Integrated power system planning
(Generation and Transmission)

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Table of contents

• Introduction
• Methodology
• Result examples
• Exercise
Table of contents

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- Methodology
- Result examples
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Power Sector Planning is a complex activity with multiple dimensions

- The **objective** of power planning studies is to determine a sequence of capacity reinforcement in generation and transmission to meet the future electricity demand.
- It is sought to minimize the investment, fuel, operation and maintenance costs, as well as the expected cost of the expected unserved energy.
- These requirements are to be achieved while meeting reliability, social, financial, political, geographical and environmental constraints.
- Requires adequate representation, of the power system operation.
Integrated Generation and Transmission Planning allows a more efficient system expansion

- The poultry problem: who is first, the egg or the chicken?
  - If you decide generation ignoring transmission costs/constrains, all the plants will be located in the zone where the primary resource is available
    - Ignoring that moving primary resources (fuels) may be cheaper
    - And that generation + transmission costs (e.g. hydro) can be non convenient (although without transmission costs it is)
  - Transmission planning will connect all the generation located far away from the demand, but it may be not optimal
    - Probably results will include much more transmission than necessary, which, further to increased costs, impact negatively on security of supply,
  - If G and T are jointly planned, you avoid the above drawbacks
The deep transformation of the power sector worldwide poses severe challenges to planners

Before planners had
- Low Penetration of RES
- Conventional CO$_2$ emission sources
- A few large generation projects as candidates
- Projects were (somehow) characterized by predictable generation

They always suffer
- Uncertainty on key variables:
  - Demand
  - Fuel Prices
  - Variable Costs
  - Private decisions
- Reliability Impact of generation loss
- Lack of long-term projects

Today planners face
- How to model low-carbon objectives
  - Explicitly
  - Implicitly
- Planning achieves a new and increased level of complexity
- Storage + RES may change the patterns of grid use
- High uncertainty over the commercial success of some carbon-free technologies:
  - Solar cost reductions
  - Storage tech. i.e. CAES, Lithium Ion
  - CCS…
- Intermittent generation effects on:
  - Dispatch
  - Reliability
- Consideration of Efficiency Measures
Need of granular approach arises from the impossibility to address all the variables at the same time
Table of contents

- Introduction
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The planning process involves three main steps: input data and scenario preparation, modelling and results analysis.

1. **Inputs and scenarios**
   - Regulatory Analysis
   - Input data update
   - National and international situation

2. **Modelling**
   - Data reading and processing
     - Warning messages if inputs inconsistent
   - Model build
     - Optimization model formulation
     - Compatible with multiple solvers
   - Call to solver
   - Results writing
     - Results as text files or in database

3. **Result analysis**
   - Capacity additions
     - Investment decisions
   - Dual variables
     - Electricity prices
   - System dispatch
     - Water values
   - Revenues and costs
     - Power generation
     - Revenues by plant
     - Operating costs

Capacity additions:• Investment decisions
- Electricity prices
- Water values
- Power generation
- Revenues by plant
- Operating costs
Scenario definition is challenging due to the large amount of information needed and the long temporal horizons.

### Macroeconomics: and Policy
- GDP scenarios
- Demand forecasts
- Capacity payments
- Investors IRR
- Climate change policy
- Renew. and EE policy

### Technology
- Market based system expansion
- Policy based expansion (e.g. RES)
- New technologies (CCS, Li Ion, etc)
- Heat distribution

### International
- Fuel prices
- CO\(_2\) price (depend. on climate change policy)
- Cross border trading

### Resources availability:
- Hydrology
- RES
- Fuels

### Constrains:
- Use of water
- Local resources
- Promotion policies
- Energy efficiency

- Credible and consistent combination of variables
- Medium and extreme scenarios
- Subjective/objective probabilities
- Long term horizon (e.g. 10 years detailed, + 20 years simplified)
Both forecasts and expert defined scenarios are required in the definition of scenarios

Some key elements can be forecasted under uncertainty and represented using probability distributions:
- Inflows forecasts
- Load forecast
- Fuel forecasts…

Other important structural elements require expert input for scenario definition as probabilities cannot be assessed:
- Government policies
- Technological development…
The planning process involves three main steps: input data and scenario preparation, modelling and results analysis.

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**3. Result analysis**
- Capacity additions
  - Investment decisions
- Dual variables
  - Electricity prices
- System dispatch
  - Water values
- Revenues and costs
  - Power generation
  - Revenues by plant
  - Operating costs
Linear programming can be used to develop and solve a large number of problems.

\[
\begin{align*}
\text{max} & \quad 2X_1 + X_2 \\
\text{s.t.} & \quad X_1 + 4X_2 \leq 16 \quad \text{(A)} \\
& \quad X_1 + X_2 \leq 6 \quad \text{(B)} \\
& \quad 3X_1 + X_2 \leq 12 \quad \text{(C)} \\
& \quad X_1 \geq 0, \quad X_2 \geq 0
\end{align*}
\]
The objective is the minimization of the net present value of:

- New G&T investments
- Total O&M costs
- Total fuel costs
- Environmental costs
- Cost of unserved energy

The constraints represent:

- Technical limits of G&T facilities
- Meeting the forecasted load
- Energy and mass conservation law
- Second Kirchhoff’s law
- Security and quality standards
- Fuel availability
- Availability of resources (sun, wind, water…)
- Emission limits
- Operation of multi-purpose reservoirs
- Eventual financial and policy constraints

In power system planning, the objective function reflects system costs and the constraints model technical aspects and policies.
Planning models enforce the balance between supply and demand on each node of the system.

Sum of generation of unit “u” of node “n”, year “k”, season “s”, demand block “b” plus imports minus exports is equal to the forecasted demand in node “n”.

\[
\sum_{u=1}^{NG_u} G_{unk}s + \sum_{m=1}^{\Gamma_n} (F_{mnks} - 0.5L_{mnks}) - \sum_{m=1}^{\Gamma_n} (F_{nmks} - 0.5L_{nmks}) + ens_{nks} = D_{nks}
\]

where:
- \(ens_{nks}\): energy not supplied in node “n”
- \(\Gamma_n\): set of nodes connected to node “n”
- \(F_{mnks}\): power flow in line from “m” to “n”
- \(L_{mnks}\): losses in line from “m” to “n”
Transmission can be both represented with the transportation model as well as with the second Kirchhoff law including losses

- Power flows can be represented with a transportation model considering the line’s capacity only:
  \[ F_{mnks} \leq CL_{mnk} \]

- As well as with the second Kirchhoff’s law assuming the DC approach:
  \[ F_{mnks} = \left( \frac{\Theta_{nks} - \Theta_{nks}}{X_{mm}} \right) (p.u.) \]

- Transmission losses are approximated by a stepwise linear function:
  \[
  F_{mnks} = \sum_{i=1}^{NF} FP_{mnks i} \\
  L_{mnks} = \sum_{i=1}^{NF} FP_{mnks i} \cdot KP_i
  \]
Models endogenously perform a cost-benefit calculation to select among candidate projects

- Planning models internally compute for each facility their costs as well as the system cost savings if the facility is available:
  
  - Capacity payment $CP_{uk}$
  - Yearly investments $YV_{uk}$
  - System cost savings $SC_{uk}$
  - Residual value $RV_{uN}$

- The equivalent investment cost for unit “u” ($EI_u$) is calculated internally as the net present value:
  
  $$EI_u = \sum_i \frac{YI_{uk} - CP_{uk} - RV_{uk}}{(1 + DR)^i}$$

- ORDENA® compares the net present value of the system cost savings with the equivalent investment cost, if positive (or equal) the candidate investment project is selected
Limitations of Modelling Results

What models can provide to investors-operators
- Answers to “what if” questions
- Scenario based prices and revenues forecasts
- Risk assessment
- State of the art support to decision making under uncertainty

What models cannot provide
- A crystal ball approach to future forecast
- The accuracy of technical models due to the use of linear constraints only
Table of contents

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The planning process involves three main steps: input data and scenario preparation, modelling and results analysis.
Planning tools can be used to produce scenarios of capacity additions and system dispatch.
Models can perform hourly dispatch to evaluate renewable power integration

Demand coverage in the last week of July 2040

MW

ST-Nuclear  CHP  ST-Coal  CCGT  OCGT  ST-FO  Other RES  Hydro  Wind  Solar
Models can also be used to assess the bankability of power generation projects...

NPV of Pumped Storage Plants (unlevered)
EUR Mn (2019)

EBITDA of Pumped Storage Plants
EUR Mn (nominal)
...making valuable recommendations on the optimal configuration and dimensioning of a power plant...

Net Present Value (unlevered)
Mn. EUR

<table>
<thead>
<tr>
<th>Base Case</th>
<th>High Eff.</th>
<th>Small setup</th>
<th>Large setup</th>
</tr>
</thead>
</table>

Internal Rate of Return (nominal, unlevered)
%

<table>
<thead>
<tr>
<th>Base Case</th>
<th>High Eff.</th>
<th>Small setup</th>
<th>Large setup</th>
</tr>
</thead>
</table>
...and evaluating the main sources of risk compromising the economic feasibility of the project

<table>
<thead>
<tr>
<th>Net Present Value (unlevered)</th>
<th>Mn. EUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod. Fast trans. Slow trans. High gas High dem. DSM PSP</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal Rate of Return (nominal, unlevered)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod. Fast trans. Slow trans. High gas High dem. DSM PSP</td>
<td></td>
</tr>
</tbody>
</table>
Besides planning models can be used to produce electricity market price scenarios spanning multiple years

Wholesale prices forecast in the Russian South zone
Example

• This very simple example is presented with the sake of showing:
  – The concepts introduced in the previous slides
  – How the real world is simplified with the purpose of planning
  – What are the variables necessary for modeling the planning process
Example: System Configuration
Example: Demand Modeling

- Actual load curve is replaced by “load blocks” (peak-Dp and off-peak-Dop)
- Energy in both load representations is the same
- A zero-duration block (P) is used to model capacity requirement plus reserve
Example: Demand Forecast

10% demand growth was assumed

<table>
<thead>
<tr>
<th>Block</th>
<th>Year</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa</td>
<td></td>
<td>'85MW+10MW res.</td>
<td>104.5</td>
<td>115.0</td>
</tr>
<tr>
<td>Dpa</td>
<td></td>
<td>77.5 MW</td>
<td>85.3</td>
<td>93.8</td>
</tr>
<tr>
<td>Dopa</td>
<td></td>
<td>58.5 MW</td>
<td>64.4</td>
<td>70.8</td>
</tr>
<tr>
<td>Pb</td>
<td></td>
<td>'100 MW + 20 MW res.</td>
<td>132.0</td>
<td>145.2</td>
</tr>
<tr>
<td>Dpb</td>
<td></td>
<td>90 MW</td>
<td>99.0</td>
<td>108.9</td>
</tr>
<tr>
<td>Dopb</td>
<td></td>
<td>70 MW</td>
<td>77.0</td>
<td>84.7</td>
</tr>
</tbody>
</table>
Example: Existent Facilities (year 0)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Variable cost $/MWh</th>
<th>Capacity MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga1</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Ga2</td>
<td>65</td>
<td>40</td>
</tr>
<tr>
<td>Gb1</td>
<td>45</td>
<td>130</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>220</td>
</tr>
</tbody>
</table>

Transmission line a-b capacity: 20 MW
Example: Expansion Alternatives

<table>
<thead>
<tr>
<th>Technology</th>
<th>Variable cost $/MWh</th>
<th>Capacity MW</th>
<th>Capital Cost $/kw</th>
<th>O&amp;M Cost $/kw-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCa1</td>
<td>30</td>
<td>50</td>
<td>800</td>
<td>5</td>
</tr>
<tr>
<td>GTa2</td>
<td>60</td>
<td>60</td>
<td>450</td>
<td>12</td>
</tr>
<tr>
<td>CCb1</td>
<td>40</td>
<td>40</td>
<td>800</td>
<td>5</td>
</tr>
<tr>
<td>GTb2</td>
<td>70</td>
<td>50</td>
<td>450</td>
<td>12</td>
</tr>
</tbody>
</table>

Line A-B capacity: 20 MW
Example: Planning Assumptions

• Discount rate: 8%
• New plants can be installed on year 1-2
• Life of new plants: 2 years
• Planning horizon: 2 years
• No emissions constrains
• Cost are deterministic
• No transmission losses
Economic Dispatch Equations

Min Objective Function:
\[
\sum_{j=1}^{2} \sum_{i=1}^{3} \text{Generation}_{ij} \times \text{Duration}_j \times \text{VarCost}_t_j
\]

Constraints:
\[
\sum_{i=1}^{2} \text{Generation}_{ij} + T_{BAj} - T_{ABj} \geq \text{Dema}_A_j
\]
\[
\sum_{i=3}^{3} \text{Generation}_{ij} - T_{BAj} + T_{ABj} \geq \text{Dema}_B_j
\]
\[
\text{Capacity}_i \geq \text{Generation}_{ij}
\]
\[
\text{LineCapacity} \geq T_{BA}
\]
\[
\text{LineCapacity} \geq -T_{AB}
\]
Economic Dispatch Year 1 - Zone A
Equations for Optimal Expansion

Min Objective Function:

\[
NPV(VC + Inv + O&M) = \sum_{a} \frac{1}{(1 + t)^a} \left( \sum_{j=1}^{2} \sum_{i=1}^{3} Generation_{ija} \cdot Duration_{j} \cdot VarCost_{i} \right) + \\
\left( \sum_{j=1}^{2} \sum_{k=1}^{4} Generation_{kja} \cdot Duration_{j} \cdot VarCost_{k} \right) + \\
\left( \sum_{k=1}^{4} (IN_{a} \cdot (CapitalCost_{k} + O&M_{k})) \right)
\]

Fuel cost of existing plants
Fuel cost of new plants
Investments and O&M cost of new plants
Generation of new plants no greater than installed capacity

Additional constraints:

\[
\sum_{m=1}^{a} IN_{km} \geq PotN_{kja}
\]
## Solution – year 1

### YEAR 1

<table>
<thead>
<tr>
<th>ZoneA</th>
<th>Peak+reserve</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Total Energy (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetA1</td>
<td>MW</td>
<td>50</td>
<td>50</td>
<td>34.3</td>
</tr>
<tr>
<td>GetA2</td>
<td>MW</td>
<td>6.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GenA3</td>
<td>MW</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>GenA4</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trans to ZoneB</td>
<td>MW</td>
<td>-2</td>
<td>-14.7</td>
<td>-20</td>
</tr>
<tr>
<td>DEMAND ZoneA</td>
<td>MW</td>
<td>104.5</td>
<td>85.3</td>
<td>64.3</td>
</tr>
<tr>
<td>Marginal cost</td>
<td>$/MWh</td>
<td>65</td>
<td>44.96</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ZoneB</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GetB1</td>
<td>MW</td>
<td>130</td>
<td>84.3</td>
<td>57</td>
</tr>
<tr>
<td>GenB2</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GenB3</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trans from ZoneA</td>
<td>MW</td>
<td>2</td>
<td>14.7</td>
<td>20</td>
</tr>
<tr>
<td>DEMAND ZoneA</td>
<td>MW</td>
<td>132</td>
<td>99</td>
<td>77</td>
</tr>
<tr>
<td>Marginal cost</td>
<td>$/MWh</td>
<td>65.07</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>
## Solution – year 2

### YEAR 2

<table>
<thead>
<tr>
<th>ZoneA</th>
<th>Peak+reserve</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetA1</td>
<td>MW</td>
<td>44.2</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>GetA2</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GenA3</td>
<td>MW</td>
<td>90.8</td>
<td>90.8</td>
<td>90.8</td>
</tr>
<tr>
<td>GenA4</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trans to ZoneB</td>
<td>MW</td>
<td>-20</td>
<td>-20</td>
<td>-20</td>
</tr>
<tr>
<td>DEMAND ZoneA</td>
<td>MW</td>
<td>115</td>
<td>93.8</td>
<td>70.8</td>
</tr>
<tr>
<td>Marginal cost</td>
<td>$/MWh</td>
<td>40</td>
<td>40</td>
<td>39.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ZoneB</th>
<th>Peak+reserve</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetB1</td>
<td>MW</td>
<td>125.2</td>
<td>88.9</td>
<td>64.7</td>
</tr>
<tr>
<td>GenB2</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GenB3</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trans from ZoneA</td>
<td>MW</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>DEMAND ZoneA</td>
<td>MW</td>
<td>145.2</td>
<td>108.9</td>
<td>84.7</td>
</tr>
<tr>
<td>Marginal cost</td>
<td>$/MWh</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>
Transmission Expansion

A better solution may be achieved if transmission can be expanded. Let us assume an expansion cost of 5M$ for a new 20MW line.

Min Objective Function:

\[ \text{Min } \text{NPV}(VC + Inv + O&M) = \sum_{a=0}^{2} \frac{1}{(1+t)^a} \left( \left( \sum_{j=1}^{3} \sum_{l=1}^{2} Pot_{ija} \ Dur_{aj} V\ C_{aj} \right) + \left( \sum_{j=1}^{4} \sum_{k=1}^{3} Pot_{kja} \ Dur_{aj} V\ C_{ka} \right) + \left( \sum_{k=1}^{4} (IN_{kj} \ (CC_{ka} + O\ &\ M_k)) \right) + DT_a \ INVT \right) \]

Additional constraints:

\[ T_{BAa}j = -T_{ABa}j \leq (20MW) + \sum_{m=1}^{a} DT_a \]
Transmission Expansion - Solution

**YEAR 1 - with transmission expansion**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Peak+reserve</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetA1</td>
<td>MW</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>GetA2</td>
<td>MW</td>
<td>35</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GenA3</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GenA4</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trans to ZoneB</td>
<td>MW</td>
<td>10</td>
<td>27.5</td>
<td>8.5</td>
</tr>
<tr>
<td>DEMAND ZoneA</td>
<td>MW</td>
<td>95</td>
<td>77.5</td>
<td>58.5</td>
</tr>
<tr>
<td>Marginal cost</td>
<td>$/MWh</td>
<td>65</td>
<td>49.7</td>
<td>45.05</td>
</tr>
</tbody>
</table>

**ZoneB**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Peak+reserve</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>GetB1</td>
<td>MW</td>
<td>130</td>
<td>117.5</td>
<td>78.5</td>
</tr>
<tr>
<td>GenB2</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GenB3</td>
<td>MW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Trans from ZoneA</td>
<td>MW</td>
<td>-10</td>
<td>-27.5</td>
<td>-8.5</td>
</tr>
<tr>
<td>DEMAND ZoneA</td>
<td>MW</td>
<td>120</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>Marginal cost</td>
<td>$/MWh</td>
<td>64.93</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>

Incremental cost (variable + investment + O&M) decreased about 0.6%
Further complications

- Area-country protection: only a percentage of load in an area can be imported (linked to security of supply)
- Minimum % of primary sources should be from indigenous resources
- Ramp of thermal plants: power output of some plants cannot change faster than some rate that depends on each technology
- Must run plants (renewable, voltage support, start-up time)
Further complications for hydropower will be presented in the next sessions

- Hydrothermal systems are complex to operate as:
  - There is a tradeoff between consuming water now or in the future
  - The production function of hydropower plants is non-linear and depends on the water level

- Additionally hydropower presents additional issues due to the conflicting water uses:
  - Power generation demands flexibility of storage operation what might compromise water availability for farming purposes
  - Needs for navigation, for urban area protection and for wildlife require setting maximum and minimum tailwater flows
Thank you for your attention

Any question?
Thanks for your attention