch
1
2
...
23
24
Monday
...
Sunday
Monday
...
Sunday
Spring
Summer
Fall
Winter
2012