Strategic Energy Planning under Uncertainty: a Mixed-Integer Linear Programming Modeling Framework for Large-Scale Energy Systems

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Outline

• Introduction
  • The energy transition
  • Energy forecasting: learning from the past
  • Gaps & Objective

• MILP model
  • Main features
  • Model structure: sets and constraints

• Results
  • Application to the Swiss energy system
  • Robust Optimization

• Conclusions
Introduction
Introduction

The energy transition

IPCC 2013: climate has changed due to human activities [2]

To target the $2^\circ C$ $\Delta T$ limit CO$_2$ emissions need to be halved by 2050 [3]

Sources:
[1] Allison et al., The Copenhagen Diagnosis, 2009 (p. 50)
[2] IPCC 2013 report, Climate change 2013 - The physical science basis
[3] IEA, Energy Technology Perspectives 2014
Introduction

The energy transition

IPCC 2013: climate has changed due to human activities [2]

To target the $2^\circ$C $\Delta T$ limit CO$_2$ emissions need to be halved by 2050 [3]

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1. Allison et al., The Copenhagen Diagnosis, 2009 (p. 50)
2. IPCC 2013 report, Climate change 2013 - The physical science basis
3. IEA, Energy Technology Perspectives 2014

Strategic Energy Planning
Large scale: urban/national
Time horizon: 20-50 years

Common approach:
Long term deterministic evolution models based on forecasts
Introduction

Energy forecasting: learning from the past

Historical U.S. AEO Natural Gas for Electricity Production Price Forecast vs Actual Price

Sources:
Introduction

Energy forecasting: learning from the past

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Introduction

Energy forecasting: learning from the past

Long-term, strategic planning for urban and national energy systems

20-50 years vs Short-term profitability
Based on forecasting

Low penetration of renewables and/or new (efficient) technologies
Overcapacity when forecasts are wrong

Furthermore:
- energy models are “non-validatable”, i.e. doomed to inaccuracy [2]
- backcasting: models have missed pivotal events [3]

> 80% primary energy [1]

Need of accounting for uncertainty in long-term energy modeling

Sources:
Introduction

Still low penetration of uncertainty in the energy field:

- Grossmann et al.\(^1\): **model complexity** and **computational time** are key barriers
- Marnay & Siddiqui\(^2\): computational time of NEMS \(\rightarrow\) scenario analysis
- Rager et al.\(^3\): **concise** models needed for robust optimization

Also, most energy models available today are **sector-specific** (usually electricity) and are based on **evolution** of the energy system with a **market**-based approach.

Concise MILP modeling framework for large-scale energy systems for strategic energy planning under uncertainty
MILP model
Main features of the developed MILP framework:

- Energy based model
- “Snapshot” model: optimization of the energy system in a future target year
- Simplified yet complete energy system: inclusion of heating and mobility
- Multiperiod formulation: seasonality of demand and energy storage
- Concise structure
- Low number of integer variables
- Life Cycle Assessment: Global Warming Potential (CO$_2$-eq. emissions)
MILP model

Model structure: sets

Legend:
- SET NAME [INDEX]
  - CONTENT
    - Content description

- LAYERS [L]

- RESOURCES [RES]
  - Fuels & electricity import
  - BIOFUELS [BF]
    - Biofuel imports

- SECTORS [S]
  - HOUSEHOLDS SERVICES
  - INDUSTRY TRANSPORT

- PERIODS [T]
  - Time periods (months, hours...)

- END USES TYPES [EUT]
  - EUT OF EUC (HEAT)
    - HEAT HIGH T
    - HEAT LOW T DHN
    - HEAT LOW T DECEN
  - EUT OF EUC (ELEC.)
    - ELECTRICITY
  - EUT OF EUC (MOB.)
    - MOB. PUBLIC
    - MOB. PRIVATE
    - MOB. FREIGHT ROAD
    - MOB. FREIGHT RAIL

- TECHNOLOGIES [TECH]
  - TECH OF EUC (HEAT)
    - Heat&CHP Industry tech.
  - TECH OF EUC (MOBILITY)
    - Private Mobility tech.
  - TECH OF EUC (ELECTRICITY)
    - Elec. production tech.
  - TECH OF EUC (EUC)
    - Heat&CHP Centralized tech.
  - TECH OF EUT (LOW T DHN)
    - Heat&CHP Decen. tech.
  - TECH OF EUT (LOW T DEC)
    - Heat&CHP Centralized tech.
  - TECH OF EUT (HIGH T)

- END USES INPUT [EUI]
  - ELECTRICITY
    - LIGHTING
  - HEAT
    - HIGH T
    - LOW T HW
    - LOW T SH
  - MOB.
    - PASSENGER
    - FREIGHT
MILP model

Model structure: sets

End-uses demand: sector-based $\rightarrow$ heating + electricity + mobility

Legend:
- SET NAME [INDEX]
  - CONTENT
    - Content description

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  - Fuels & electricity import
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  - TECH OF EUT (LOW T DEC)
    - Heat&CHP Decen. tech.
  - TECH OF EUC (ELECTRICITY)
    - Elec. production tech.
  - TECH OF EUT (PUBLIC)
    - Public Mobility tech.
  - TECH OF EUT (PRIVATE)
    - Private Mobility tech.
  - TECH OF EUT (FR. ROAD)
    - TRUCK
  - TECH OF EUT (FR. RAIL)
    - TRAIN
  - STORAGE TECH [STO]
    - Storage tech.

- END USES INPUT [EUI]
  - ELECTRICITY
  - HEAT HIGH T
  - HEAT LOW T HW
  - HEAT LOW T SH
  - MOB. PASSENGER
  - MOB. FREIGHT
#### MILP model

**Model structure: sets**

**Distinction between resources (including biofuels) and technologies**

<table>
<thead>
<tr>
<th>RESOURCES [RES]</th>
<th>LAYERS [L]</th>
<th>TECHNOLOGIES [TECH]</th>
</tr>
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<td>Heat&amp;CHP Decen. tech.</td>
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<td><strong>TECH OF EUC (ELEC.)</strong></td>
<td>TECH OF EUC (PUBLIC)</td>
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<td>Public Mobility tech.</td>
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<td>Private Mobility tech.</td>
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<td>TECH OF EUC (LOW T DEC)</td>
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<tr>
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<td><strong>TECH OF EUC (FR. ROAD)</strong></td>
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<tr>
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<td>LIGHTING</td>
<td>TECH OF EUC (FR. RAIL)</td>
<td>Storage tech.</td>
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<td><strong>TECH OF EUC (FR. RAIL)</strong></td>
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<td><strong>TECH OF EUC (FR. RAIL)</strong></td>
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<td>HEAT LOW T HW</td>
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<td><strong>TECH OF EUC (FR. RAIL)</strong></td>
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MILP model

Model structure: constraints

- Input to the model: end-uses for the target year from demand-side model[1]
- Decision variables: level of centralization for heating, penetration of public mobility and of rail transport in freight

\[
\text{EndUsesInput}(eui) = \sum_{s \in S} \text{endUses}_{year}(eui, s) \forall eui
\]

- ELECTRICITY
- LIGHTING
- HEAT HIGH T
- HEAT LOW T (SH)
- HEAT LOW T (HW)
- MOB. PASSENGER
- MOB. FREIGHT

\[
\text{EndUses}(eut, t)
\]

Sources:
[1] Codina Gironés et al., Strategic energy planning for large-scale energy systems: A modelling framework to aid decision-making. 2015
MILP model

Model structure: constraints

Objective: supplying this end-use demand at the lowest total annual cost

\[
\min \sum_{j \in TECH} (\tau(j)C_{inv}(j) + C_{maint}(j)) + \sum_{i \in RES} C_{op}(i)
\]  

(1)
MILP model

Model structure: constraints

Objective: supplying this end-use demand at the lowest total annual cost

\[
\min \sum_{j \in TECH}(\tau(j)C_{inv}(j) + C_{maint}(j)) + \sum_{i \in RES}C_{op}(i) \tag{1}
\]

Distinction between technologies and resources

\[
\tau(j) = \frac{i_{rate}(i_{rate} + 1)^{n(j)}}{(i_{rate} + 1)^{n(j)} - 1} \quad \forall j \in TECH \tag{2}
\]

\[
C_{inv}(j) = c_{inv}(j) * Mult(j) \quad \forall j \in TECH \tag{3}
\]

\[
C_{maint}(j) = c_{maint}(j) * Mult(j) \quad \forall j \in TECH \tag{4}
\]

\[
f_{min}(j) \leq Mult(j) \leq f_{max}(j) \quad \forall j \in TECH \tag{5}
\]

\[
N(j)mult_{ref}(j) = Mult(j) \quad \forall j \in TECH \tag{6}
\]

\[
C_{op}(i) = \sum_{i \in T}c_{op}(i,t)Mult_t(i,t)to_p(t) \quad \forall i \in RES \tag{9}
\]

\[
\sum_{i \in T}Mult_t(i,t)to_p(t) \leq avail(i) \quad \forall i \in RES \tag{10}
\]
MILP model

Model structure: constraints

This allows an easy integration of *Global Warming Potential* in the model: extraction, transportation and combustion emissions attributed to resources, construction, O&M and end-of-life emissions to technologies.

Distinction between technologies and resources

\[
\tau(j) = \frac{i_{rate} (i_{rate} + 1)^{n(j)}}{(i_{rate} + 1)^{n(j)} - 1} \quad \forall j \in TECH \ (2)
\]

\[
C_{inv}(j) = c_{inv}(j) \times Mult(j) \quad \forall j \in TECH \ (3)
\]

\[
C_{maint}(j) = c_{maint}(j) \times Mult(j) \quad \forall j \in TECH \ (4)
\]

\[
f_{min}(j) \leq Mult(j) \leq f_{max}(j) \quad \forall j \in TECH \ (5)
\]

\[
N(j)mult_{ref}(j) = Mult(j) \quad \forall j \in TECH \ (6)
\]

\[
C_{op}(i) = \sum_{i \in T} c_{op}(i, t) Mult_{t}(i, t) t_{op}(t) \quad \forall i \in RES \ (9)
\]

\[
\sum_{i \in T} Mult_{t}(i, t) t_{op}(t) \leq avail(i) \quad \forall i \in RES(10)
\]
MILP model

Model structure: constraints

This allows an easy integration of Global Warming Potential in the model: extraction, transportation and combustion emissions attributed to resources, construction, O&M and end-of-life emissions to technologies.

Capacity factor:
- $c_{p,t}$ depending on resource availability (e.g. renewables)
- yearly capacity factor $c_p$ accounting for technology downtime and maintenance

\[
\text{Mult}_t(j, t) \leq \text{Mult}(j)c_{p,t}(j, t) \quad \forall j \in TECH, \forall t \in T \quad (7)
\]
\[
\sum_{t \in T} \text{Mult}_t(j, t)top(t) \leq \text{Mult}(j)c_p(j)\sum_{t \in T}top(t) \quad \forall j \in TECH \quad (8)
\]
MILP model

Model structure: constraints

Layers: power balance in each time period

\[
\sum_{i \in \text{RES\&TECH}\setminus\text{STO}} f(i, l) \cdot \text{Mult}_t(i, t) + \sum_{j \in \text{STO}} (\text{Sto}_{\text{out}}(j, l, t) - \text{Sto}_{\text{in}}(j, l, t)) - \text{EndUses}(l, t) = 0 \quad \forall l \in L, \forall t \in T \quad (11)
\]
**MILP model**

**Model structure: constraints**

Layers: power balance in each time period

\[
\sum_{i \in \text{RES\&TECH \setminus STO}} f(i, l) \cdot \text{Mult}_t(i, t) + \sum_{j \in \text{STO}} (\text{Sto}_\text{out}(j, l, t) - \text{Sto}_\text{in}(j, l, t)) - \text{EndUses}(l, t) = 0 \quad \forall l \in L, \forall t \in T \quad (11)
\]
## MILP model

### Model structure: constraints

**Layers:** power balance in each time period

\[
\sum_{i \in RES \cup TECH \setminus STO} f(i,l) \cdot Mult(i,t) + \sum_{j \in STO} (Sto_{out}(j,l,t) - Sto_{in}(j,l,t)) - EndUses(l,t) = 0 \\
\forall l \in L, \forall t \in T \quad (11)
\]

<table>
<thead>
<tr>
<th>TECH/STO</th>
<th>RESOURCES/BIOFUELS</th>
<th>END USES TYPES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELEC</td>
<td>NG</td>
<td>HEAT DHN</td>
</tr>
<tr>
<td>NG</td>
<td>SNG</td>
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<tr>
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<td>...</td>
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<tr>
<td>HP</td>
<td>CHP</td>
<td>1</td>
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</tr>
</tbody>
</table>

Unitary output in main end-use type \( \rightarrow Mult \) corresponds to installed size of technology [GW]
**MILP model**

Model structure: constraints

\[ \text{Mult}_t(j, t) = \text{Mult}_t(j, t - 1) + t_{op}(t). \]

\[ (\sum_{l \in L|\varepsilon_{sto,in}(j, l) > 0} \text{Sto}_{in}(j, l, t)\varepsilon_{sto,in}(j, l) - \sum_{l \in L|\varepsilon_{sto,out}(j, l) > 0} \text{Sto}_{out}(j, l, t)/\varepsilon_{sto,out}(j, l)) \]

\[ \forall j \in STO, \forall t \in T \quad (12) \]

**Mult** \(_t\) storage level [GWh]

**Mult** max. level (inv. cost)

[Diagram of a storage system with input and output states]

\[ \text{Sto}_{in}(j, l, t)(\lceil \varepsilon_{sto,in}(j, l) \rceil - 1) = 0 \]

\[ \forall j \in STO, \forall l \in L, \forall t \in T \quad (13) \]

\[ \text{Sto}_{out}(j, l, t)(\lceil \varepsilon_{sto,out}(j, l) \rceil - 1) = 0 \]

\[ \forall j \in STO, \forall l \in L, \forall t \in T \quad (14) \]

\[ \left[ \sum_{l \in L|\varepsilon_{sto,in}(j, l) > 0} \text{Sto}_{in}(j, l, t)\varepsilon_{sto,in}(j, l) \frac{t_{op}(t)}{f_{max}(j)} \right] + \left[ \sum_{l \in L|\varepsilon_{sto,out}(j, l) > 0} \text{Sto}_{out}(j, l, t)/\varepsilon_{sto,out}(j, l) \frac{t_{op}(t)}{f_{max}(j)} \right] \leq 1 \]

\[ \forall j \in STO, \forall t \in T \quad (15) \]
Results
Results

Application to the Swiss energy system

Excel\(^2\) → MILP

Introduction

MILP model

Results

Conclusions

Sources:

SWISS ENERGY Scope

Excel\(^2\) → MILP

COMPARE SITUATION 2011 TO 2050CH Low(E)
Robust optimization: methodology

Soyster\cite{1}: Protection against all uncertain parameters at worst case. Very conservative

Bertsimas & Sim\cite{2}: reduction of the "price of robustness" through probabilistic approach

\[
\text{minimize } c^T x
\]

The vector \( c \) (cost coefficients) has some uncertain elements belonging to the set \( J \). The \( j \)-th uncertain parameter can vary of a maximum value \( d_j \)

\[
c_j = [c_j, c_j + d_j] \quad j \in J
\]

The "protection parameter" controls the number of uncertain parameters at worst case:

\[
\Gamma_0 = [0, |J|]
\]

\[
\Gamma_0 = 0 \quad \text{Deterministic MILP, no parameter at worst case}
\]

\[
\Gamma_0 = |J| \quad \text{All parameter at worst case (Soyster)}
\]

Application of the methodology to \( c_{\text{op}} (+40 \%) \) and \( c_{\text{inv}} (+20 \%) \rightarrow 178 \) params
Results

Robust optimization: methodology

New Parameters

\( \Gamma_0 \): protection parameter

\( d_{op}(i) \ \forall i \in RES \): variation from the nominal value of the operating cost

\( d_{inv}(j) \ \forall j \in TECH \): variation from the nominal value of the investment cost

New Variables

\( z_0, p_{0,op}(i,t), y_{op}(i,t), p_{0,inv}(j), y_{inv}(j) \ \forall i \in RES, \forall j \in TECH/STO, \forall t \in T \)

New Constraints

\( z_0 + p_{0,op}(i,t) \geq d_{op}(i,t)y_{op}(i,t) \ \forall i \in RES, \forall t \in T \)

\( z_0 + p_{0,inv}(j) \geq d_{inv}(j)y_{inv}(j) \ \forall j \in TECH/STO \)

\(-y_{op}(i,t) \leq \text{Mult}_t(i,t)t_{op} \leq y_{op}(i,t) \ \forall i \in RES, \forall t \in T \)

\(-y_{inv}(j) \leq \tau(j)\text{Mult}(j) \leq y_{inv}(j) \ \forall j \in TECH/STO \)

New Objective

\[
\min \sum_{j \in TECH} (\tau(j)C_{inv}(j) + C_{maint}(j)) + \sum_{i \in RES} C_{op}(i) \\
+z_0 \Gamma_0 + \sum_{i \in RES} \sum_{t \in T} p_{0,op}(i,t) + \sum_{j \in TECH/STO} p_{0,inv}(j)
\]
Results

Robust optimization: first results
Robust optimization: first results
Conclusions
Conclusions

Summary

MILP framework for strategic energy planning under uncertainty:

- Energy based model
- “Snapshot” model: optimization of the energy system in a future target year
- Simplified yet complete energy system: inclusion of heating and mobility
- Multiperiod formulation: seasonality of demand and energy storage
- Concise structure
- Low complexity: low number of integer variables
- Life Cycle Assessment: Global Warming Potential (CO$_2$-eq. emissions)

Application to case study → preliminary results:

- Global Sensitivity Analysis
- Robust optimization

Impact of uncertainty on energy strategy
Conclusions

Future work

Legend:
- Action
- Data/Information
Thank you! Questions?

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Appendix
### MILP model

#### Model structure: parameters

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<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$endUses_{year}(eui, s)$</td>
<td>[GWh/y]$^a$</td>
<td>Annual end-uses in energy services per sector</td>
</tr>
<tr>
<td>$i_{rate}$</td>
<td>[-]</td>
<td>Real discount rate</td>
</tr>
<tr>
<td>$%<em>{public,min}, %</em>{public,max}$</td>
<td>[-]</td>
<td>Upper and lower limit to $%_{Public}$</td>
</tr>
<tr>
<td>$%<em>{rail,min}, %</em>{rail,max}$</td>
<td>[-]</td>
<td>Upper and lower limit to $%_{Rail}$</td>
</tr>
<tr>
<td>$%<em>{dhn,min}, %</em>{dhn,max}$</td>
<td>[-]</td>
<td>Upper and lower limit to $%_{Dhn}$</td>
</tr>
<tr>
<td>$t_{op}(t)$</td>
<td>[h]</td>
<td>Time periods duration</td>
</tr>
<tr>
<td>$%_{lighting}(t)$</td>
<td>[-]</td>
<td>Yearly share (adding up to 1) of lighting end-uses</td>
</tr>
<tr>
<td>$%_{sh}(t)$</td>
<td>[-]</td>
<td>Yearly share (adding up to 1) of SH end-uses</td>
</tr>
<tr>
<td>$f(res \cup tech \setminus sto, l)$</td>
<td>[GW]$^b$</td>
<td>Input from ($&lt; 0$) or output to ($&gt; 0$) layers. $f(i, j) = 1$ if $j$ is main output layer for technology/resource $i$</td>
</tr>
<tr>
<td>$mult_{ref}(tech)$</td>
<td>[GW]$^{bc}$</td>
<td>Reference size with respect to main output</td>
</tr>
<tr>
<td>$c_{inv}(tech)$</td>
<td>[M€/GW]$^{bc}$</td>
<td>Technology specific investment cost</td>
</tr>
<tr>
<td>$c_{main}(tech)$</td>
<td>[M€/GW/y]$^{bc}$</td>
<td>Technology specific yearly maintenance cost</td>
</tr>
<tr>
<td>$n(tech)$</td>
<td>[y]</td>
<td>Technology lifetime</td>
</tr>
<tr>
<td>$f_{min}, f_{max}(tech)$</td>
<td>[GW]$^{bc}$</td>
<td>Min./max. installed size of the technology</td>
</tr>
<tr>
<td>$avail(res)$</td>
<td>[GWh/y]</td>
<td>Resource yearly total availability</td>
</tr>
<tr>
<td>$c_{p,t}(tech, t)$</td>
<td>[-]</td>
<td>Period capacity factor (default 1)</td>
</tr>
<tr>
<td>$c_{p}(tech)$</td>
<td>[-]</td>
<td>Yearly capacity factor</td>
</tr>
<tr>
<td>$c_{op}(res, t)$</td>
<td>[M€/GWh]</td>
<td>Specific cost of resources</td>
</tr>
<tr>
<td>$\varepsilon_{sto,in}, \varepsilon_{sto,out}(sto, l)$</td>
<td>[-]</td>
<td>Efficiency $[0; 1]$ of storage input from/output to layer. Set to 0 if storage not related to layer.</td>
</tr>
<tr>
<td>$%_{lossElec}$</td>
<td>[-]</td>
<td>Losses $[0; 1]$ in the electricity grid</td>
</tr>
</tbody>
</table>
## MILP model

### Model structure: variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{EndUsesInput}(eui)$</td>
<td>[GWh/y]$^a$</td>
<td>Total annual end-uses in energy services</td>
</tr>
<tr>
<td>$\text{EndUses}(l,t)$</td>
<td>[GW]$^b$</td>
<td>End-uses demand. Set to 0 if $l \notin \text{EUT}$</td>
</tr>
<tr>
<td>$% \text{Public}$</td>
<td>[-]</td>
<td>Ratio $[0; 1]$ public mobility over total passenger mobility</td>
</tr>
<tr>
<td>$% \text{Rail}$</td>
<td>[-]</td>
<td>Ratio $[0; 1]$ rail transport over total freight transport</td>
</tr>
<tr>
<td>$% \text{Dhn}$</td>
<td>[-]</td>
<td>Ratio $[0; 1]$ centralized over total low-temperature heat</td>
</tr>
<tr>
<td>$\text{N}(\text{tech}) \in \mathbb{N}$</td>
<td>[-]</td>
<td>Number of installed units of size $\text{multi}_{\text{ref}}$</td>
</tr>
<tr>
<td>$\text{Mult}(\text{tech})$</td>
<td>[GW]$^{bc}$</td>
<td>Installed capacity with respect to main output</td>
</tr>
<tr>
<td>$\text{Mult}_t(\text{tech} \cup \text{res},t)$</td>
<td>[GW]$^{bc}$</td>
<td>Operation in each period</td>
</tr>
<tr>
<td>$\text{C}_{\text{inv}}(\text{tech})$</td>
<td>[M€]</td>
<td>Technology total investment cost</td>
</tr>
<tr>
<td>$\text{C}_{\text{maint}}(\text{tech})$</td>
<td>[M€/y]</td>
<td>Technology yearly maintenance cost</td>
</tr>
<tr>
<td>$\text{C}_{\text{op}}(\text{res})$</td>
<td>[M€/y]</td>
<td>Total cost of resources</td>
</tr>
<tr>
<td>$\tau(\text{tech})$</td>
<td>[-]</td>
<td>Investment cost annualization factor</td>
</tr>
<tr>
<td>$\text{Sto}<em>{\text{in}}, \text{Sto}</em>{\text{out}}(\text{sto},l,t)$</td>
<td>[GW]</td>
<td>Input to/output from storage units</td>
</tr>
<tr>
<td>$\text{Loss}_{\text{Elec}}(t)$</td>
<td>[GW]</td>
<td>Electricity transmission losses</td>
</tr>
</tbody>
</table>

$^a$[Mpkm] (millions of passenger-km) for passenger, [Mtkm] (millions of ton-km) for freight mobility end-uses

$^b$[Mpkm/h] for passenger, [Mtkm/h] for freight mobility end-uses

$^c$[GWh] if $\text{tech} \in \text{STO}$
MILP model

Model structure: constraints

\[
\text{Loss}_{\text{Elec}}(t) = (\text{EndUses}(k) - \sum_{j \in \text{TECH} \setminus \text{STO}} f(j, k) \text{Mult}_t(j, t)) \%_{\text{loss} \text{Elec}} \quad k = \text{Elec}, \forall t \in T \quad (16)
\]

\[
\text{Mult}_t(j, t) + \text{Mult}_t(k, t) \geq \\
\frac{\text{EndUses}(\text{HeatLowTDHN}, t) + \text{EndUses}(\text{HeatLowTDec}, t)}{\text{EndUsesInput}(\text{HeatLowTSH}) + \text{EndUsesInput}(\text{HeatLowTHW})} \sum_{t \in T} \text{Mult}_t(j, t) t_{op}(t) \\
\]  \[k = \text{Dec}_{\text{Solar}}, \forall j \in \text{TECH OF EUT(HeatLowTDec)} \setminus \{k\}, \forall t \in T \quad (17)
\]
Results

Global Sensitivity Analysis: First results

- Morris method for factor fixing.
- ± 20% variation for all the parameters.
- Parameters outside the $\nabla$ are influential

Legend:
- Action
- Data/Information