IPESE
INDUSTRIAL PROCESS AND
ENERGY SYSTEMS ENGINEERING

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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

Stefano Moret*,[a], Michel Bierlaire[b], François Maréchal[a]

[a] Industrial Process and Energy Systems Engineering (IPESE)
[b] Transport and Mobility Laboratory
École Polytechnique Fédérale de Lausanne
*stefano.moret@epfl.ch

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Outline

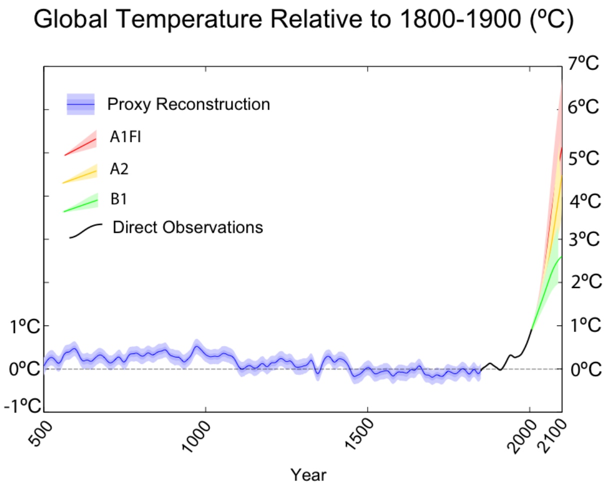
- **Introduction**
  - The energy transition
  - Energy forecasting: learning from the past
  - Gaps & Objective
- **MILP model**
  - Main features
  - Model structure: sets and constraints
- **Results**
  - Application to the Swiss energy system
  - Robust Optimization
- **Conclusions**

Introduction

Introduction

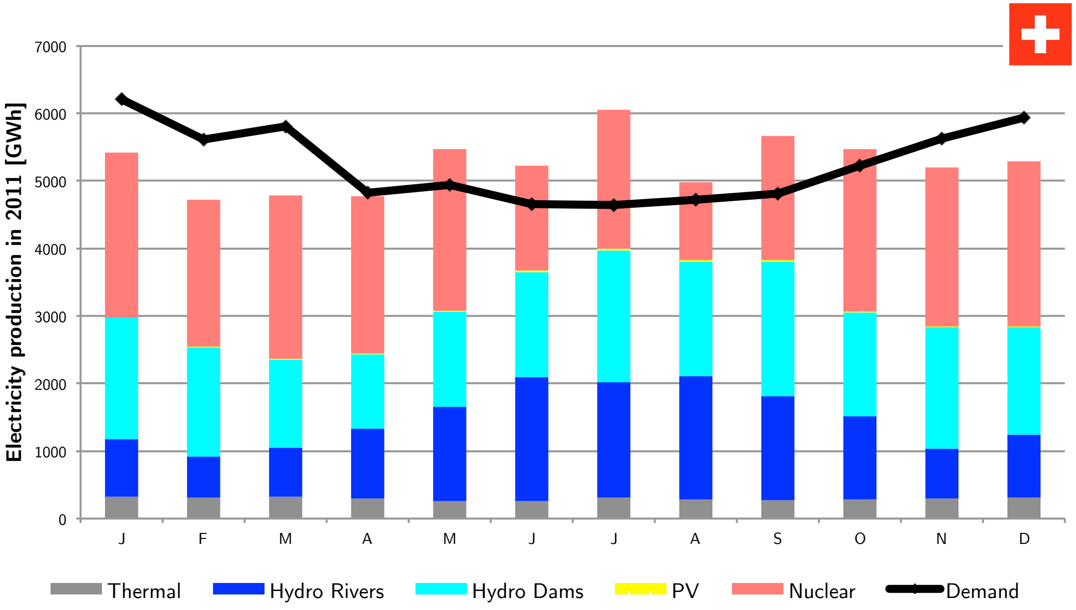
The energy transition

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
[4] Swiss Federal Office of Energy, Swiss electricity statistics, 2011



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

To target the 2°C ΔT limit CO_2 emissions need to be halved by 2050 [3]



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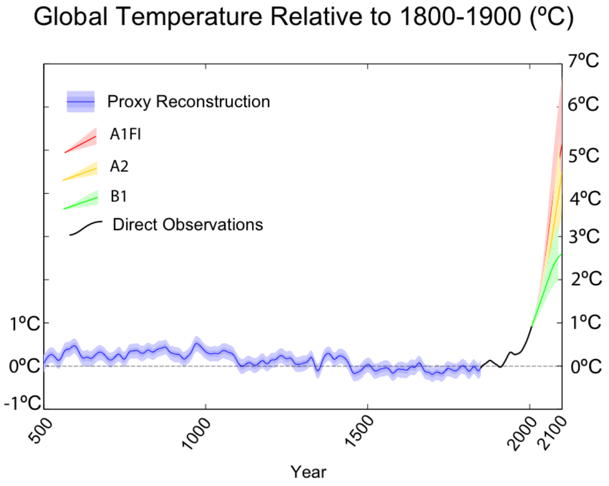

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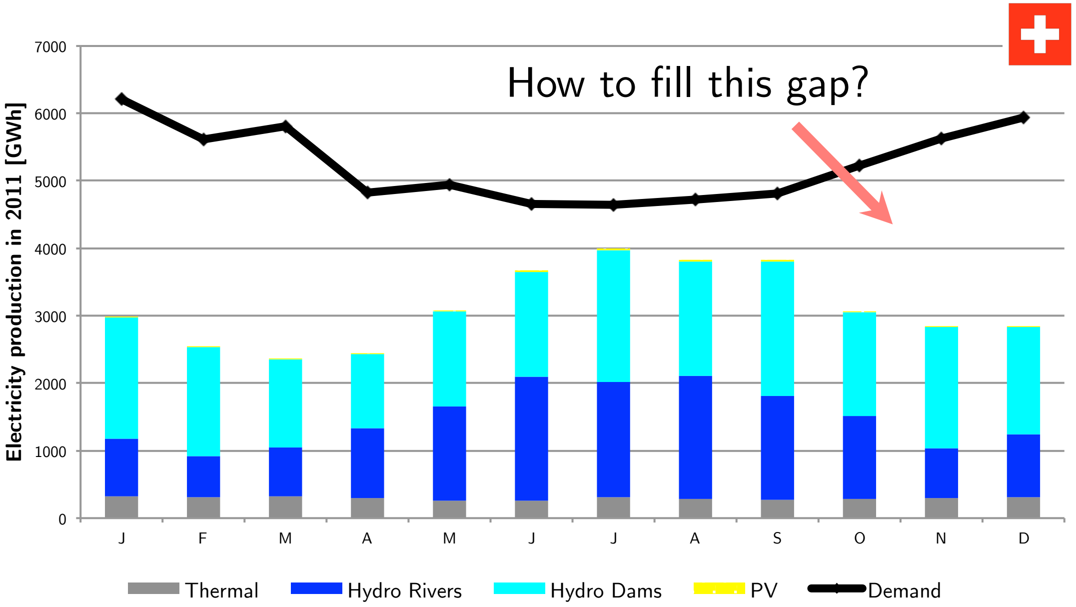


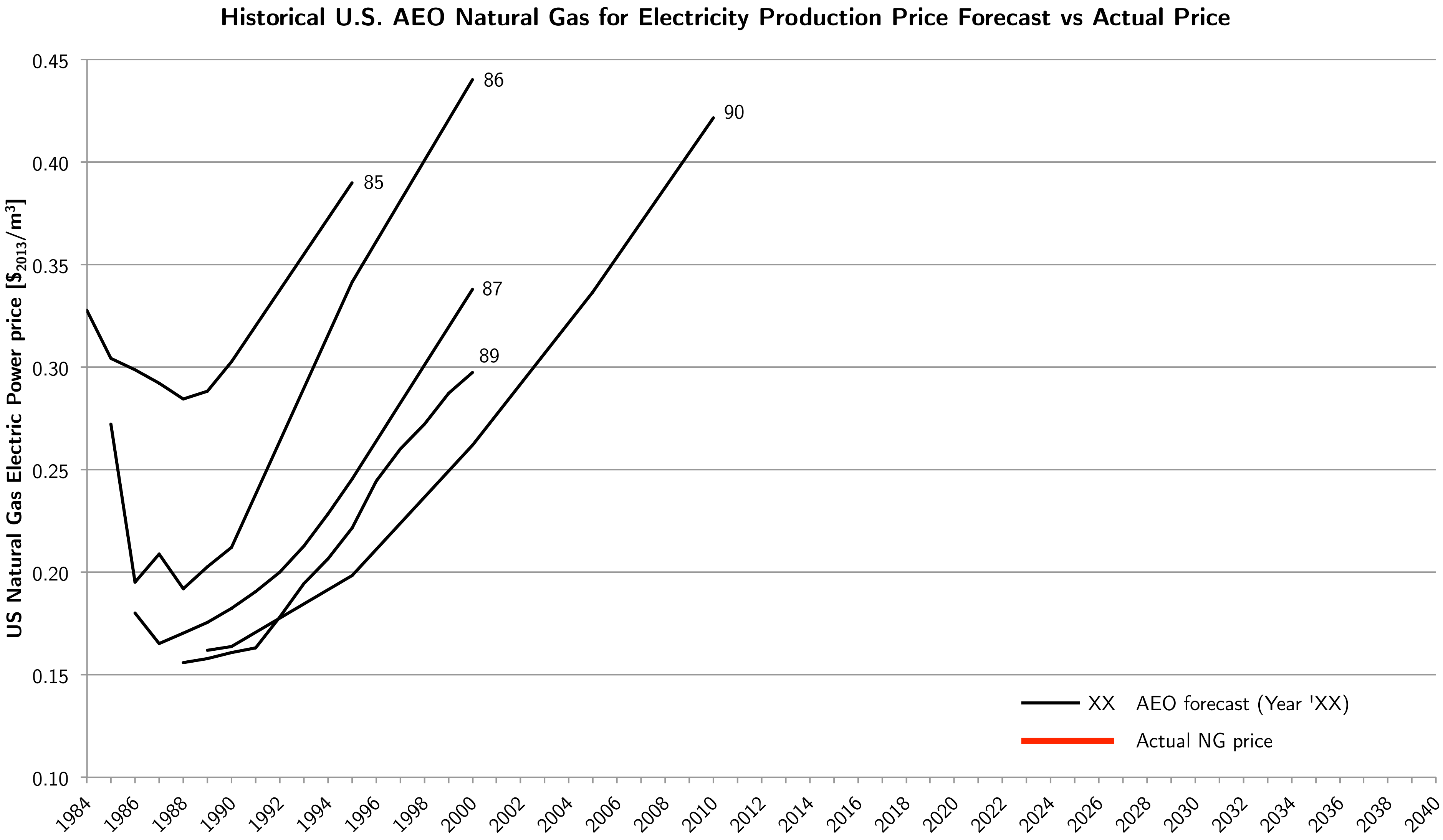
Strategic Energy Planning
Large scale: urban/national
Time horizon: 20-50 years

Common approach:
Long term deterministic evolution models based on forecasts

Introduction

Energy forecasting: learning from the past

Sources:
[1] U.S. EIA - Energy Information Administration.
[2] R. Wiser and M. Bolinger. An Overview of Alternative Fossil Price and Carbon Regulation Scenarios. 2004



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

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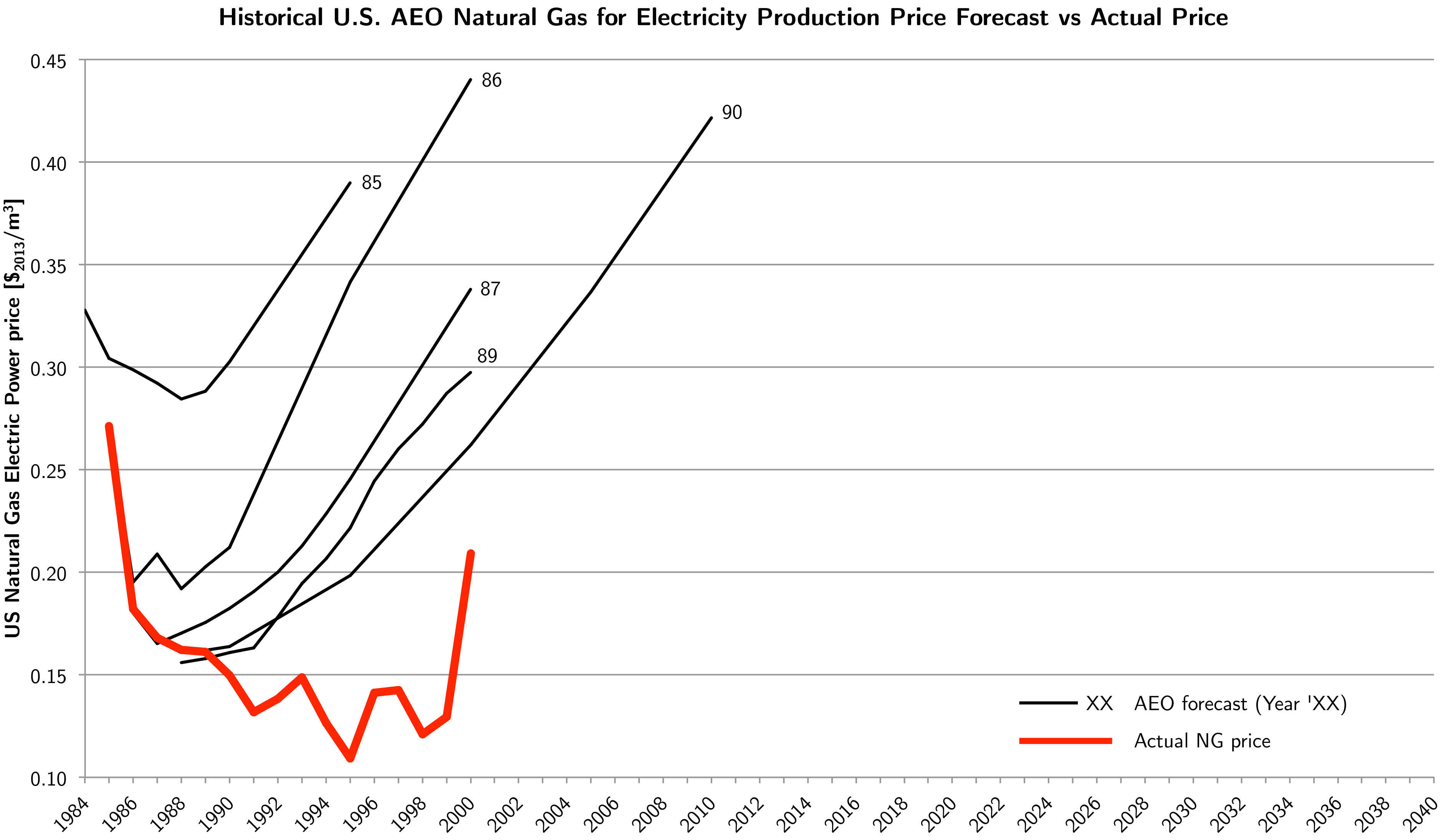

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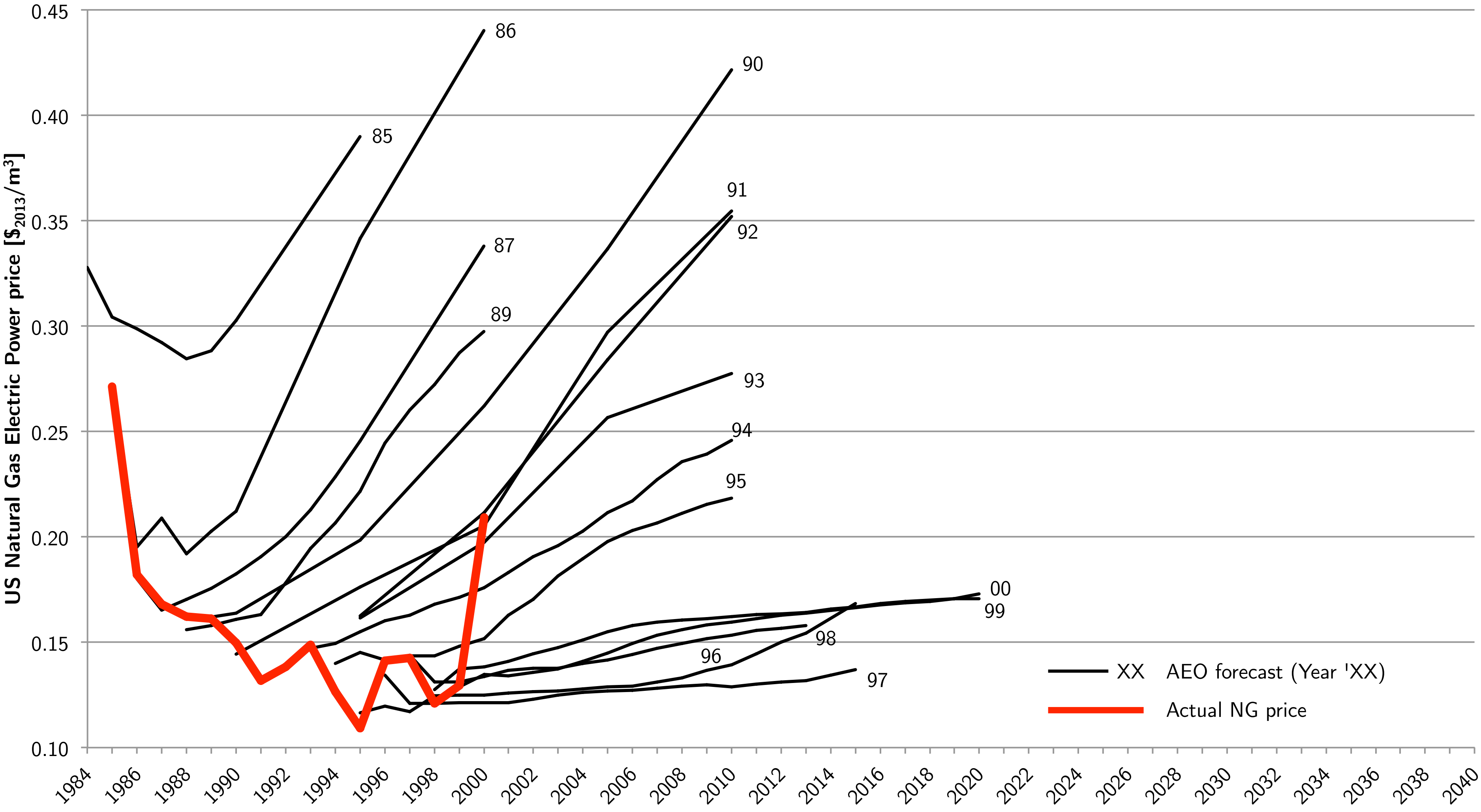

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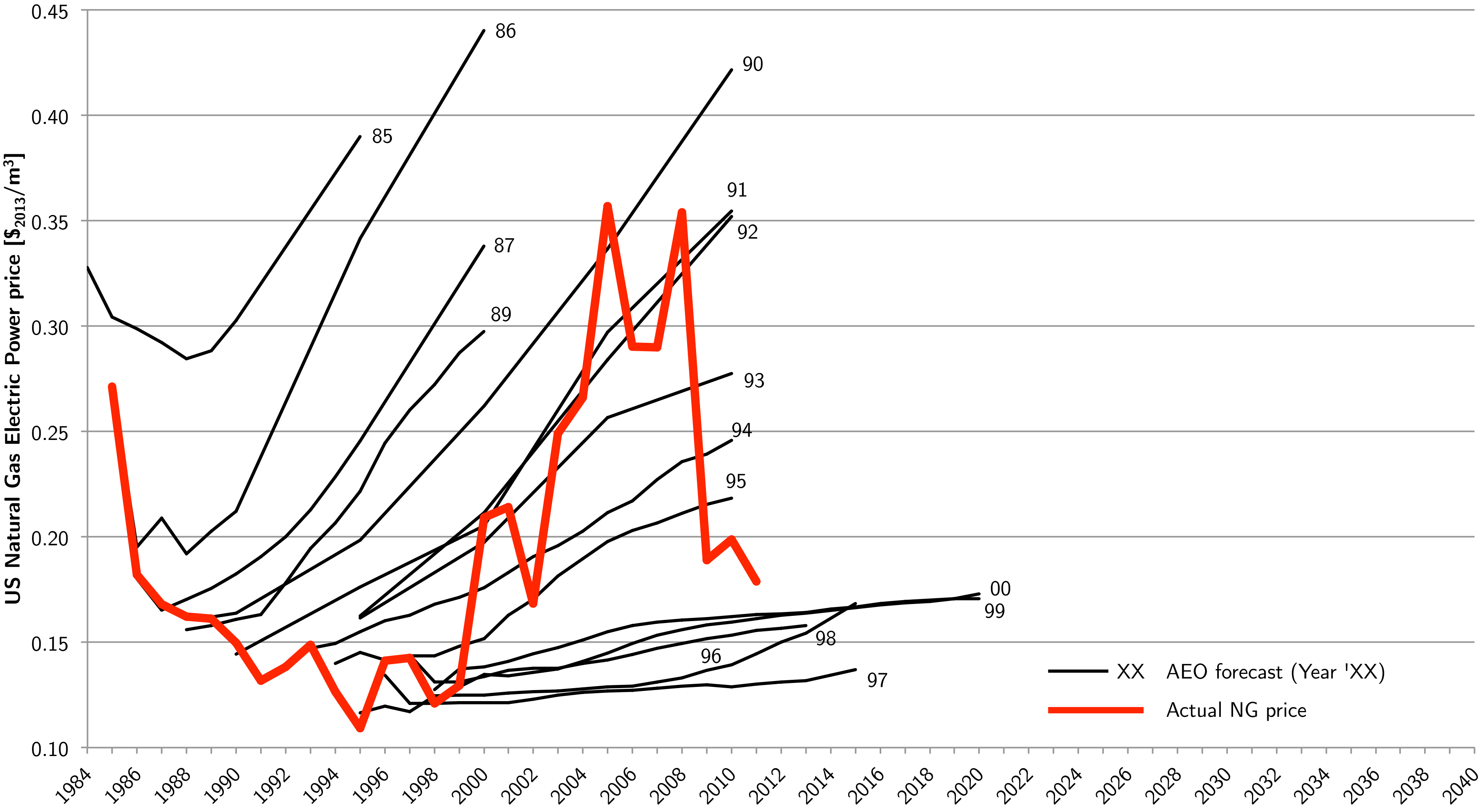

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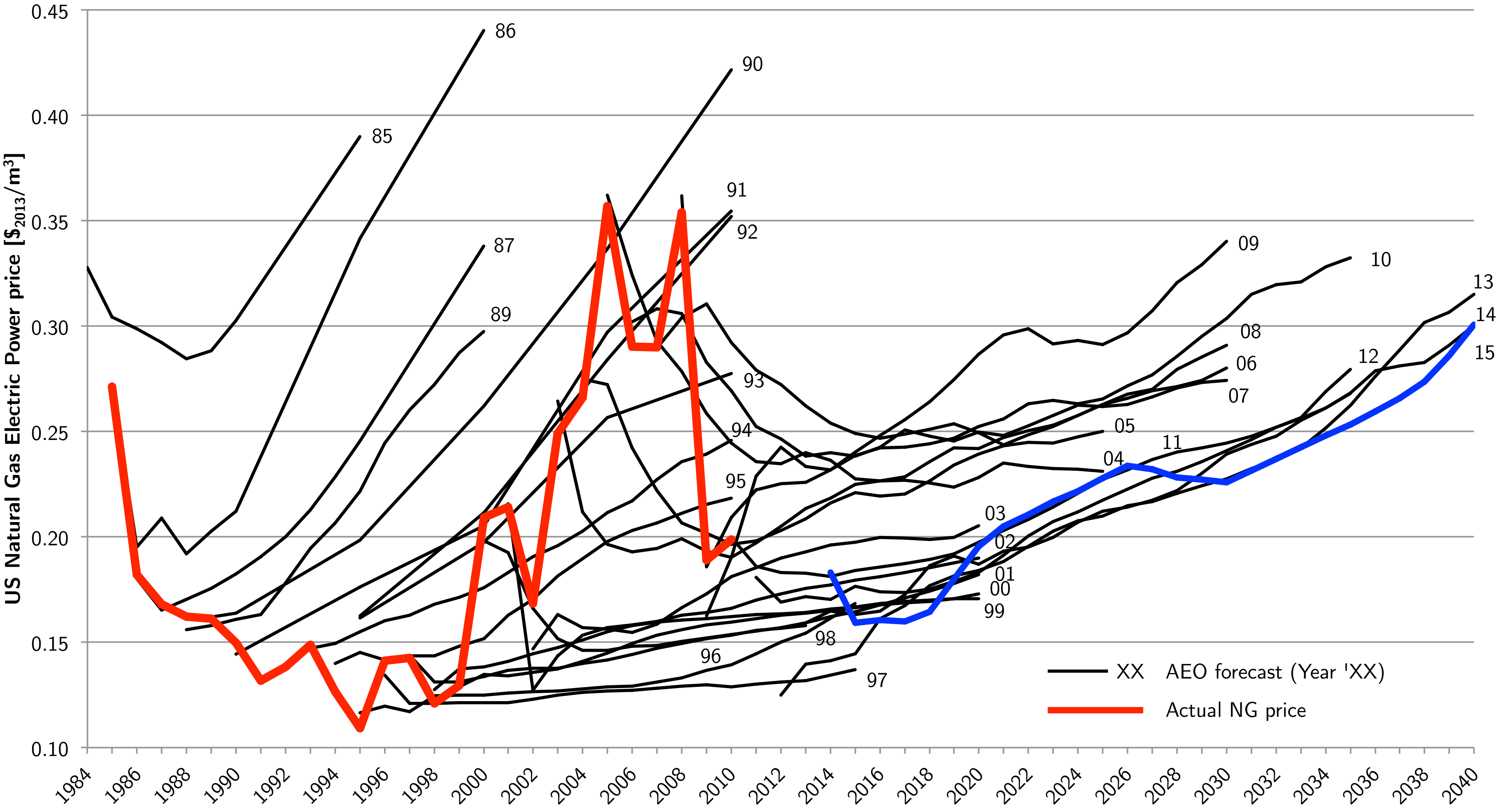

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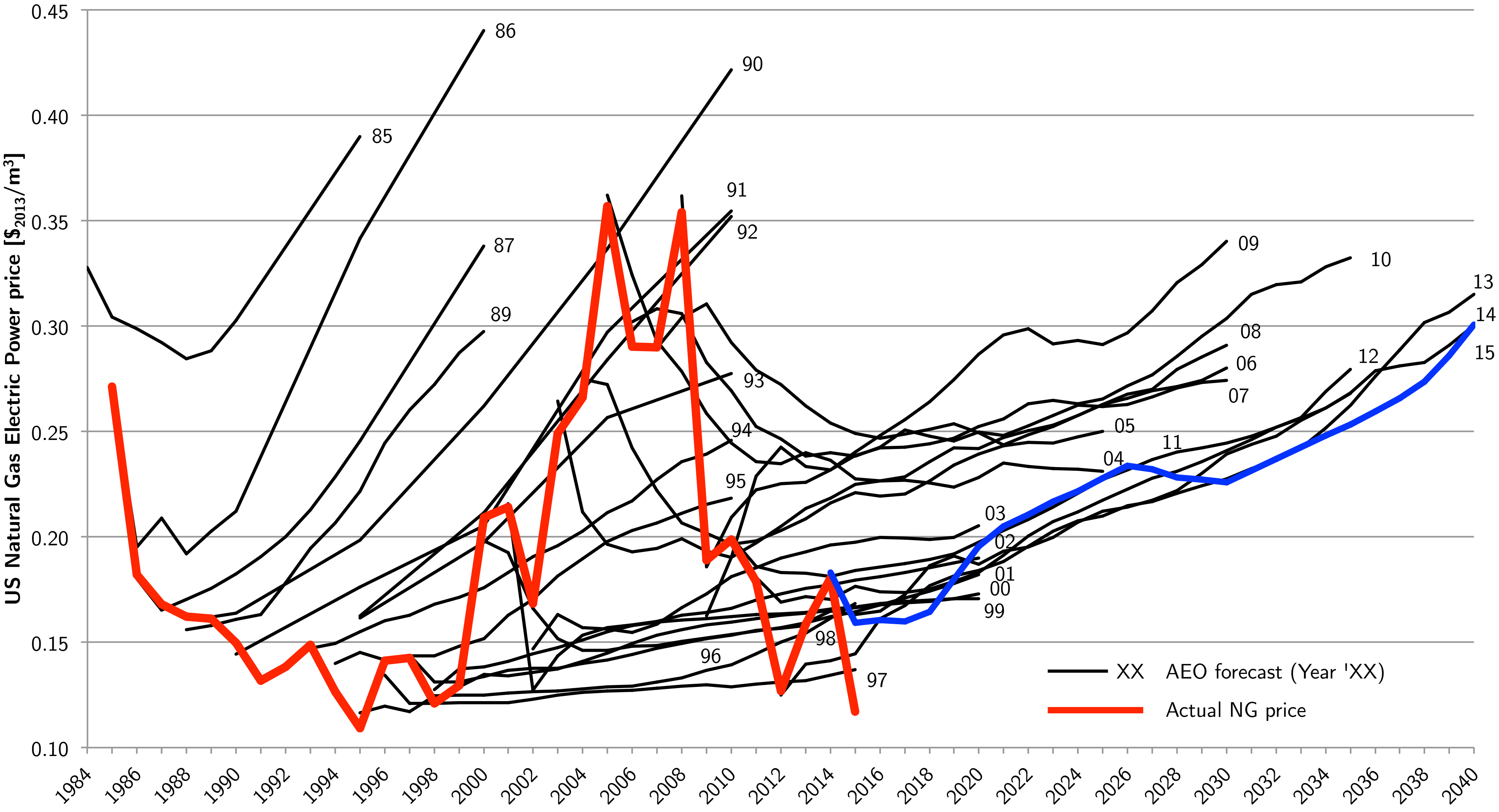
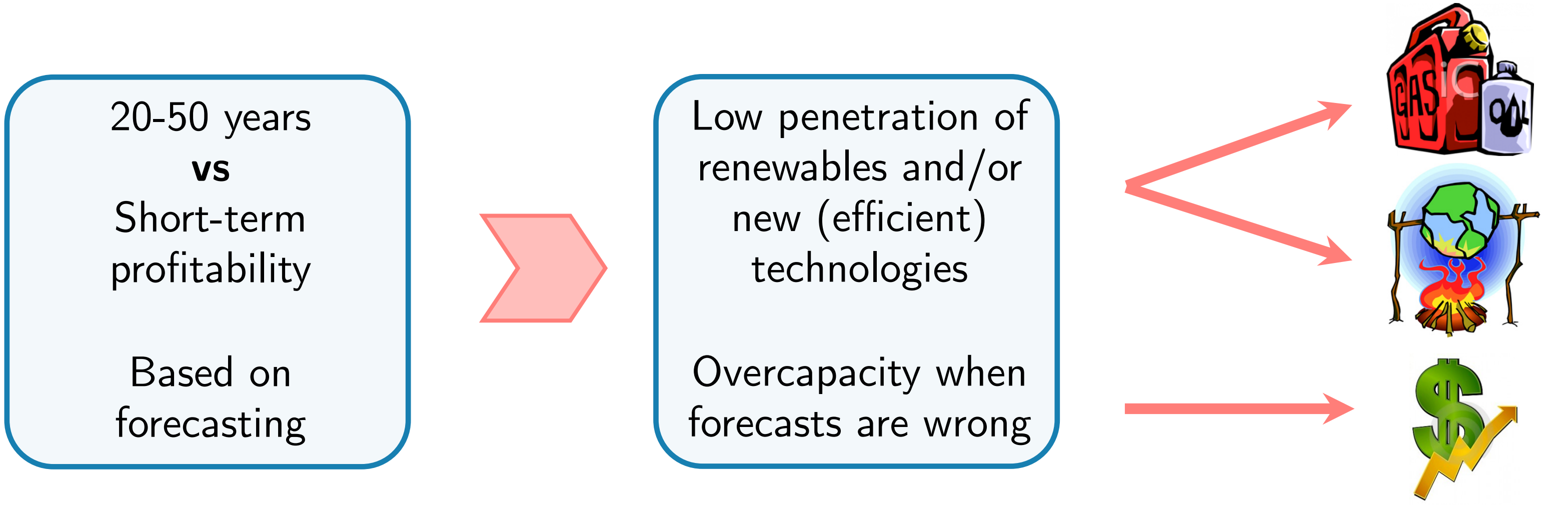


Introduction

Energy forecasting: learning from the past

Sources:
[1] IEA, Key world energy statistics, 2014
[2] James S. Hodges and James A. Dewar. Is it you or your model talking? a framework for model validation. 1992
[3] J. Koomey et al. Improving long-range energy modeling: A plea for historical retrospectives. 2003.

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

> 80% primary energy [1]

Furthermore:

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

Need of accounting for uncertainty in long-term energy modeling

Introduction

Gaps & Objective

Sources:
[1] Grossmann et al., Recent Advances in Mathematical Programming Techniques for the Optimization of Process Systems under Uncertainty. ESCAPE 25, 2015.
[2] Marnay and Siddiqui, Addressing an Uncertain Future Using Scenario Analysis. 2006
[3] Rager et al., Integrating Uncertainty into Urban Energy System Design. ESCAPE 26, 2016.

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 → 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

MILP model

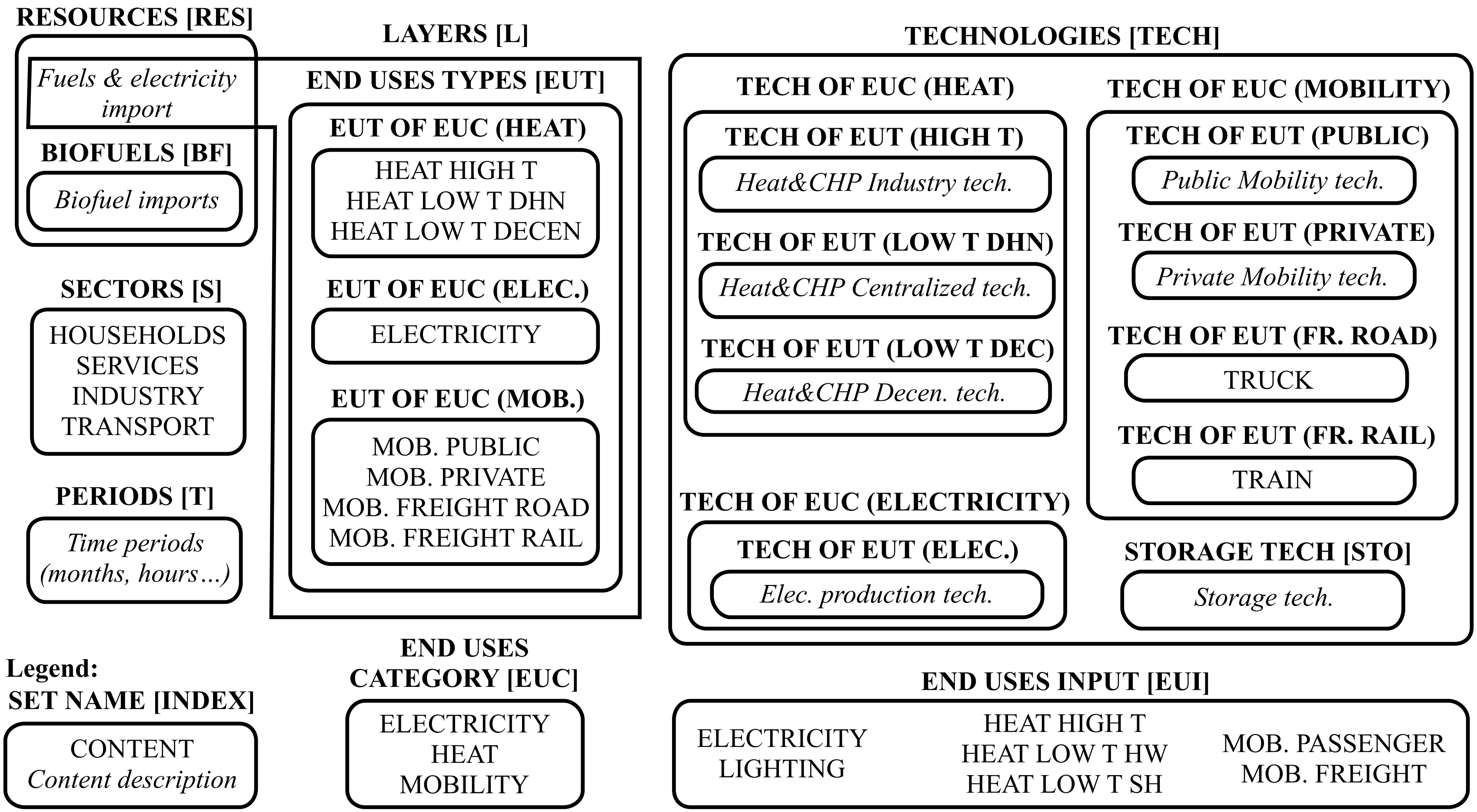
Main features

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



RESOURCES [RES]

Fuels & electricity import

BIOFUELS [BF]

Biofuel imports

SECTORS [S]

HOUSEHOLDS
SERVICES
INDUSTRY
TRANSPORT

PERIODS [T]

Time periods (months, hours...)

LAYERS [L]

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)

TECH OF EUT (HIGH T)

Heat&CHP Industry tech.

TECH OF EUT (LOW T DHN)

Heat&CHP Centralized tech.

TECH OF EUT (LOW T DEC)

Heat&CHP Decen. tech.

TECH OF EUC (ELECTRICITY)

TECH OF EUT (ELEC.)

Elec. production tech.

TECH OF EUC (MOBILITY)

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.

Legend:
SET NAME [INDEX]

CONTENT
Content description

END USES CATEGORY [EUC]

ELECTRICITY
HEAT
MOBILITY

END USES INPUT [EUI]

ELECTRICITY
LIGHTING

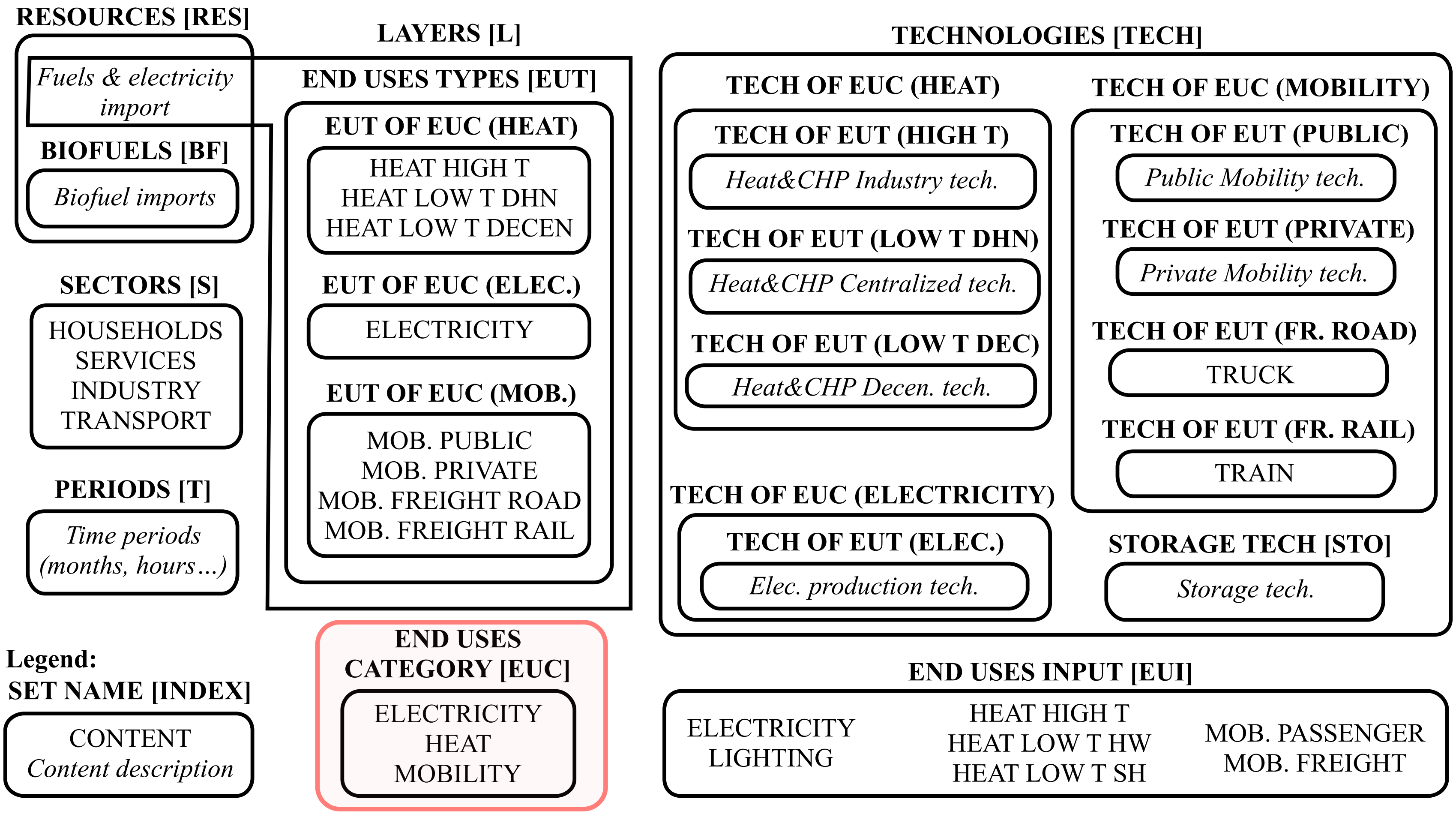
HEAT HIGH T
HEAT LOW T HW
HEAT LOW T SH

MOB. PASSENGER
MOB. FREIGHT

MILP model

Model structure: sets

End-uses demand: sector-based → heating + electricity + mobility



RESOURCES [RES]

Fuels & electricity import

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TRUCK

TECH OF EUT (FR. RAIL)

TRAIN

STORAGE TECH [STO]

Storage tech.

END USES INPUT [EUI]

ELECTRICITY
LIGHTING

HEAT HIGH T
HEAT LOW T HW
HEAT LOW T SH

MOB. PASSENGER
MOB. FREIGHT

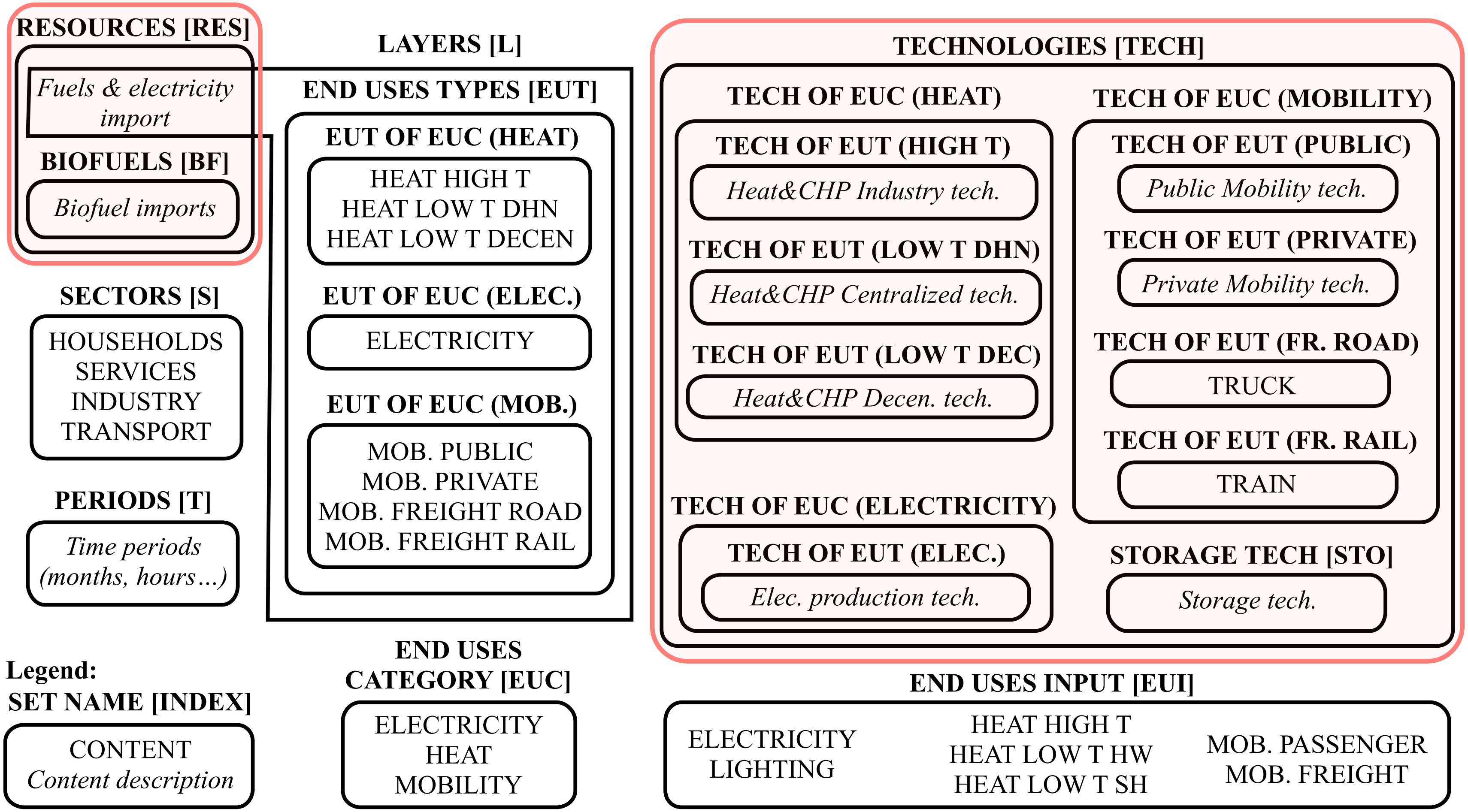
Legend:
SET NAME [INDEX]

CONTENT
Content description

MILP model

Model structure: sets

Distinction between resources (including biofuels) and technologies



RESOURCES [RES]

Fuels & electricity import

BIOFUELS [BF]

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SET NAME [INDEX]

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MOB. PASSENGER
MOB. FREIGHT

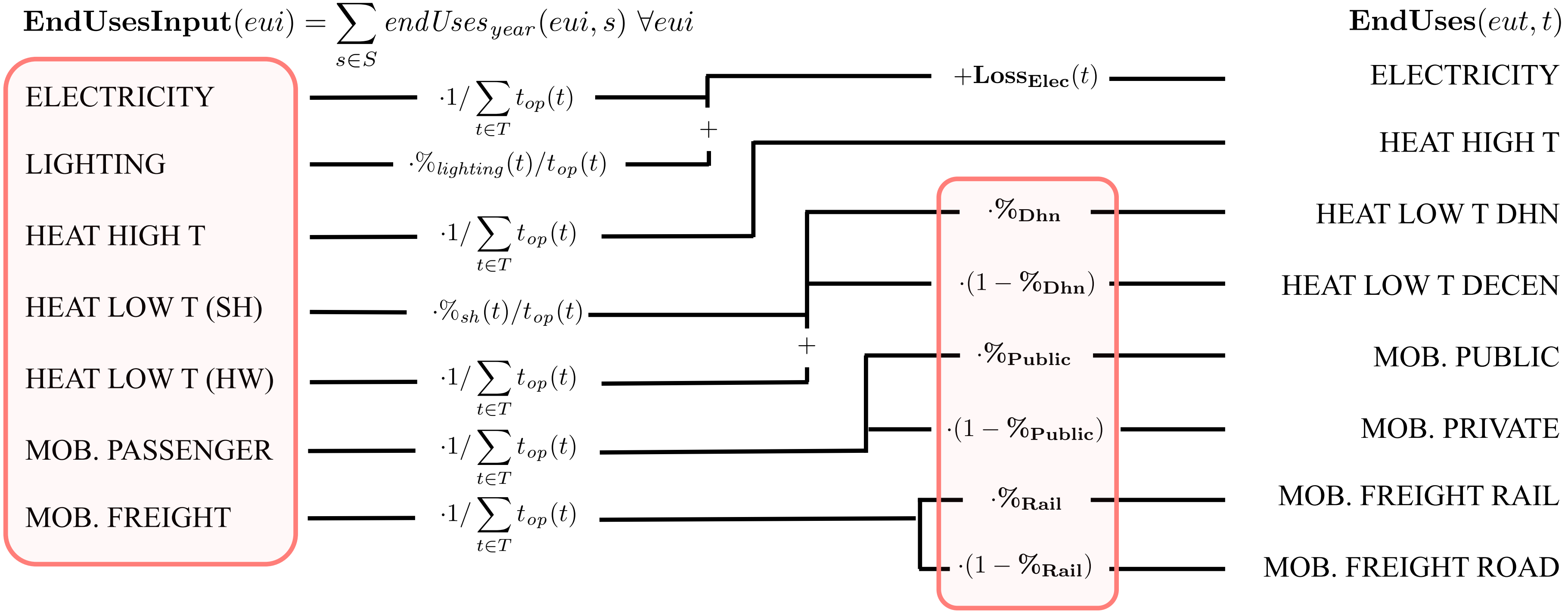
MILP model

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

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

$$\mathbf{EndUsesInput}(eui) = \sum_{s \in S} endUses_{year}(eui, s) \; \forall eui$$



$\mathbf{EndUses}(eut, t)$

ELECTRICITY — $\cdot 1/\sum_{t \in T} t_{op}(t)$ — + — $+\mathbf{Loss_{Elec}}(t)$ — ELECTRICITY

LIGHTING — $\cdot \%_{lighting}(t)/t_{op}(t)$ — +

HEAT HIGH T — $\cdot 1/\sum_{t \in T} t_{op}(t)$ — HEAT HIGH T

HEAT LOW T (SH) — $\cdot \%_{sh}(t)/t_{op}(t)$ — +

HEAT LOW T (HW) — $\cdot 1/\sum_{t \in T} t_{op}(t)$ — +

$\cdot \%_{\mathbf{Dhn}}$ — HEAT LOW T DHN

$\cdot (1 - \%_{\mathbf{Dhn}})$ — HEAT LOW T DECEN

MOB. PASSENGER — $\cdot 1/\sum_{t \in T} t_{op}(t)$

$\cdot \%_{\mathbf{Public}}$ — MOB. PUBLIC

$\cdot (1 - \%_{\mathbf{Public}})$ — MOB. PRIVATE

MOB. FREIGHT — $\cdot 1/\sum_{t \in T} t_{op}(t)$

$\cdot \%_{\mathbf{Rail}}$ — MOB. FREIGHT RAIL

$\cdot (1 - \%_{\mathbf{Rail}})$ — MOB. FREIGHT ROAD

MILP model

Model structure: constraints

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

$$\min \sum_{j \in TECH} \left(\tau(j)\mathbf{C_{inv}}(j) + \mathbf{C_{maint}}(j)\right) + \sum_{i \in RES} \mathbf{C_{op}}(i) \tag{1}$$

MILP model

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Distinction between technologies and resources

$$\text{s.t. } \tau(j) = \frac{i_{rate}(i_{rate}+1)^{n(j)}}{(i_{rate}+1)^{n(j)}-1} \qquad \forall j \in TECH \tag{2}$$

$$\mathbf{C_{inv}}(j) = c_{inv}(j) * \mathbf{Mult}(j) \qquad \forall j \in TECH \tag{3}$$

$$\mathbf{C_{maint}}(j) = c_{maint}(j) * \mathbf{Mult}(j) \qquad \forall j \in TECH \tag{4}$$

$$f_{min}(j) \leq \mathbf{Mult}(j) \leq f_{max}(j) \qquad \forall j \in TECH \tag{5}$$

$$\mathbf{N}(j) mult_{ref}(j) = \mathbf{Mult}(j) \qquad \forall j \in TECH \tag{6}$$

$$\mathbf{C_{op}}(i) = \sum_{t \in T} c_{op}(i,t)\mathbf{Mult_t}(i,t)t_{op}(t) \qquad \forall i \in RES \tag{9}$$

$$\sum_{t \in T} \mathbf{Mult_t}(i,t)t_{op}(t) \leq avail(i) \qquad \forall i \in RES \tag{10}$$

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

$$\text{s.t. } \tau(j) = \frac{i_{rate}(i_{rate}+1)^{n(j)}}{(i_{rate}+1)^{n(j)}-1} \qquad \forall j \in TECH \quad (2)$$

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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

$$\mathbf{Mult_t}(j,t) \leq \mathbf{Mult}(j) c_{p,t}(j,t) \qquad \forall j \in TECH, \forall t \in T \quad (7)$$

$$\sum_{t \in T} \mathbf{Mult_t}(j,t) t_{op}(t) \leq \mathbf{Mult}(j) c_p(j) \sum_{t \in T} t_{op}(t) \qquad \forall j \in TECH \quad (8)$$

MILP model

Model structure: constraints

Layers: power balance in each time period

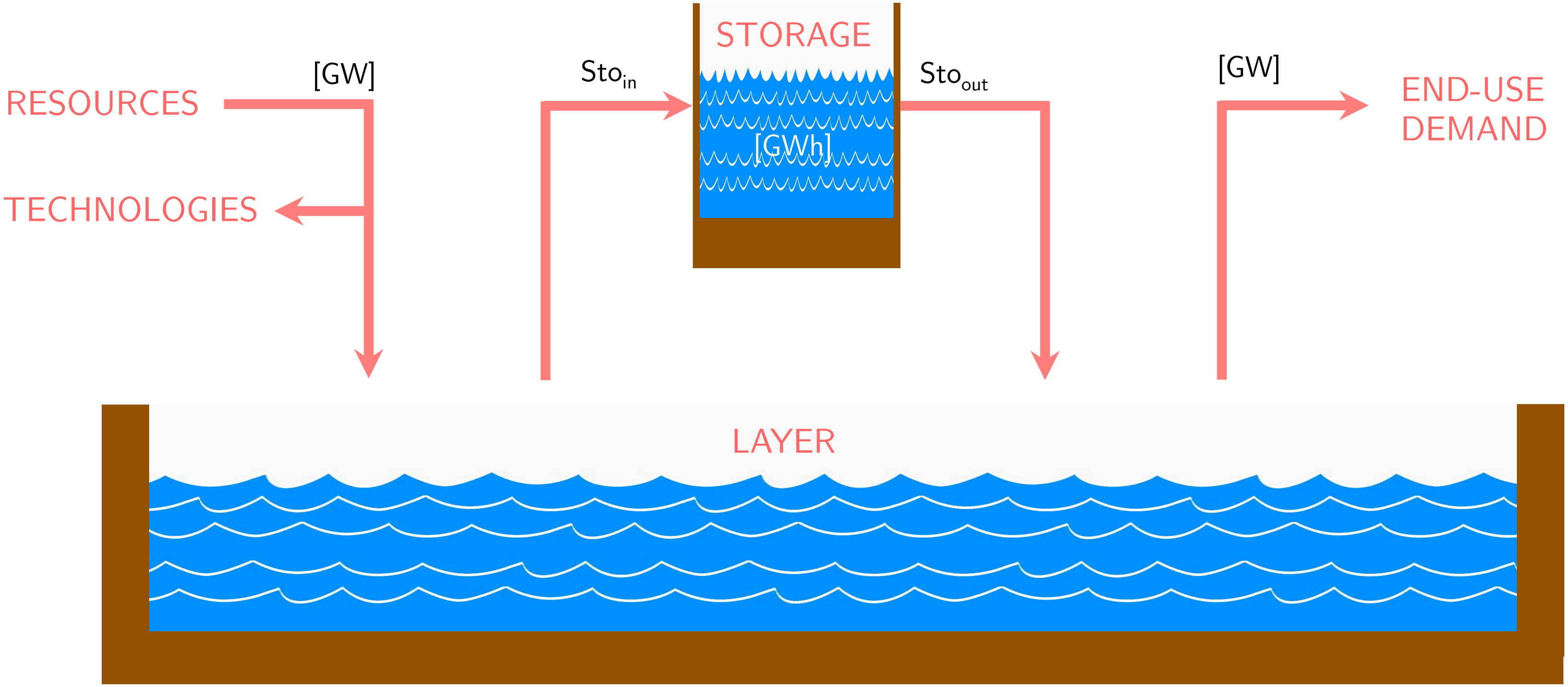
$$\sum_{i \in RES \cup TECH \setminus STO} f(i,l)\mathbf{Mult_t}(i,t) + \sum_{j \in STO} (\mathbf{Sto_{out}}(j,l,t) - \mathbf{Sto_{in}}(j,l,t)) - \mathbf{EndUses}(l,t) = 0 \qquad \forall l \in L, \forall t \in T \quad (11)$$

MILP model

Model structure: constraints

Layers: power balance in each time period

$$\sum_{i \in RES \cup TECH \setminus STO} f(i,l)\,\mathbf{Mult_t}(i,t) + \sum_{j \in STO} \left(\mathbf{Sto_{out}}(j,l,t) - \mathbf{Sto_{in}}(j,l,t)\right) - \mathbf{EndUses}(l,t) = 0 \qquad \forall l \in L, \forall t \in T \quad (11)$$



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$$\sum_{i\in RES\cup TECH\setminus STO} f(i,l)\,\mathbf{Mult_t}(i,t)+\sum_{j\in STO}\left(\mathbf{Sto_{out}}(j,l,t)-\mathbf{Sto_{in}}(j,l,t)\right)-\mathbf{EndUses}(l,t)=0 \qquad \forall l\in L,\forall t\in T \quad (11)$$

LAYERS

		RESOURCES/BIOFUELS			END USES TYPES	
		ELEC	NG	...	HEAT DHN	...
RESOURCES	ELEC	1	0			
	NG	0	1			
	SNG	0	1			
	...					
TECH/STO	HP	-0.25	0		1	
	CHP	1.25	-2.5		1	
	...					

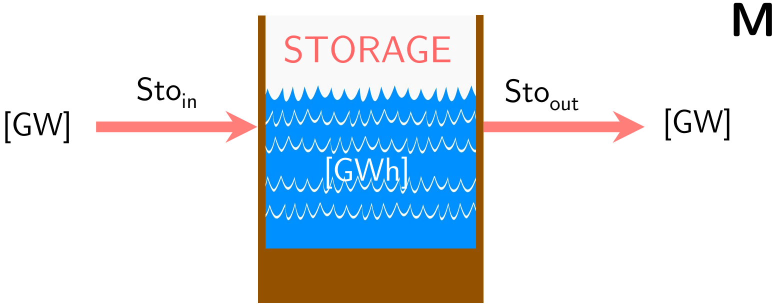
Unitary output in main end-use type → **Mult** corresponds to installed size of technology [GW]

MILP model

Model structure: constraints

$$\mathbf{Mult_t}(j,t) = \mathbf{Mult_t}(j,t-1) + t_{op}(t)\cdot \left(\sum_{l\in L|\varepsilon_{sto,in}(j,l)>0} \mathbf{Sto_{in}}(j,l,t)\varepsilon_{sto,in}(j,l) - \sum_{l\in L|\varepsilon_{sto,out}(j,l)>0} \mathbf{Sto_{out}}(j,l,t)/\varepsilon_{sto,out}(j,l)\right) \quad \forall j \in STO, \forall t \in T \quad (12)$$

$\mathbf{Mult_t}$ storage level [GWh]
Mult max. level (inv. cost)



$$\mathbf{Sto_{in}}(j,l,t)(\lceil \varepsilon_{sto,in}(j,l)\rceil - 1) = 0 \quad \forall j \in STO, \forall l \in L, \forall t \in T \quad (13)$$

$$\mathbf{Sto_{out}}(j,l,t)(\lceil \varepsilon_{sto,out}(j,l)\rceil - 1) = 0 \quad \forall j \in STO, \forall l \in L, \forall t \in T \quad (14)$$

$$\left\lceil \sum_{l\in L|\varepsilon_{sto,in}(j,l)>0} \mathbf{Sto_{in}}(j,l,t)\varepsilon_{sto,in}(j,l)\frac{t_{op}(t)}{f_{max}(j)}\right\rceil + \left\lceil \sum_{l\in L|\varepsilon_{sto,out}(j,l)>0} \mathbf{Sto_{out}}(j,l,t)/\varepsilon_{sto,out}(j,l)\frac{t_{op}(t)}{f_{max}(j)}\right\rceil \leq 1$$

$$\forall j \in STO, \forall t \in T \quad (15)$$

Results

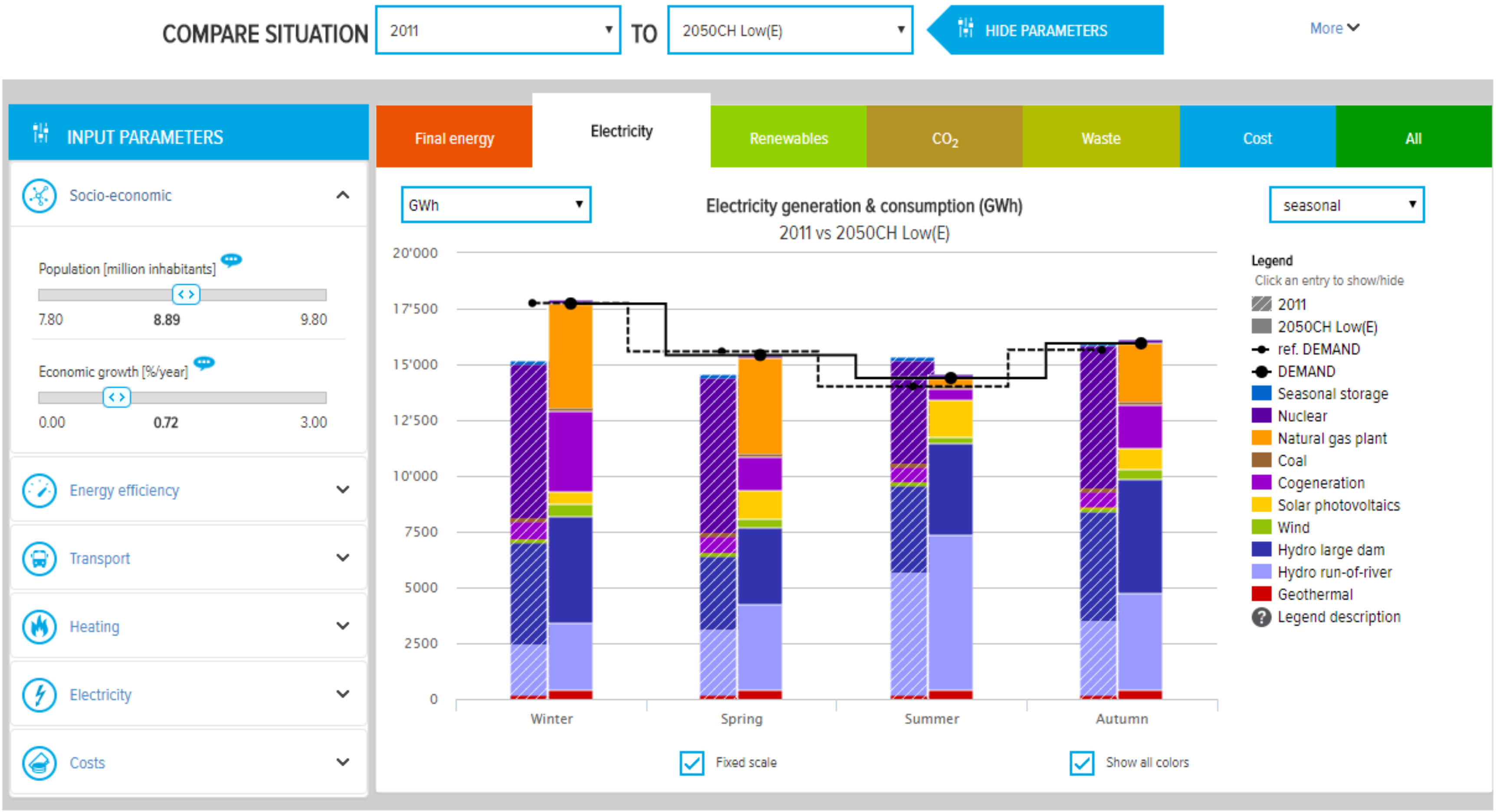
Results

Sources:
[1] Moret et al., Swiss-EnergyScope.ch: a Platform to Widely Spread Energy Literacy and Aid Decision-Making. 2014
[2] Codina Gironès et al., Strategic energy planning for large-scale energy systems: A modelling framework to aid decision-making. 2015

Application to the Swiss energy system

SWISS ENERGYScope

Excel[2] → MILP



COMPARE SITUATION 2011 TO 2050CH Low(E)

INPUT PARAMETERS

Socio-economic

Population [million inhabitants]: 7.80 – **8.89** – 9.80

Economic growth [%/year]: 0.00 – **0.72** – 3.00

Energy efficiency

Transport

Heating

Electricity

Costs

Electricity generation & consumption (GWh)
2011 vs 2050CH Low(E)

GWh

seasonal

☑ Fixed scale

☑ Show all colors

Sources:
[1] Soyster. Convex programming with set-inclusive constraints and applications to inexact linear programming. 1974
[2] Bertsimas & Sim. The price of robustness. 2004.

Robust optimization: methodology

Soyster[1]: Protection against all uncertain parameters at worst case. Very conservative
Bertsimas & Sim[2]: reduction of the "price of robustness" through probabilistic approach

$$\text{minimize } \mathbf{c}^T\mathbf{x}$$

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

$$c_j = [c_j, c_j + d_j] \qquad j \in J$$

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

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

$\Gamma_0 = 0$ Deterministic MILP, no parameter at worst case

$\Gamma_0 = |J|$ All parameter at worst case (Soyster)

Application of the methodology to c_{op} (+40 %) and c_{inv} (+20 %) → 178 params

Results

Sources:
[1] Moret et al., Robust optimization for strategic energy planning, 2014
[2] Bertsimas & Sim. The price of robustness. 2004.

Robust optimization: methodology

New Parameters

Γ_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

$\mathbf{z}_0, \mathbf{p}_{0,\mathbf{op}}(i,t), \mathbf{y}_{\mathbf{op}}(i,t), \mathbf{p}_{0,\mathbf{inv}}(j), \mathbf{y}_{\mathbf{inv}}(j)\ \forall i \in RES, \forall j \in TECH/STO, \forall t \in T$

New Constraints

$$\mathbf{z}_0 + \mathbf{p}_{0,\mathbf{op}}(i,t) \geq d_{op}(i,t)\mathbf{y}_{\mathbf{op}}(i,t) \quad \forall i \in RES, \forall t \in T$$

$$\mathbf{z}_0 + \mathbf{p}_{0,\mathbf{inv}}(j) \geq d_{inv}(j)\mathbf{y}_{\mathbf{inv}}(j) \quad \forall j \in TECH/STO$$

$$-\mathbf{y}_{\mathbf{op}}(i,t) \leq \mathbf{Mult}_{\mathbf{t}}(i,t)t_{op} \leq \mathbf{y}_{\mathbf{op}}(i,t) \quad \forall i \in RES, \forall t \in T$$

$$-\mathbf{y}_{\mathbf{inv}}(j) \leq \tau(j)\mathbf{Mult}(j) \leq \mathbf{y}_{\mathbf{inv}}(j) \quad \forall j \in TECH/STO$$

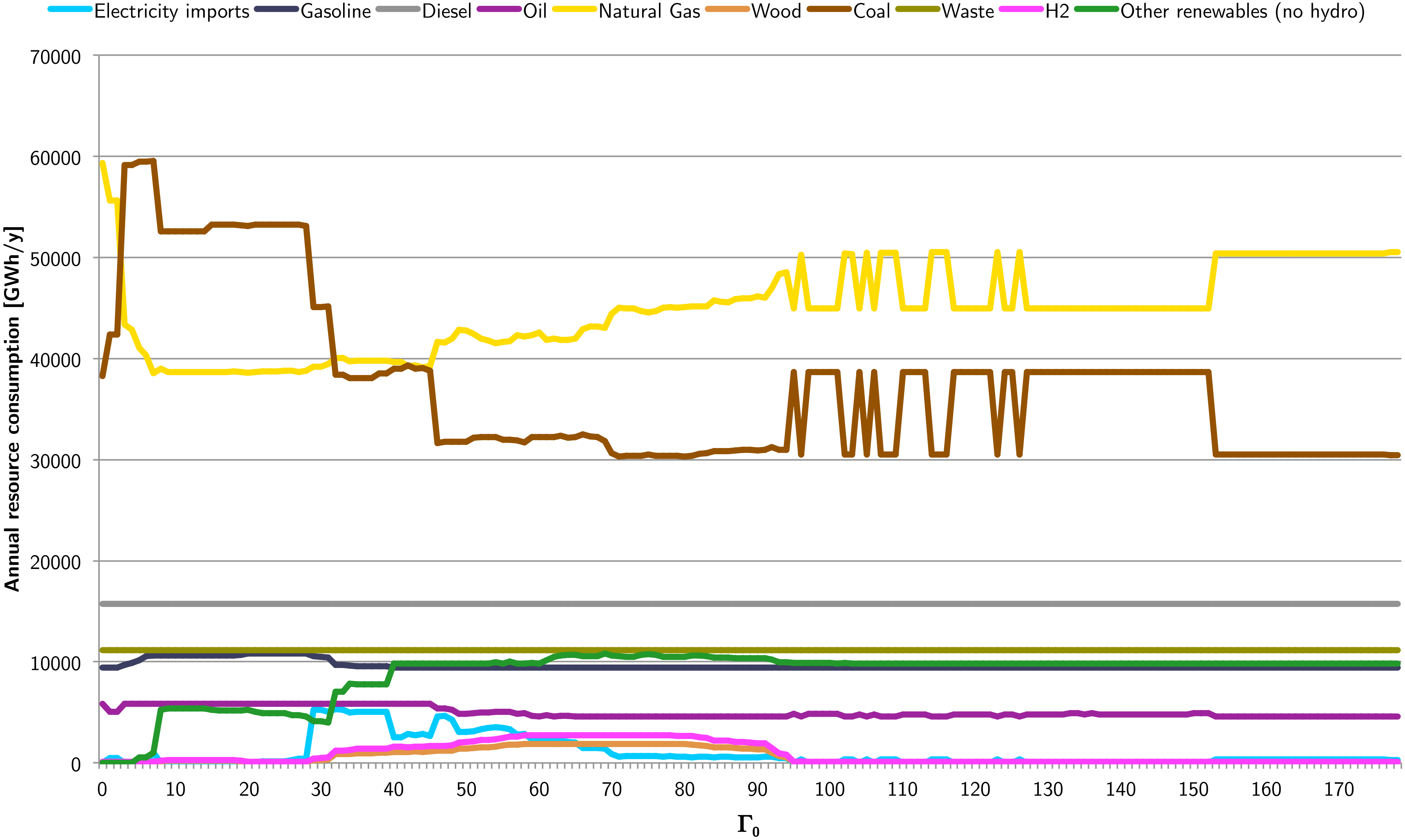
New Objective

$$\min \sum_{j \in TECH}(\tau(j)\mathbf{C}_{\mathbf{inv}}(j) + \mathbf{C}_{\mathbf{maint}}(j)) + \sum_{i \in RES}\mathbf{C}_{\mathbf{op}}(i)$$

$$+\mathbf{z}_0\Gamma_0 + \sum_{i \in RES}\sum_{t \in T}\mathbf{p}_{0,\mathbf{op}}(i,t) + \sum_{j \in TECH/STO}\mathbf{p}_{0,\mathbf{inv}}(j)$$

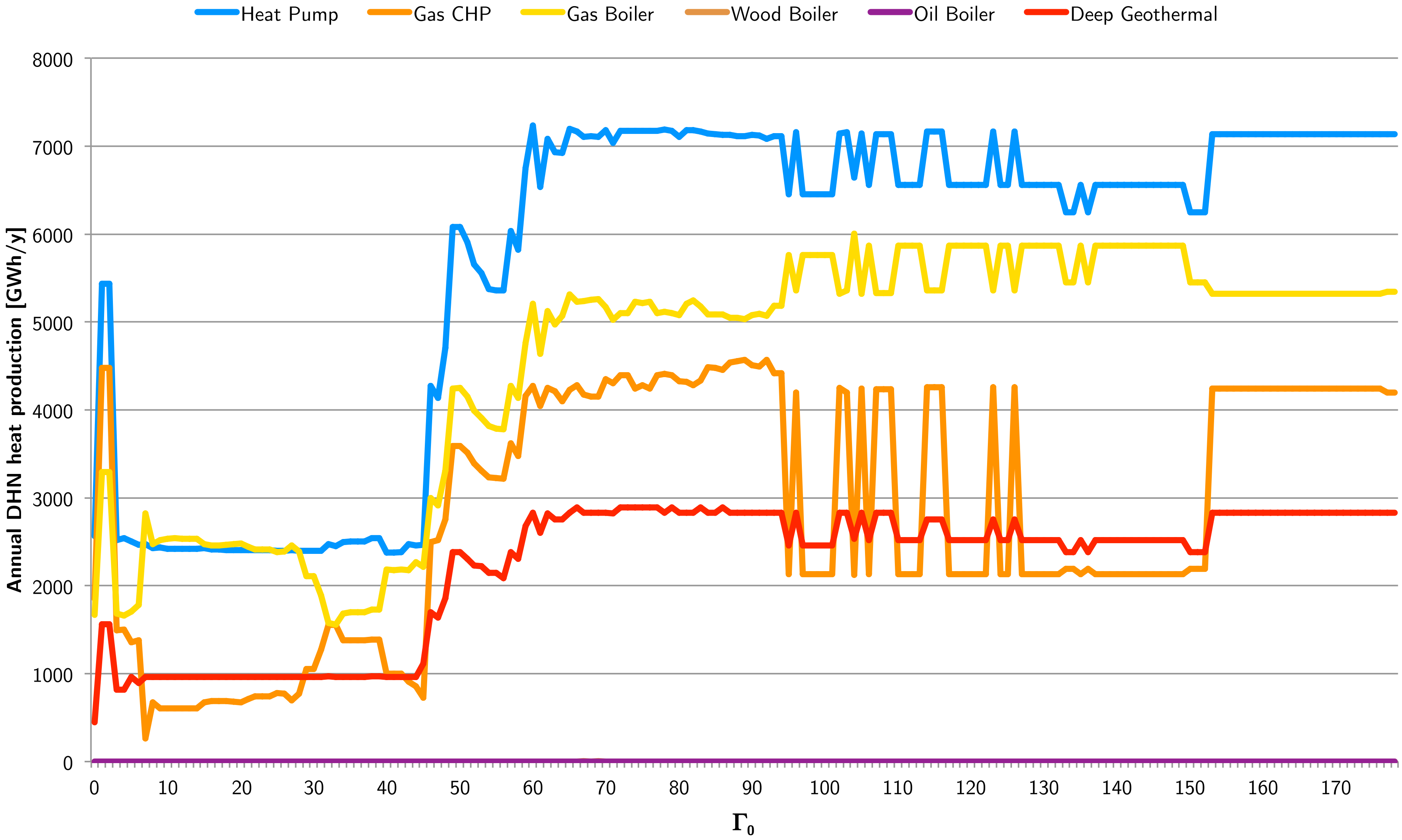
Results

Robust optimization: first results



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)

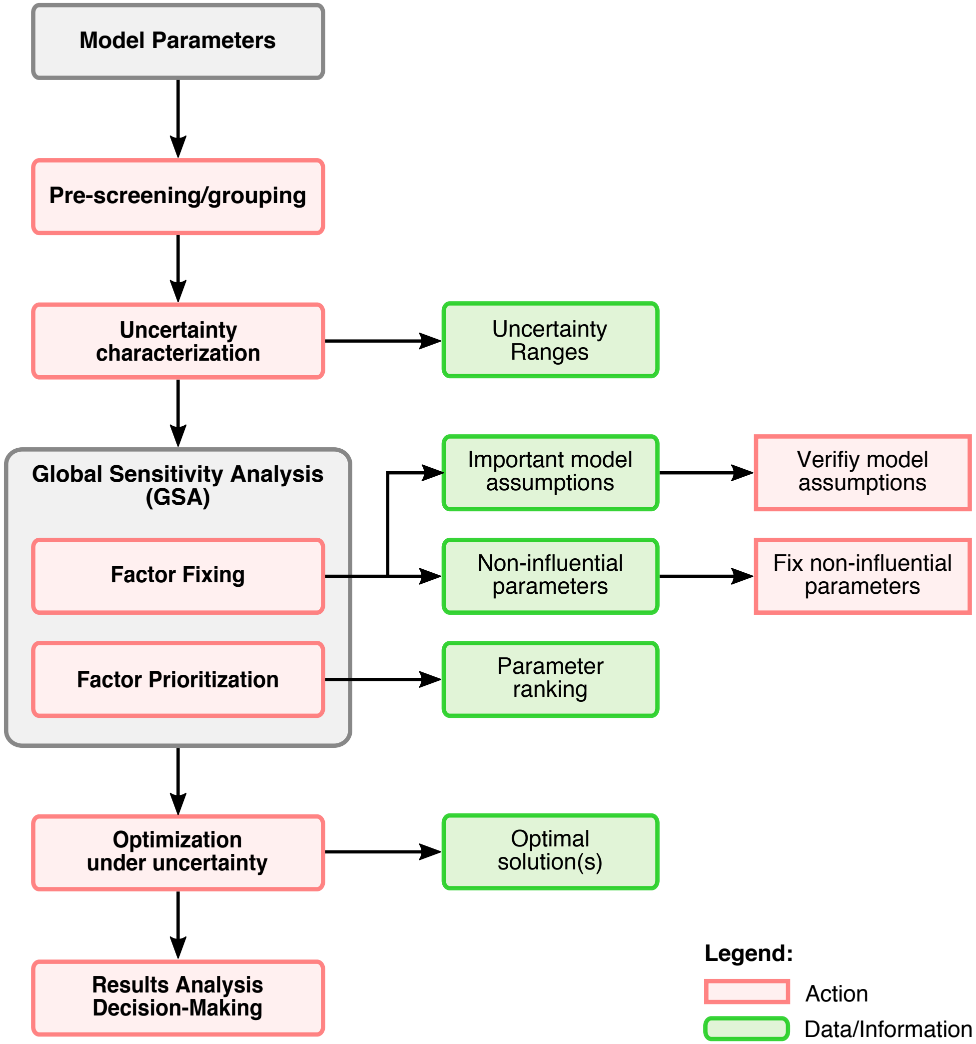
Application to case study → preliminary results:

- Global Sensitivity Analysis
- Robust optimization

Impact of uncertainty on energy strategy

Conclusions

Future work



Model Parameters

Pre-screening/grouping

Uncertainty characterization

Uncertainty Ranges

Global Sensitivity Analysis (GSA)

Factor Fixing

Factor Prioritization

Important model assumptions

Verifiy model assumptions

Non-influential parameters

Fix non-influential parameters

Parameter ranking

Optimization under uncertainty

Optimal solution(s)

Results Analysis Decision-Making

Legend:

🟥 Action

🟩 Data/Information

IPESE
INDUSTRIAL PROCESS AND
ENERGY SYSTEMS ENGINEERING

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FÉDÉRALE DE LAUSANNE

Thank you! Questions?

Stefano Moret
Industrial Process and Energy Systems Engineering (IPESE)
École Polytechnique Fédérale de Lausanne

stefano.moret@epfl.ch

ESCAPE 26
European Symposium on Computer Aided Process Engineering

Appendix

MILP model

Model structure: parameters

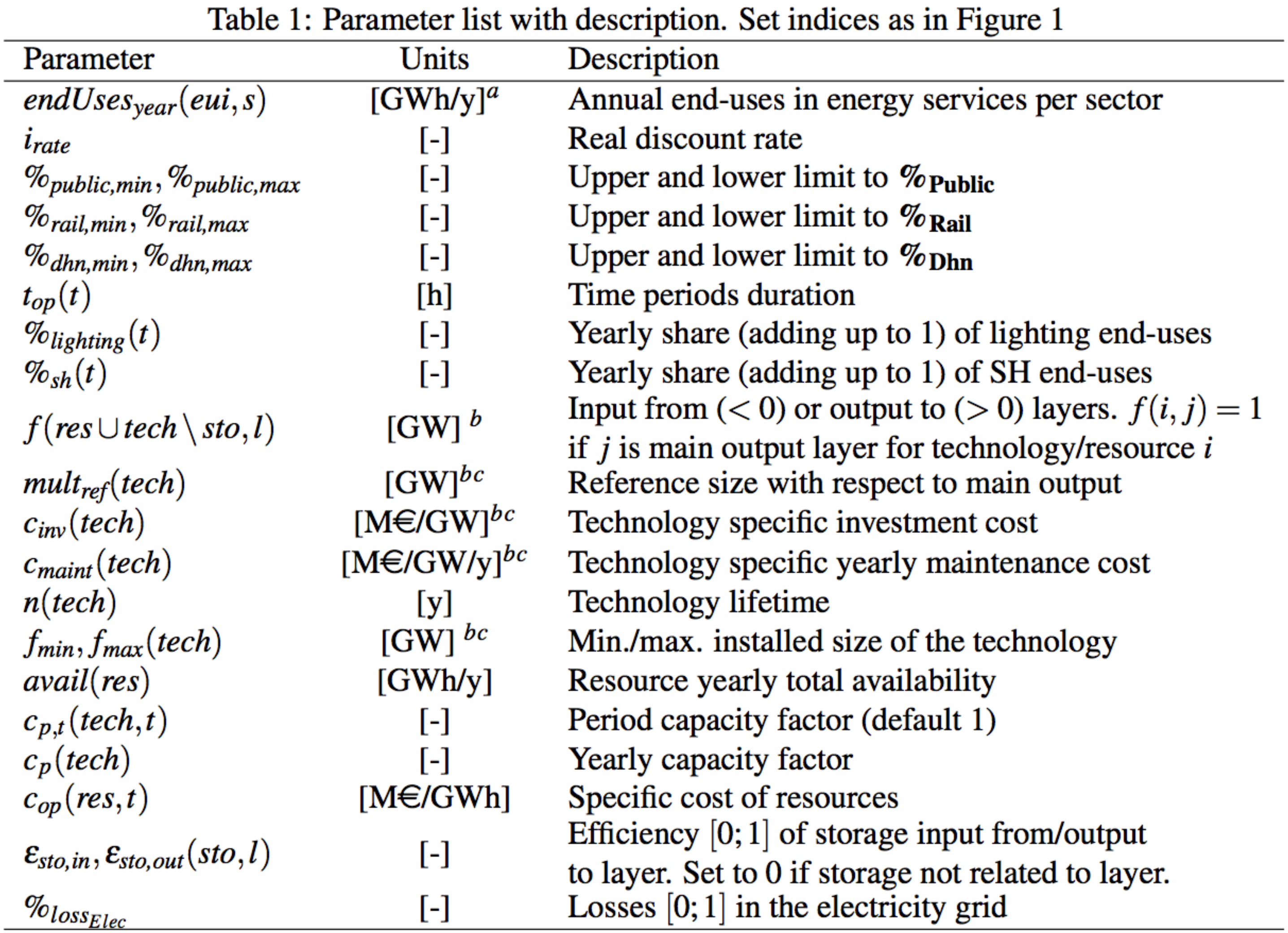


Table 1: Parameter list with description. Set indices as in Figure 1

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

MILP model

Model structure: variables

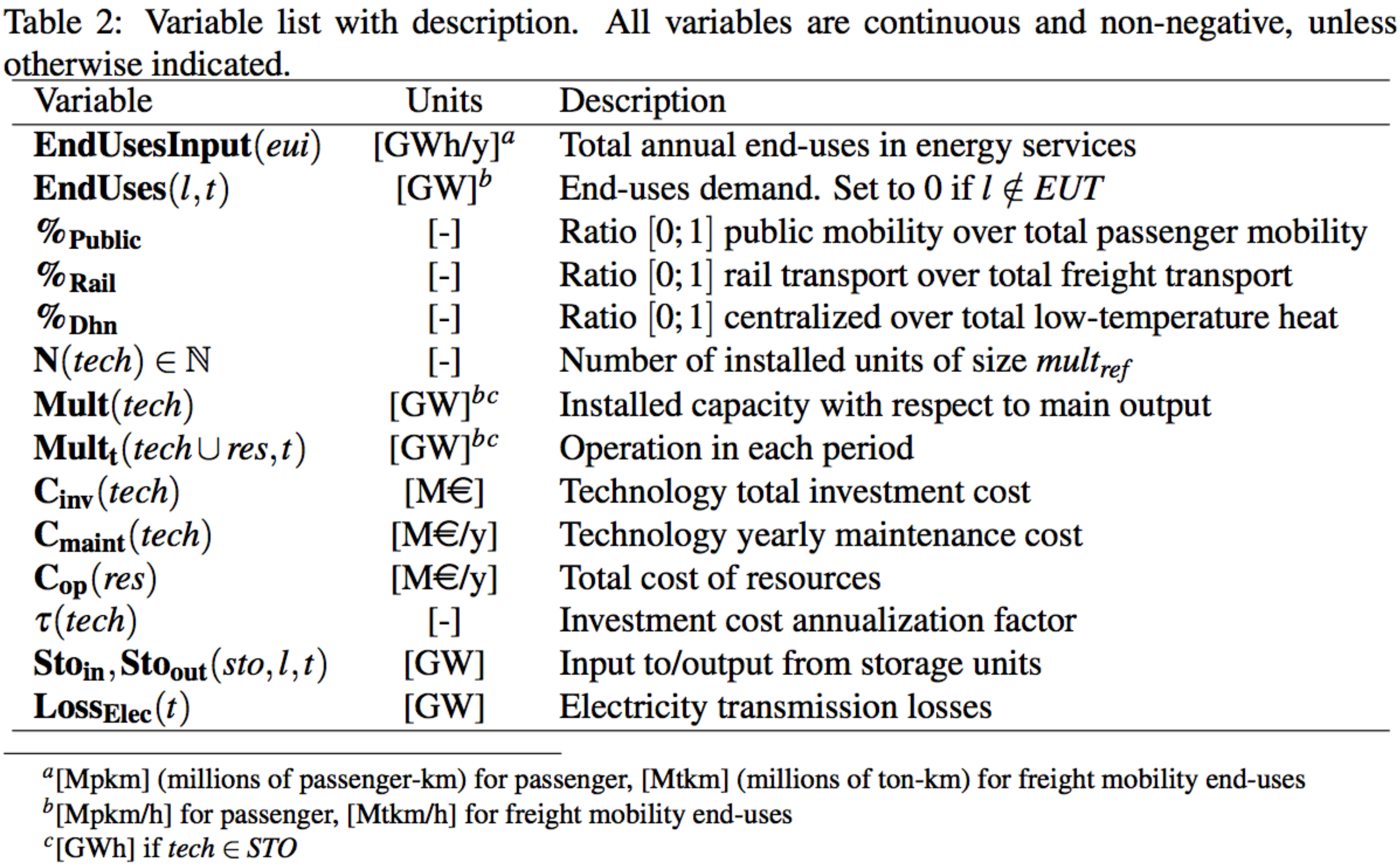


Table 2: Variable list with description. All variables are continuous and non-negative, unless otherwise indicated.

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

---

[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 $tech \in STO$

MILP model

Model structure: constraints

$$\mathbf{Loss_{Elec}}(t) = \left(\mathbf{EndUses}(k) - \sum_{j \in TECH \setminus STO | f(j,k)<0} f(j,k)\mathbf{Mult_t}(j,t)\right)\%_{loss_{Elec}} \qquad k = Elec, \forall t \in T \quad (16)$$

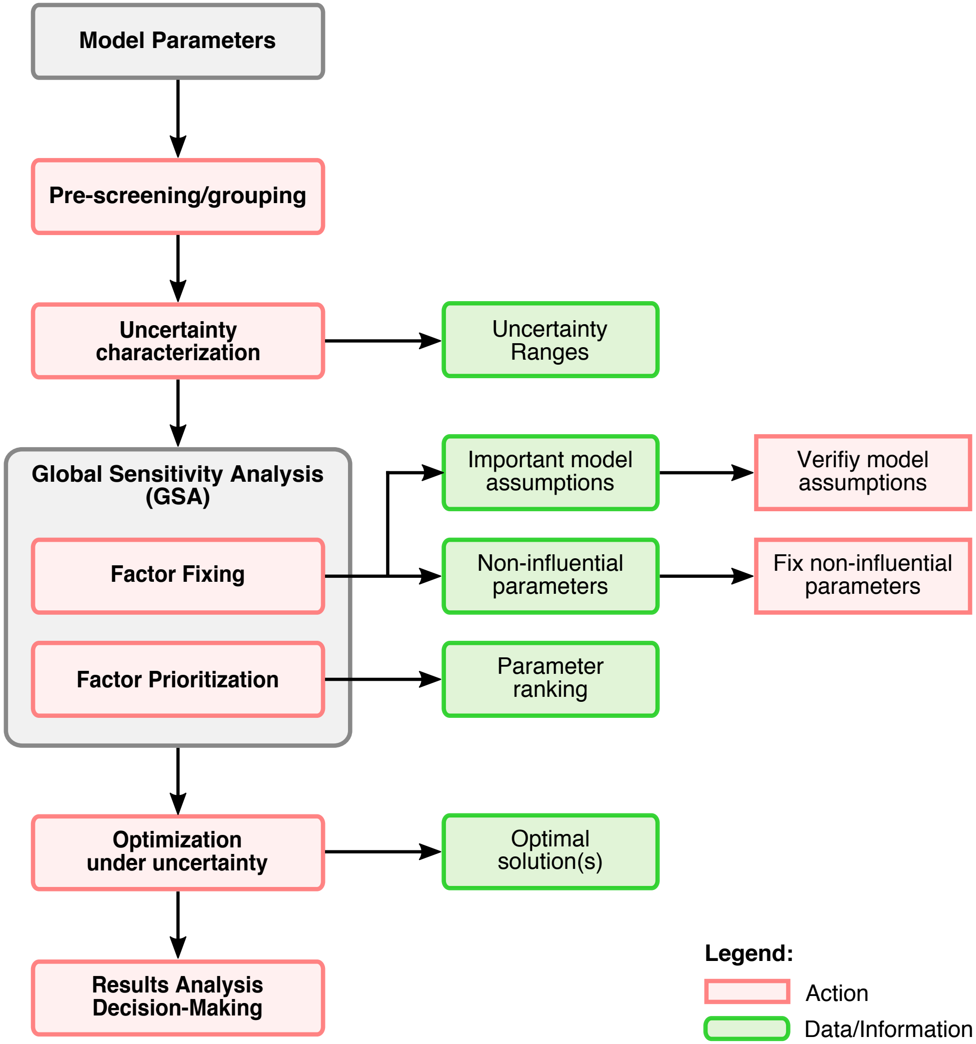
$$\mathbf{Mult_t}(j,t) + \mathbf{Mult_t}(k,t) \geq$$

$$\frac{\mathbf{EndUses}(HeatLowTDHN,t) + \mathbf{EndUses}(HeatLowTDec,t)}{\mathbf{EndUsesInput}(HeatLowTSH) + \mathbf{EndUsesInput}(HeatLowTHW)} \sum_{t \in T} \mathbf{Mult_t}(j,t) t_{op}(t)$$

$$k = Dec_{Solar}, \forall j \in TECH\ OF\ EUT(HeatLowTDec) \setminus \{k\}, \forall t \in T \quad (17)$$

Results

Global Sensitivity Analysis: First results



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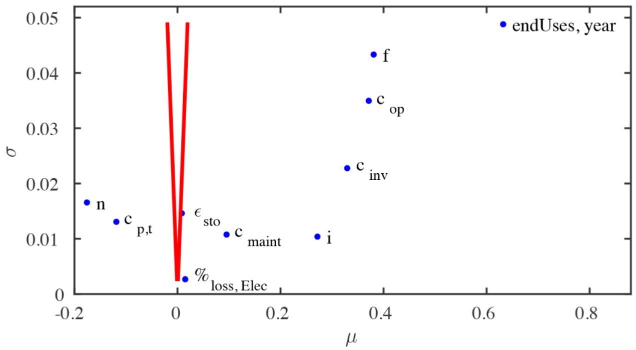

- Morris method for factor fixing.
- ± 20 % variation for all the parameters.
- Parameters outside the V are influential