Robust optimization for strategic energy planning

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OUTLINE

Robust optimization for strategic energy planning

- Introduction & Literature Review
- The optimization model
- Uncertainty classification
- Robust optimization
- Post-sensitivity
- Conclusions & Next Steps

INTRODUCTION
Outline

The energy transition

Energy systems forecasting and uncertainty

Literature review

Goals & Approach

INTRODUCTION
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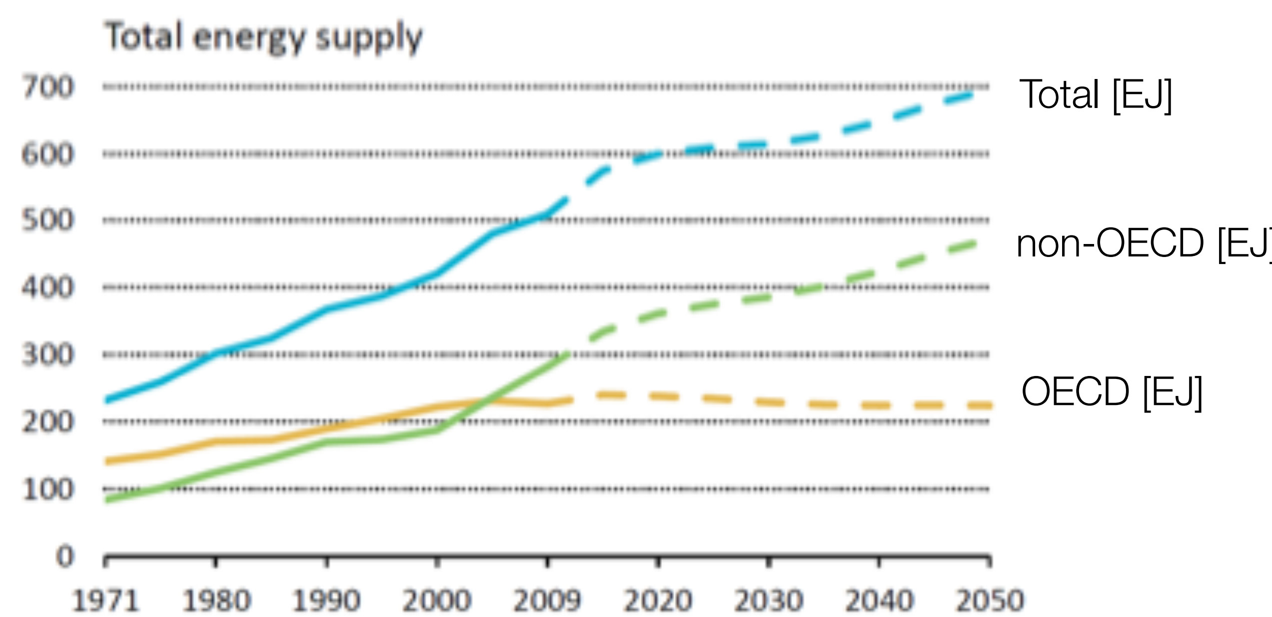
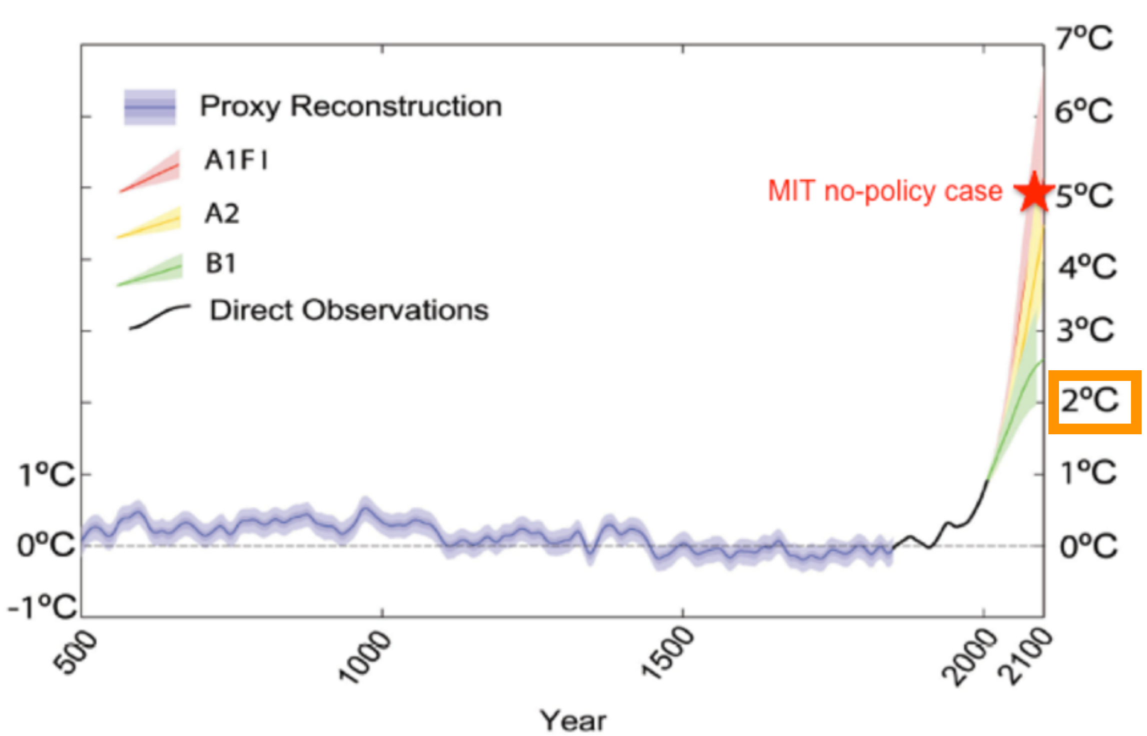
INTRODUCTION
The energy transition

Sources:
- Copenhagen Diagnosis 2009, with MIT data taken from Sokolov et al. 2009.
- Jonathan Koomey, “Energy and society” lecture notes, UC Berkeley 2011
- IPCC 2013 report, Climate change 2013 - The physical science basis
- IEA, ETP 2012

Growing trend in energy consumption, mainly from non-OECD countries

CO_2 Emissions 2050 = **2x** emissions today





IPCC 2013: climate has changed due to human activities

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

Challenge: **4x** emissions reduction by:
- efficiency
- renewables
- technologies

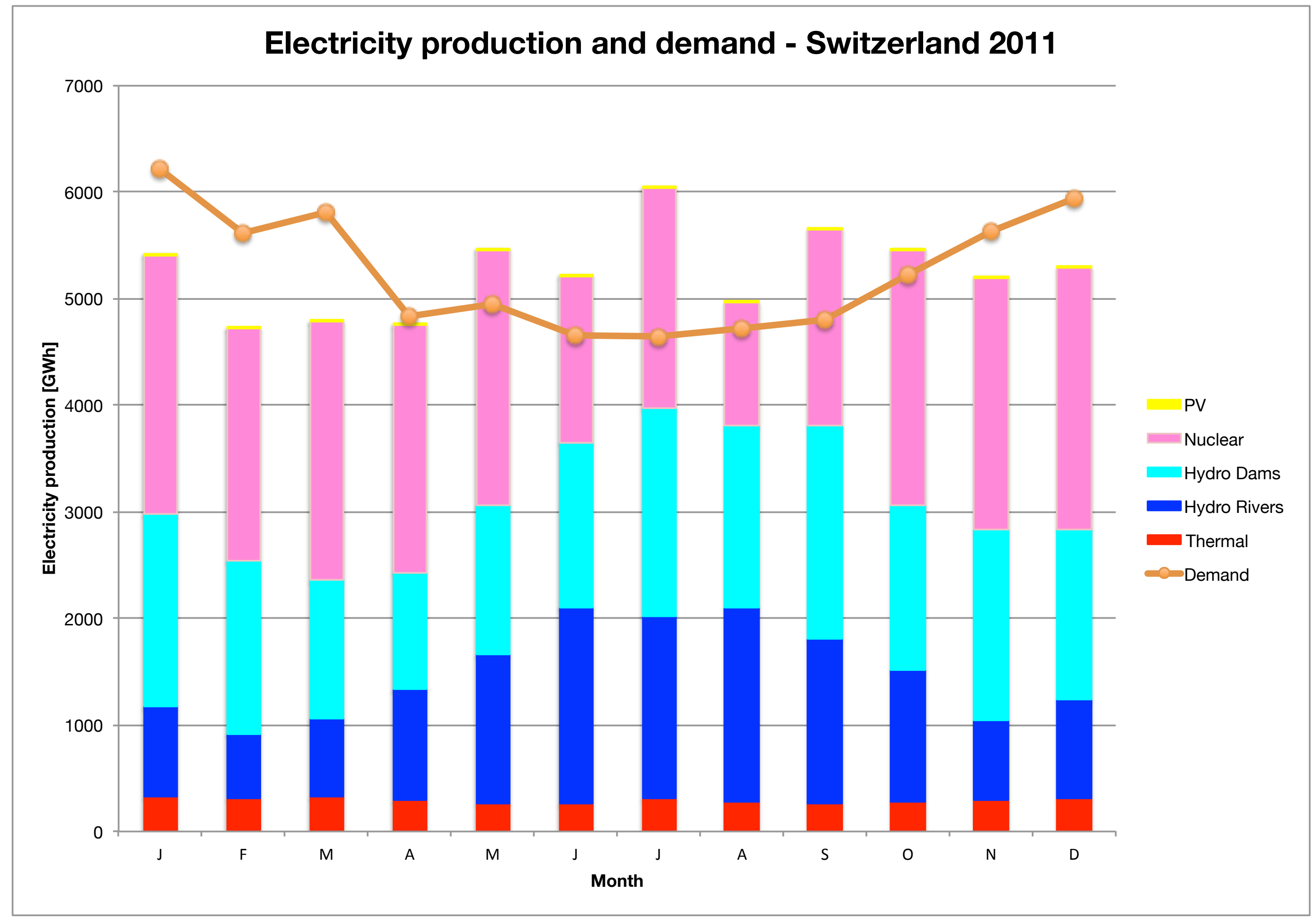
Sources:
- SFOE, Swiss electricity statistics 2011
- SFOE, Energy strategy 2050 explanatory document

INTRODUCTION
The energy transition

Various countries taking strategic decisions about their energy future

March 11th, 2011

Fukushima nuclear disaster



2034: Phase-out of nuclear power plants

Strategic decisions for the energy future!

Sources:
- SFOE, Swiss electricity statistics 2011
- SFOE, Energy strategy 2050 explanatory document

INTRODUCTION
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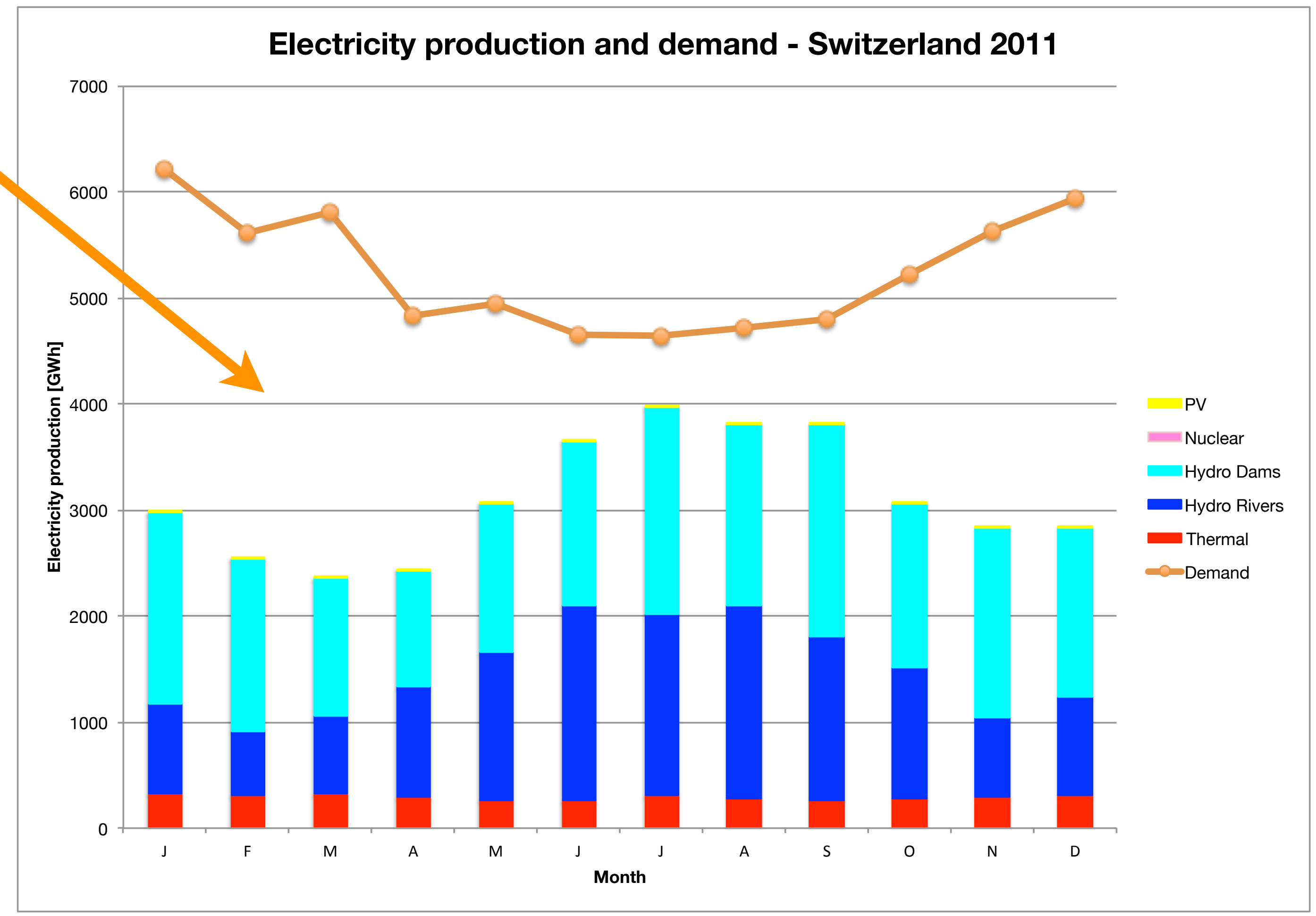
Various countries taking strategic decisions about their energy future

How to fill the gap?

March 11th, 2011

Fukushima nuclear disaster



2034: Phase-out of nuclear power plants

Strategic decisions for the energy future!

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- IEA, ETP 2012
- James S. Hodges and James A. Dewar. Is it you or your model talking? a framework for model validation. 1992
- J. Koomey et al. Improving long-range energy modeling: A plea for historical retrospectives. 2003.

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 innovative (efficient) technologies

Overcapacity when forecasts are wrong

> 80% of primary energy consumption

Standard approach: deterministic modelling of energy systems over time. But…

- energy models are "**non-validatable**", i.e. doomed to inaccuracy
- backcasting: models have missed pivotal events

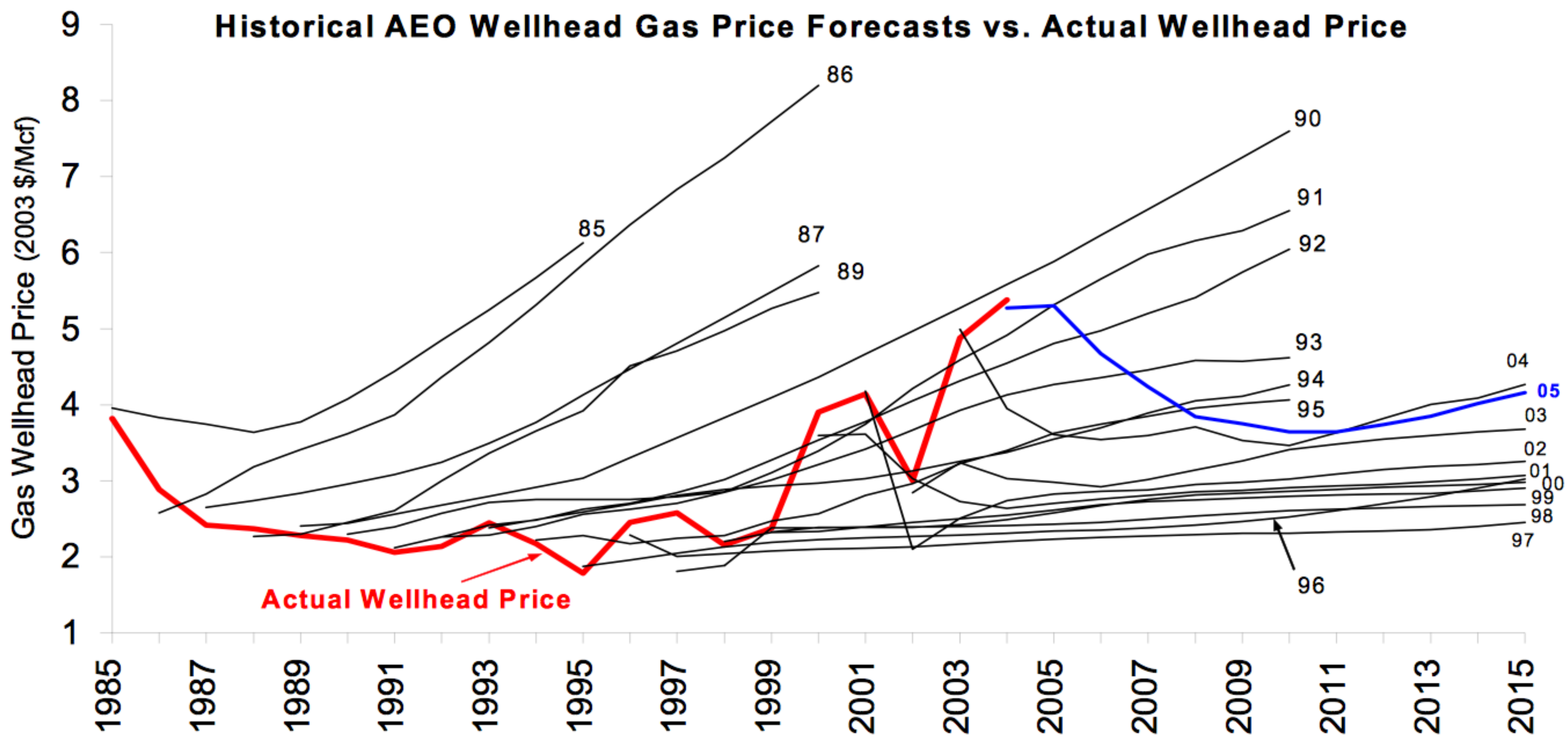
It's most likely vane to hope that a huge modelling effort will make us able to "know" the future!

Sources:
- Chris Marnay and Afzal S. Siddiqui. Addressing an uncertain future using scenario analysis. 2006
- U.S. EIA - Energy Information Administration. Natural gas data.

INTRODUCTION

Energy forecasting: learning from the past

Fossil fuel prices forecasting models are subject to very relevant errors..



Intro & Literature | Model | Uncertainty Classification | Robust Optimization | Post-sensitvity | Conclusions

Sources:
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- U.S. EIA - Energy Information Administration. Natural gas data.
- oregonstate.edu: conversion factors for 2003 $ table

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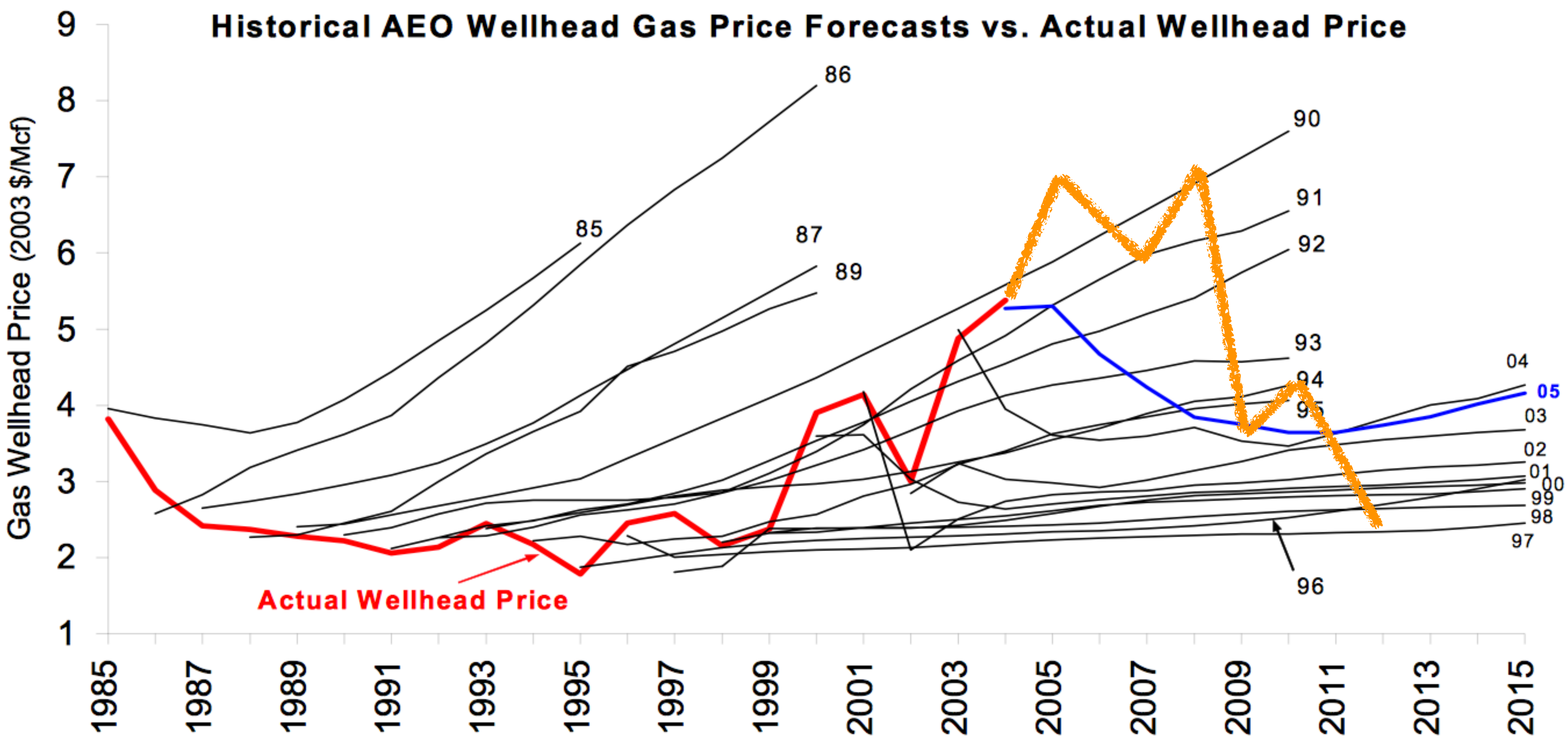

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Sources:
- Eurelectric report 2011
- TERNA - Dati statistici sull'energia elettrica in Italia - anno 2011
- Paul Krugman. Gambling with civilization. *The New York Review of Books*, November 2013.
- William D. Nordhaus. The allocation of energy resources. *Brookings Papers on Economic Activity*, 1973.
- De Volkskrant, 6.2.2014

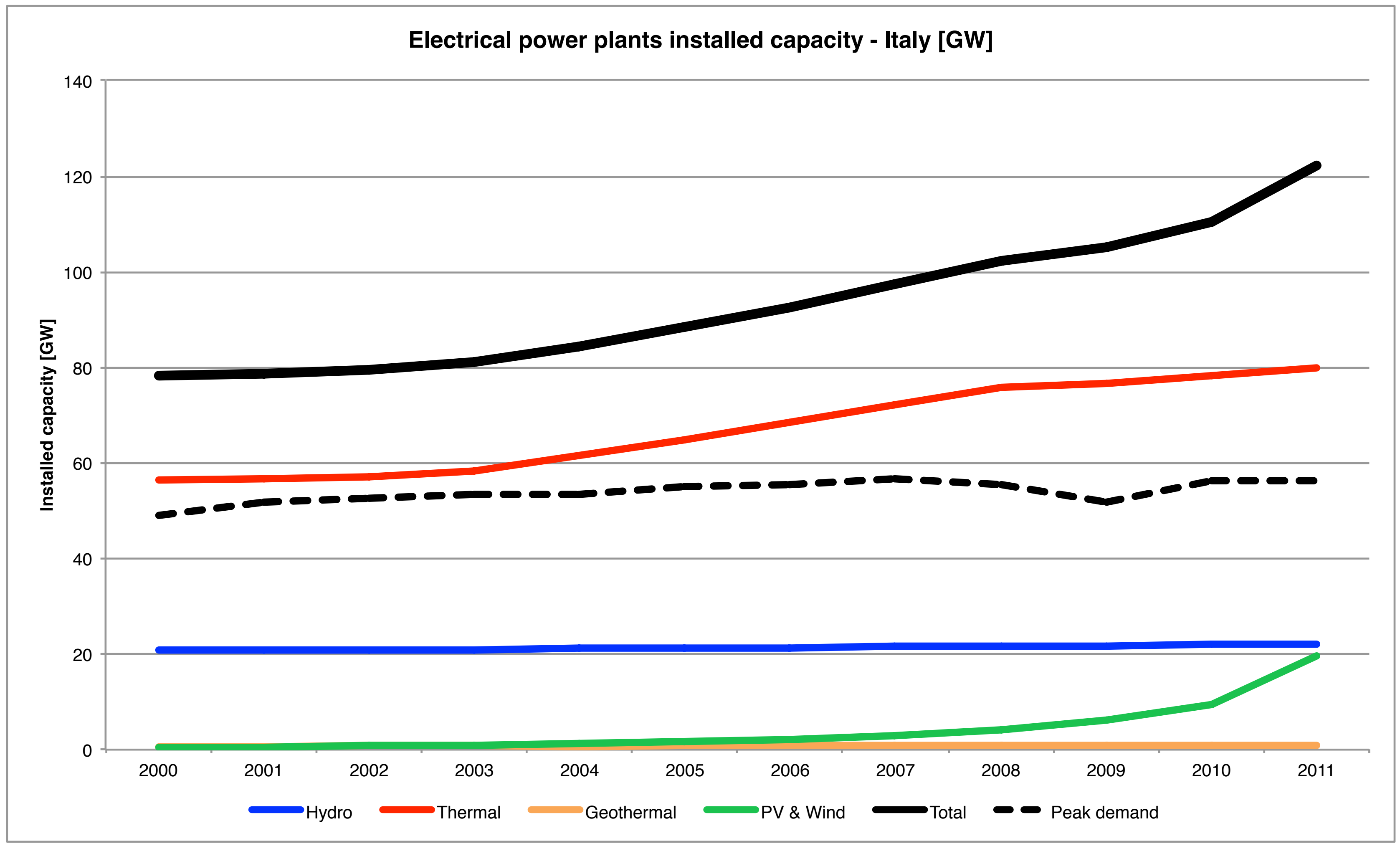
INTRODUCTION

Energy forecasting: learning from the past

What is the effect of decisions taken based on this approach?

- **60%** electricity production overcapacity in EU-27 (2010)
- Overcapacity in Italy: CCGT plants used on average 2500-3000 h/year (2011)
- 5 CCGT plants never used in NL

Overcapacity implies cost!



Sources:

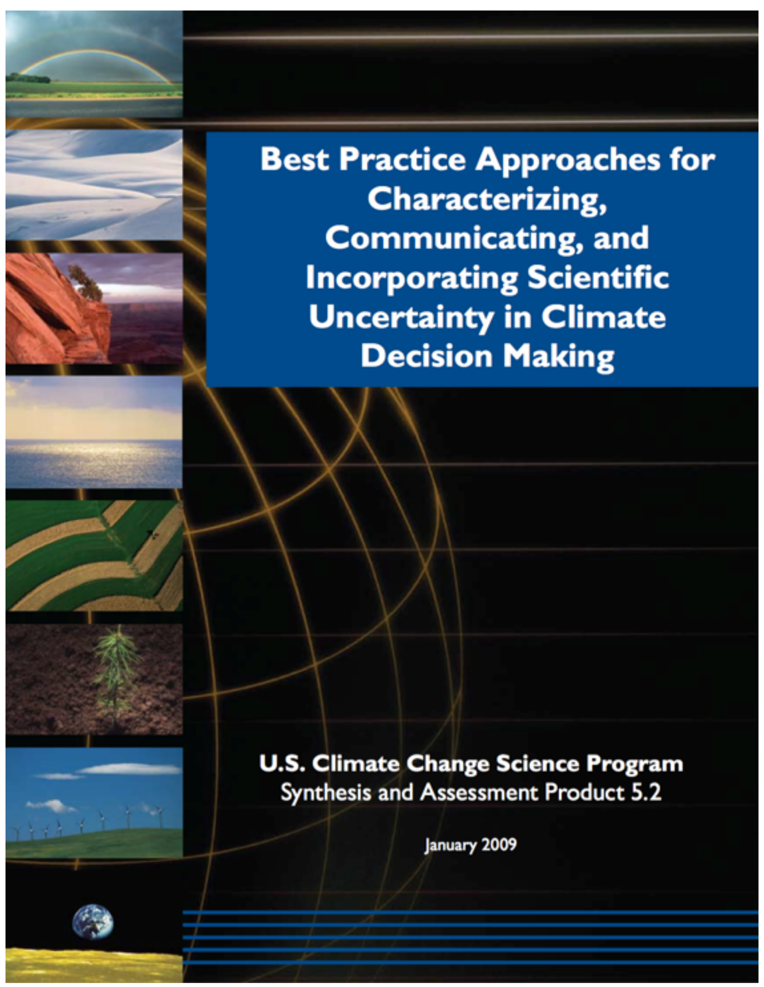
- Ines Azevedo. The need to account for uncertainty in forecasting, 2013
- Richard de Neufville. Flexibility in systems planning and design, 2013
- M. Granger Morgan. CCSP, 2009: Best practice approaches for characterizing, communicating and incorporating scientific uncertainty in climate decision making. 2009

INTRODUCTION

The need of taking uncertainty into account

CRAG Conference (EPFL, 2013):

- Need of taking into account uncertainty in energy forecasting (Azevedo)
- flexible design, taking into account uncertainty, can lead to higher expected values (De Neufville)



Key guidelines (Granger-Morgan):

- Uncertainty can be irreducible
- Probability is the language of uncertainty
- Not all quantities can be associated with a PDF
- Sometimes scenario analysis needs to be performed

Need of rigorous classification!

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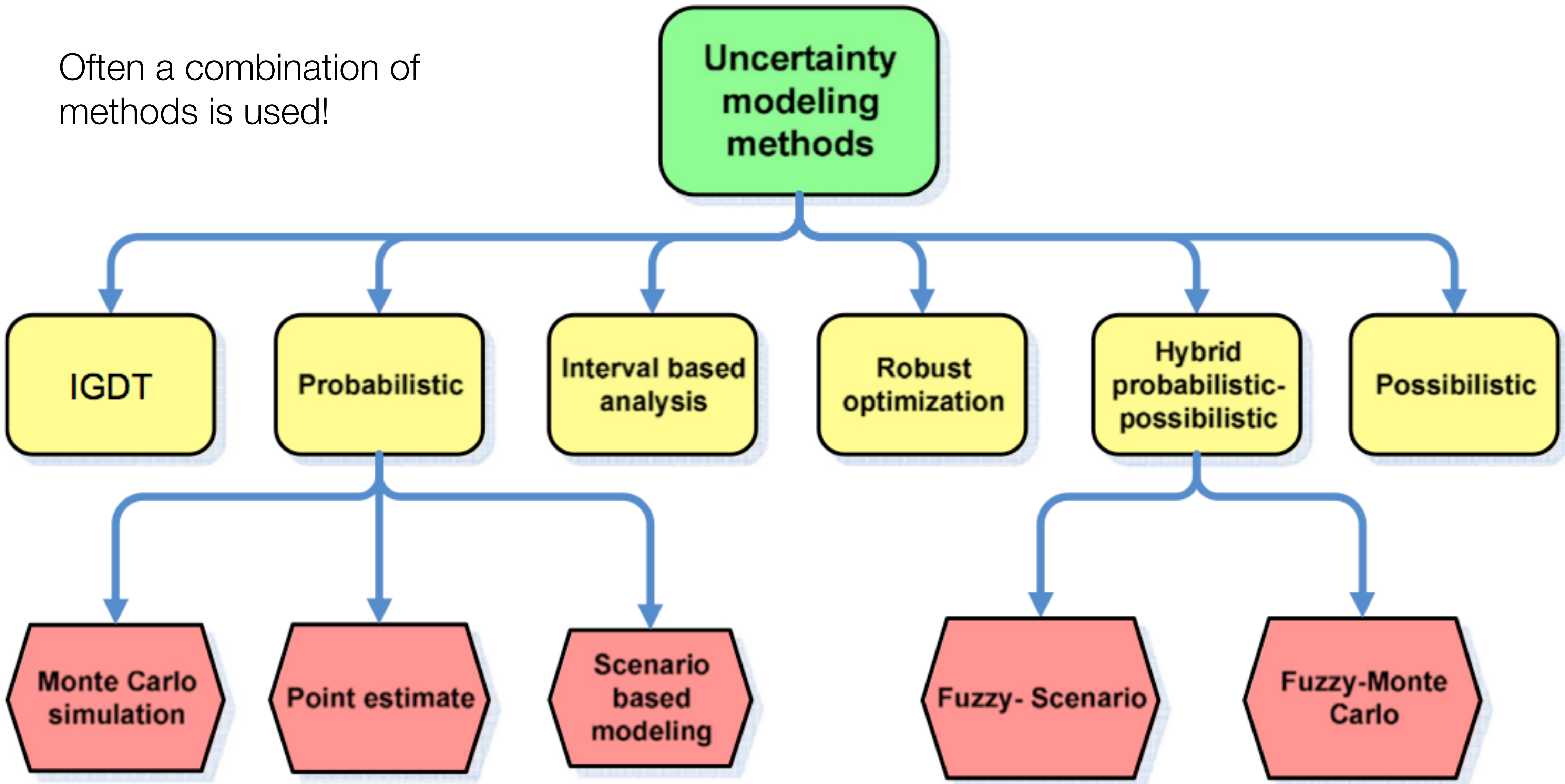
Sources:
- Alireza Soroudi and Turaj Amraee. Decision making under uncertainty in energy systems: State of the art. 2013

INTRODUCTION
Literature review

Robust optimisation: I can't define a PDF for my parameters, but a range of variation (worst-case)

Key applications: PHEV, renewables operations, electricity markets, electricity transmission/generation

Often a combination of methods is used!

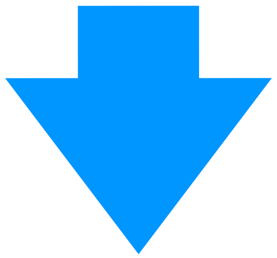


- Alireza Soroudi and Turaj Amraee. Decision making under uncertainty in energy systems: State of the art. 2013
- Chris Marnay and Afzal S. Siddiqui. Addressing an uncertain future using scenario analysis. 2006
- M. Granger Morgan. CCSP, 2009: Best practice approaches for characterizing, communicating and incorporating scientific uncertainty in climate decision making. 2009
- Matthias Dubuis and François Maréchal. *Energy system design under uncertainty*. 2012.
- E. Loeken et al. Decision analysis and uncertainties in planning local energy systems. 2006

INTRODUCTION

Literature review: uncertainty classification

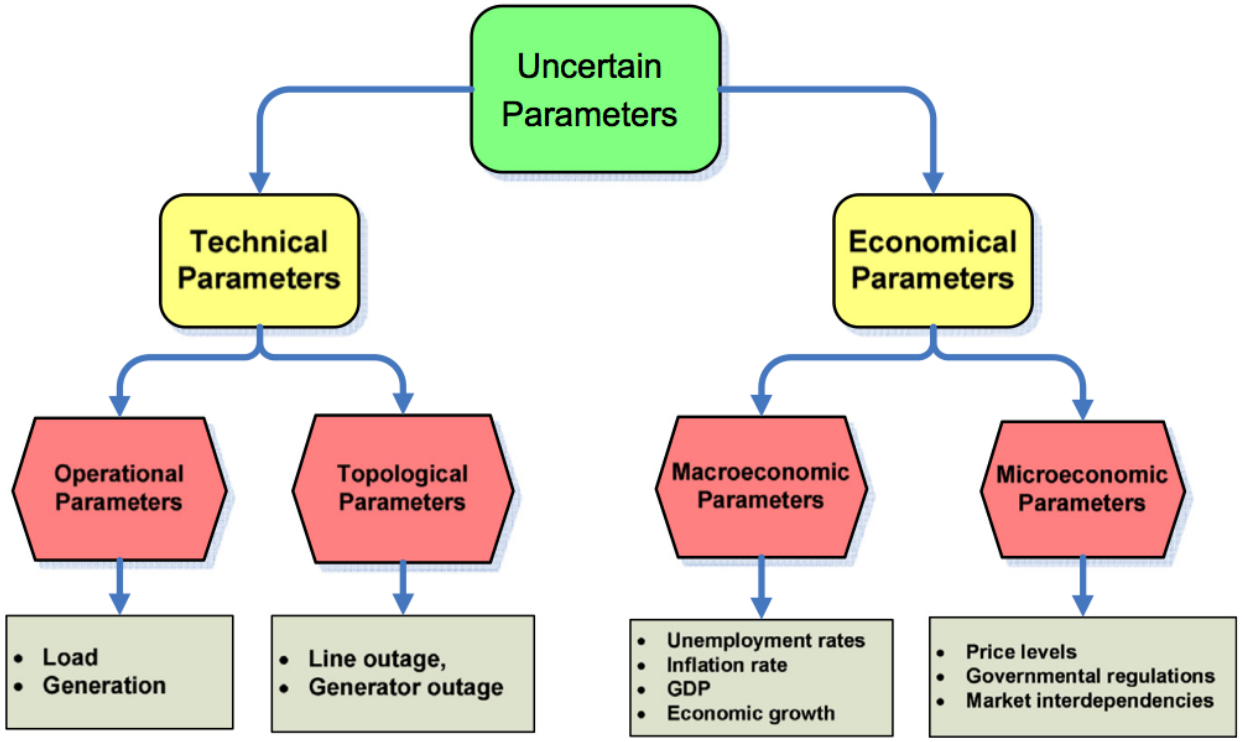
"An expected kWh output from a wind generator in a future year, which is not exposed to volatile and unpredictable fuel prices, should be truly worth more than an equivalent kWh from an alternative fossil fuel fired technology"



Uncertainty classification by type and degree

Key contributions:

- Generic classification of uncertainty (technical vs economic) (Soroudi)
- Internal VS External uncertainties (physical, economic, regulatory) (Loeken)
- Process design uncertainties (Dubuis)



INTRODUCTION
Literature review

Some models have been extended to include uncertainties. Nonetheless (Marnay):

- The formalism of stochastic models sometimes hides very poor knowledge of distribution parameters
- Uncertainty might overcome the complexities of the models themselves

Key conclusion: Need of acknowledging uncertainty of the future!

Key gaps in research:

- **Uncertainty classification**: Rigorous classification missing, by type and degree.
- **Methods**: Various methods, often used in combination. No clear methodology defined.
- **Energy systems applications**: Most methods limited to single applications, or max. electricity market. Need of holistic view of the energy system (heating/cogeneration and transportation), electricity is only a part of the picture.

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INTRODUCTION
Goals & Approach

Renewables and/or innovative (efficient) technologies

Lower resources consumption

Lower emissions

Higher investment costs

How does taking uncertainty into account influence strategic energy planning?

Key **goals**:

- Preliminary classification of uncertainty
- Robust optimisation for typical energy planning MILP
- Preliminary conclusions -> future work guidelines

MILP development & tuning

↓

Uncertainty Classification (Pre-Sensitivity)

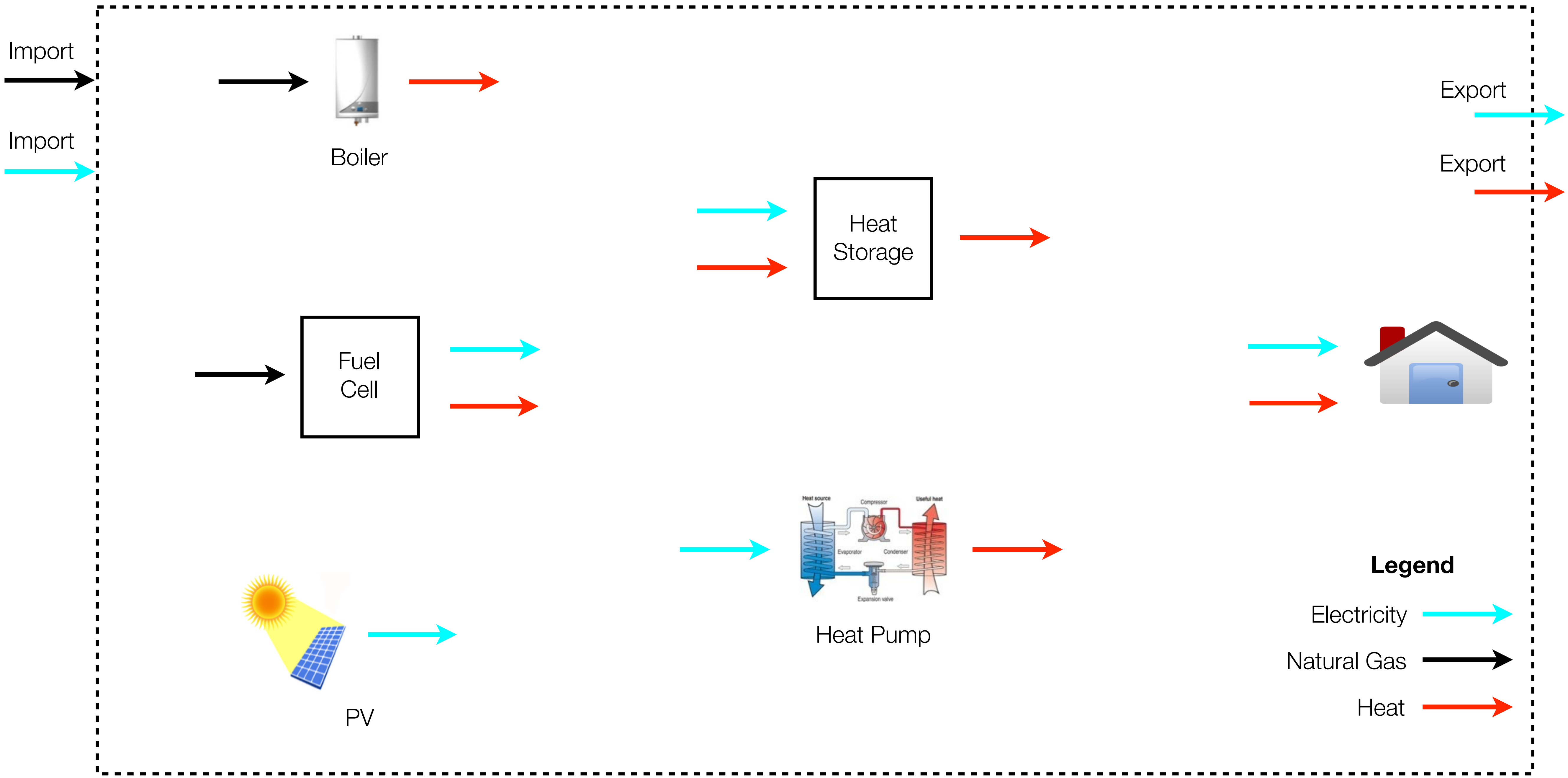
↓

Robust optimisation

↓

Post-Sensitivity analysis

OPTIMIZATION MODEL
Model description



OPTIMIZATION MODEL
Model description

Key features:

- Typical, simplified MILP for energy planning: household -> urban/national scale
- Electricity and Heating yearly demand for SFH in Switzerland (SIA 380/1 compliant)
- multi-period problem: 12 times (monthly averages) + 1 peak period (sizing)
- Simplifying assumptions: day/night electricity balance managed by the grid
- Default average prices: 0.18 CHF/kWh_e, 0.097 CHF/kWh_{NG} (Switzerland)

Technology	Efficiency (total) [-]	Efficiency (electrical) [-]	Efficiency (thermal) [-]	Standard size	C_inv
Boiler	0.9	-	0.9	10 kW_th	4206
Fuel Cell	0.9	0.55	0.35	3 kW_e	20000
Storage	1	-	-	10 m^3	1500 (centr.)
PV	0.15	0.15	-	3 kW_e	10500
Heat Pump	4	-	4	10 kW_th	14167

OPTIMIZATION MODEL
MILP formulation

Implementation of the problem in the AMPL programming language

Sets

$$\text{UNITS } u = \{1, \ldots, U\} = \{BOIL, FC, STO, PV, HP\}$$
$$\text{TIMES } t = \{1, \ldots, T\} = \{1, \ldots, 13\}$$

Key Variables

$y(u) \in \{0,1\}$: binary variable, investment decision for unit u

$f(u,t)$: multiplication factor for each unit u at time t

$f_{size}(u)$: size of the units

Key Constraints

$$f(u,t) \leq f_{size}(u) \qquad \forall t$$

$$C_{inv}(u) = C_{inv,1}(u) \cdot y(u) + f_{size}(u) \cdot C_{inv,2}(u) \qquad \forall u$$

$$\dot{E}_{buy}(t) + \sum_u \dot{E}_{out}(u,t) - \sum_u \dot{E}_{in}(u,t) - \dot{E}_{demand}(t) \geq 0 \qquad \forall t$$

$$\dot{E}_{buy}(t) + \sum_u \dot{E}_{out}(u,t) - \sum_u \dot{E}_{in}(u,t) - \dot{E}_{demand}(t) - \dot{E}_{sell}(t) = 0 \qquad \forall t$$

Similar equations for Heating

Sources:
- Fourer et al., AMPL: A Modeling Language for Mathematical Programming

OPTIMIZATION MODEL
MILP formulation

Objective Function: **minimize** Total Annual Cost (Annualised Investment + Yearly Operating cost)

Annualisation factor
(i = 5%, n = 20 years)

$$\tau = \frac{i(i+1)^n}{(1+i)^n - 1}$$

Prices of gas and electricity import at *t* [CHF/kWh]

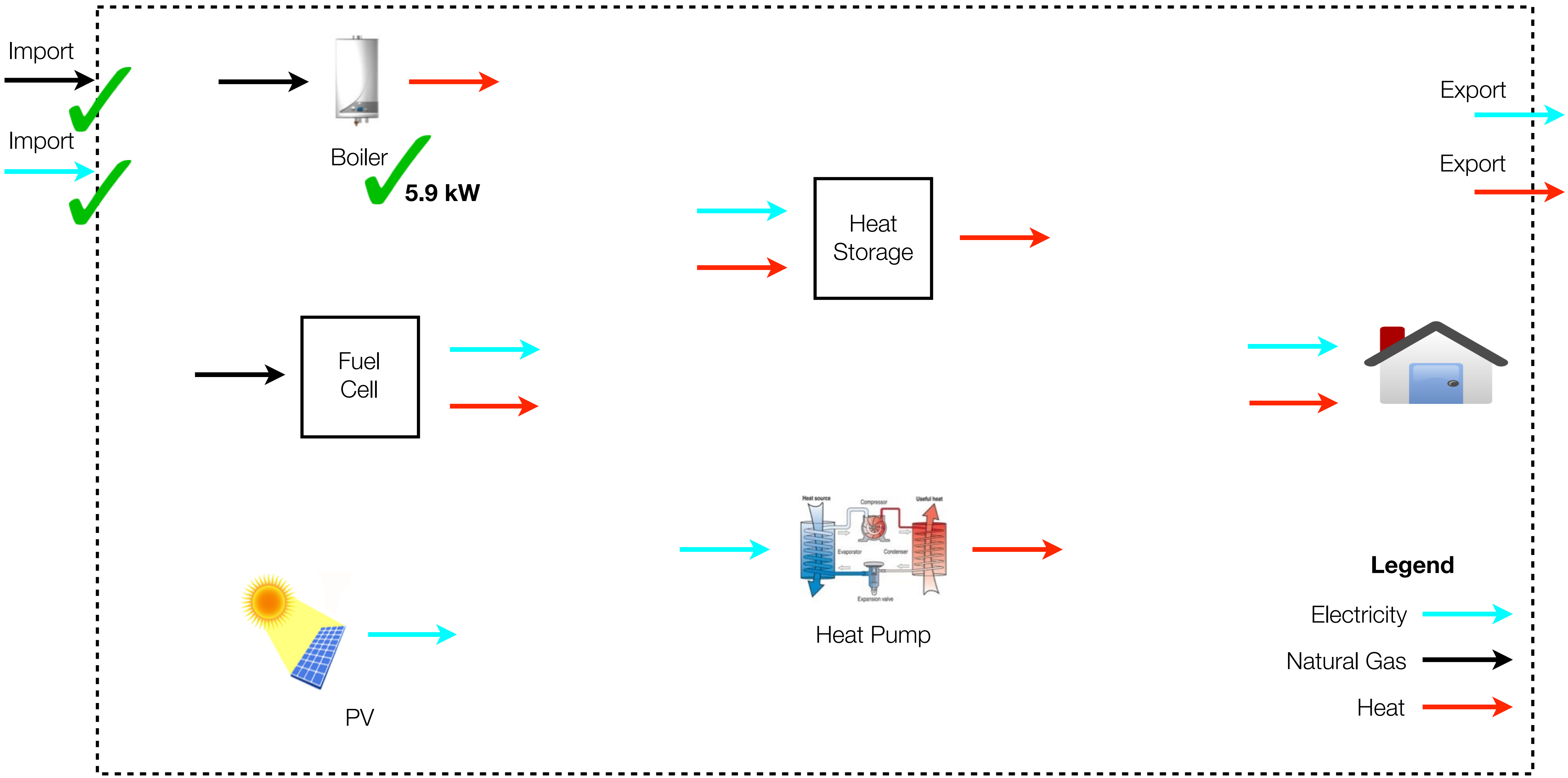
0.4 * $c_{el,buy}$

Operating time [h]

$$\underbrace{(\boxed{\tau}\sum_u C_{inv}(u)}_{\text{Annualised investment}} + \underbrace{\sum_t(\sum_u \boxed{c_{ng}(t)}\dot{Q}_{NG}(u,t) + \boxed{c_{el,buy}(t)}\dot{E}_{buy}(t) - \boxed{p_{el,sell}(t)}\dot{E}_{sell}(t)) \cdot \boxed{t_{op}(t)})}_{\text{Yearly operating cost}}$$

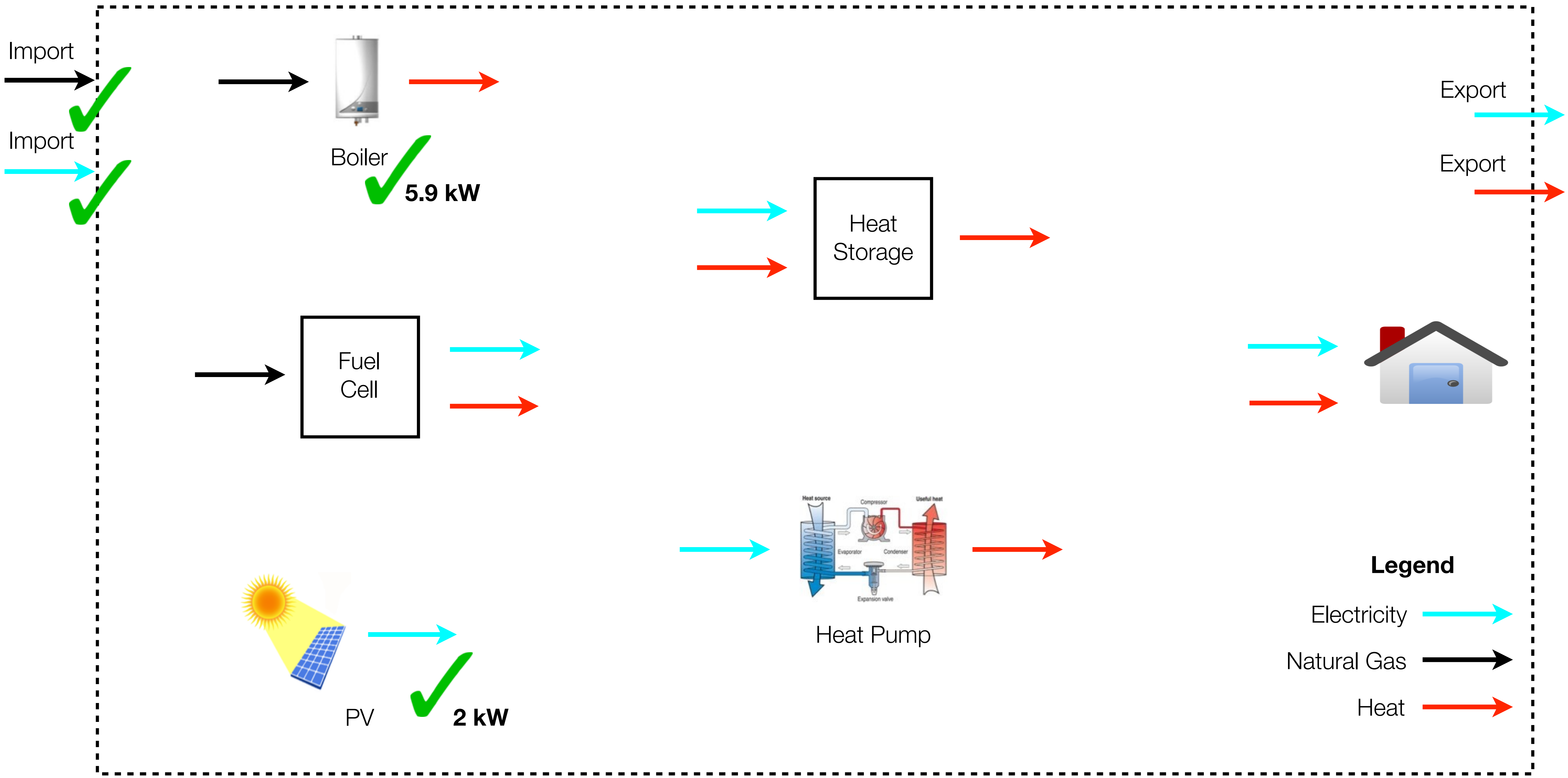
OPTIMIZATION MODEL

Obj = 1813. Case 1: $c_{el,buy}$ default, c_{ng} default



OPTIMIZATION MODEL

Obj = 2186. Case 2: $c_{el,buy}$ high, c_{ng} default



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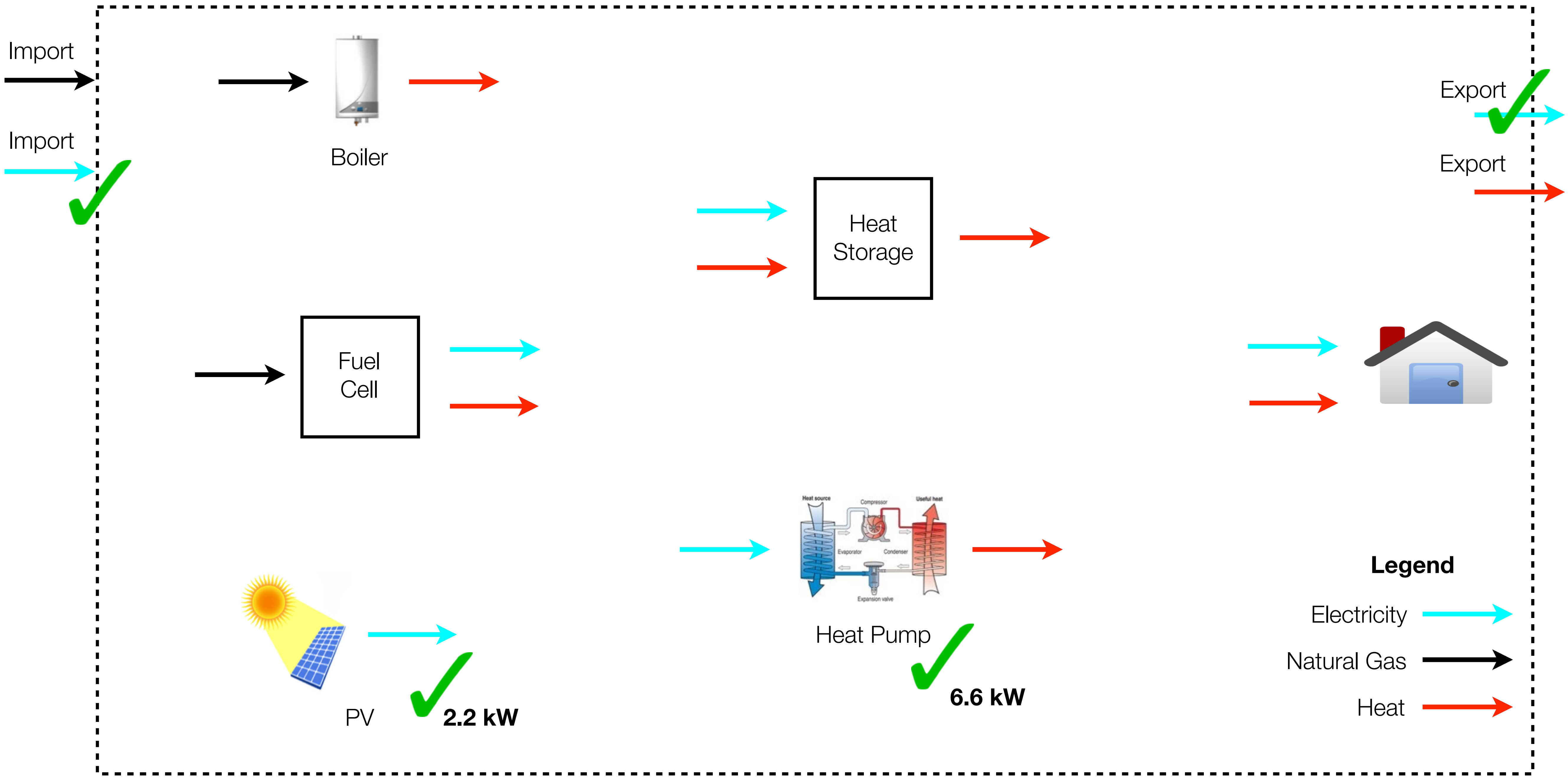
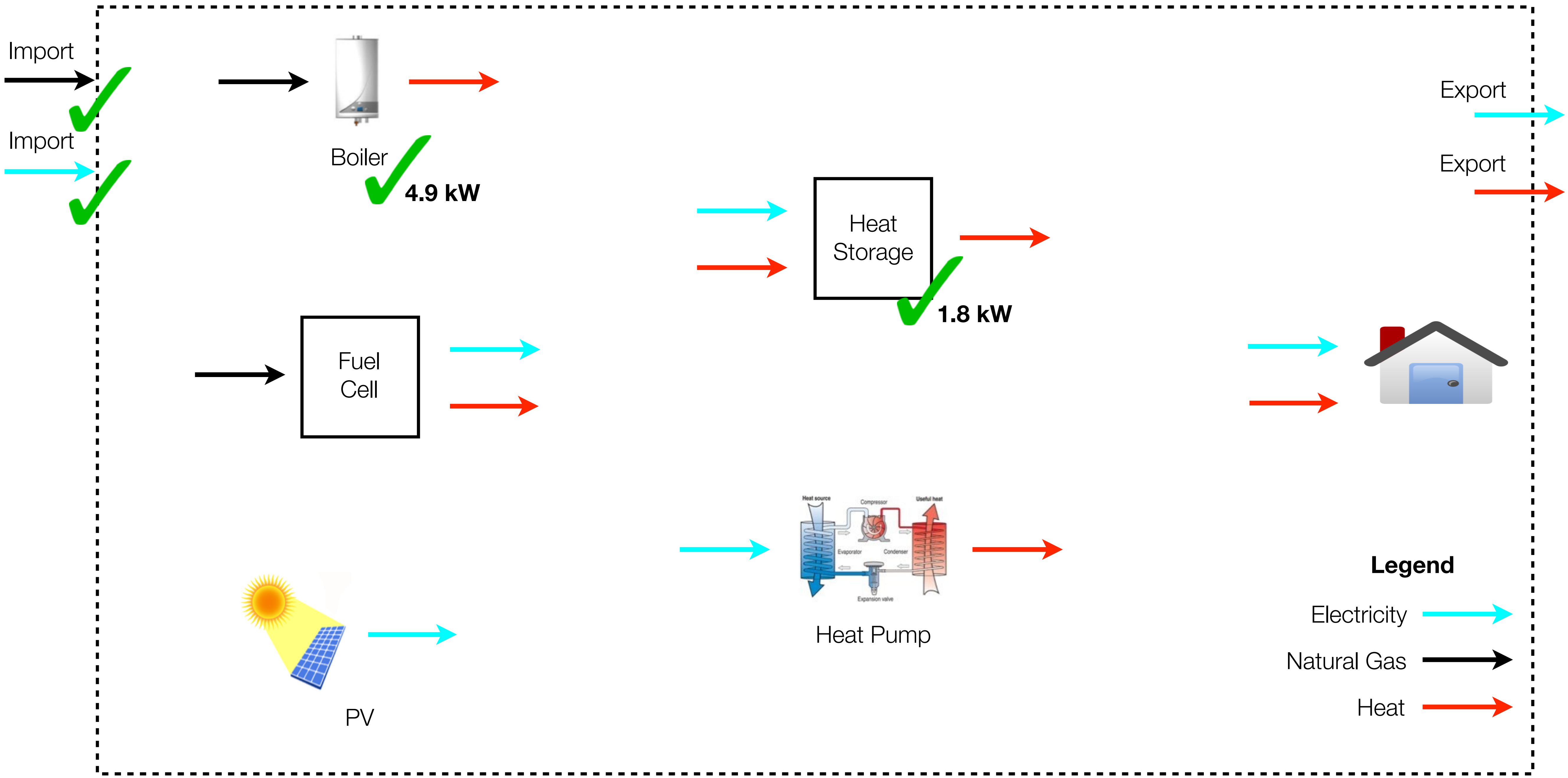
OPTIMIZATION MODEL

Obj = 2689. Case 3: $c_{el,buy}$ high, c_{ng} high



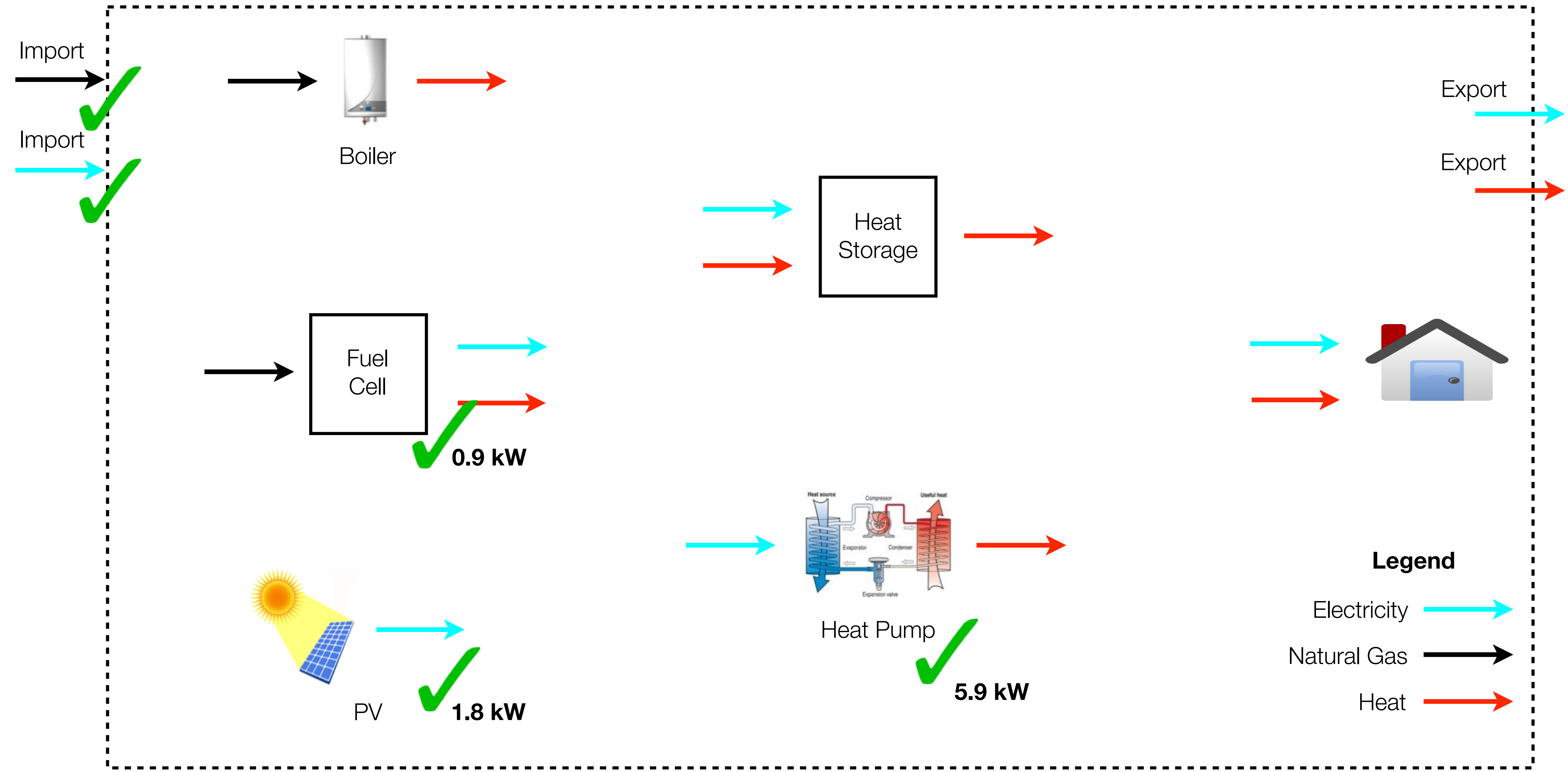
OPTIMIZATION MODEL

Obj = 1653. Case 4: $c_{el,buy}$ default, c_{ng} oscillating



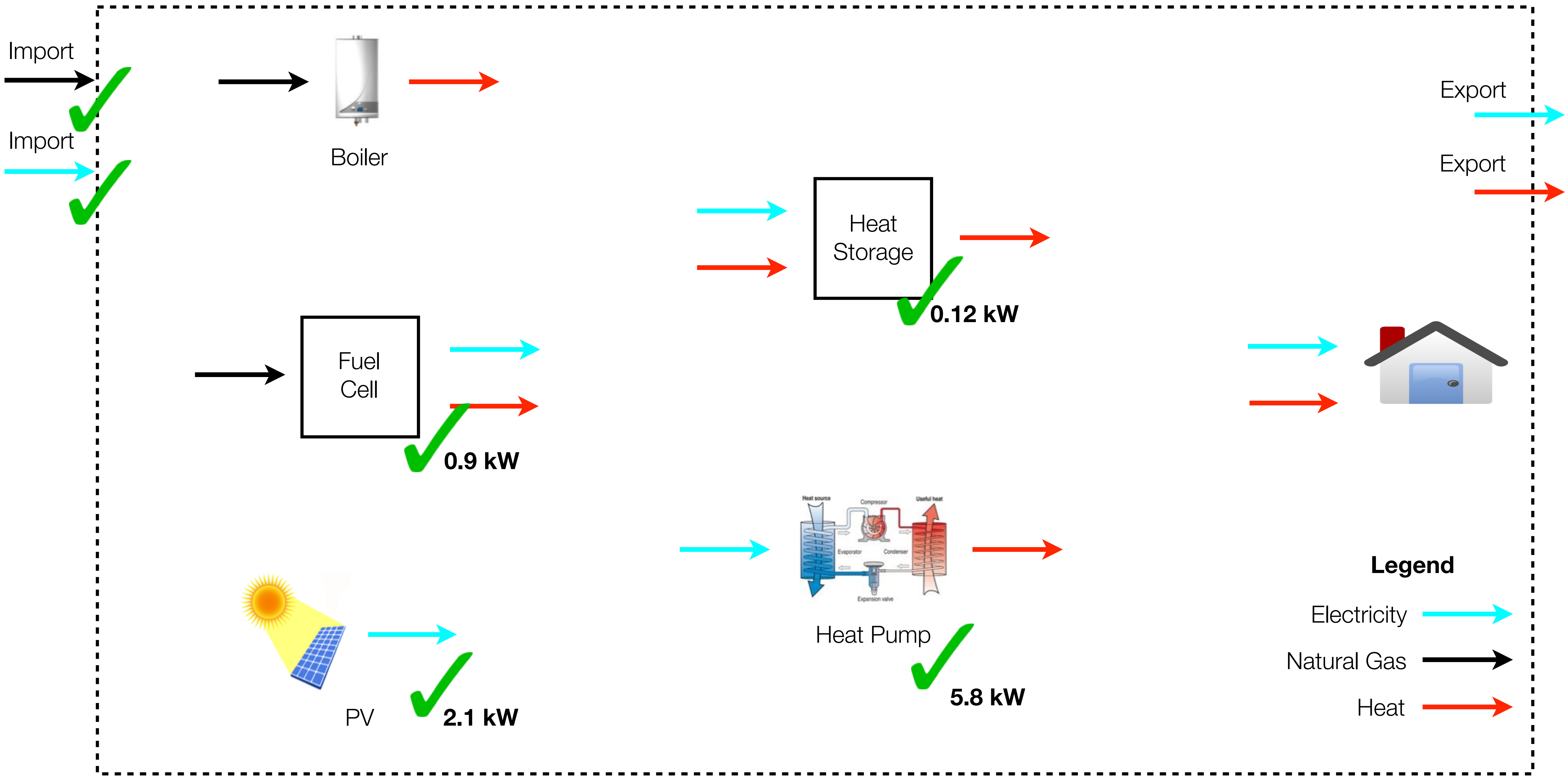
OPTIMIZATION MODEL

Obj = 2890. Case 5: $c_{el,buy}$ very high, c_{ng} high



OPTIMIZATION MODEL

Obj = 3020. Case 6: $c_{el,buy}$ very high, c_{ng} high&oscill.



UNCERTAINTY CLASSIFICATION
Methodology

All model parameters have an associated uncertainty, but which are the most important ones? The goal is identifying **priorities** for the uncertainty analysis

Parameters

i, interest rate

n, lifetime

BOIL: efficiency, C_{inv}(2), c_p(13)

FC: efficiency, C_{inv}(2), c_p(13)

STO: C_{inv}(2), c_p(13)

PV: C_{inv}(2), c_p(13)

HP: efficiency, C_{inv}(2), c_p(13)

Q_{demand} (13)

E_{demand} (13)

$c_{el,buy}$ (13)

c_{ng} (13)

= **~130** parameters

Group parameters

Qualitative classification

Quantitative classification (GSA - Morris)

UNCERTAINTY CLASSIFICATION

Qualitative classification

To run a global sensitivity analysis we need to define plausible limits of variations for each parameter

#	Param. Group	Hic et nunc?	Formulas/models?	Historical data?	Choice?	Range
1	i (interest rate)	✓			✓	± 10%
2	n (lifetime)			✓		±15%
3	BOIL: efficiency		✓		✓	±5%
4	BOIL: C_inv	✓				±5%
5	FC: efficiency		✓		✓	±10%
6	FC: C_inv	✓				±10%
7	HP: efficiency		✓			±10%
8	HP: C_inv	✓				±5%
9	HP: c_p mult			✓		±5%
10	PV: C_inv	✓				±5%
11	PV: c_p mult			✓		±10%
12	Q_demand		✓	✓	✓	±20%
13	E_demand		✓	✓	✓	±20%
14	c_el,buy					±50%
15	c_ng mult					±50%
16	STO: C_inv	✓				±10%

UNCERTAINTY CLASSIFICATION
Global SA - Morris's EE method

Sources:
- Sin G et al., Good Modeling Practice for PAT Applications: Propagation of Input Uncertainty and Sensitivity Analysis. 2009
- Saltelli et al., Global Sensitivity Analysis - The primer. 2008
- Pernet et al, Smart Heat Design - Urban Energy System Design under Uncertainty, Master Thesis EPFL, 2014 (Dirs. J. Rager, F. Maréchal)

Global **S**ensitivity **A**nalysis ”studies how variation (uncertainty) in the outputs of a model can be apportioned to different sources in the input of a model”

Model ***f***: the output ***Y*** is function of a set of ***k*** uncertain parameter ***X***

$$Y = f(X_1, X_2, ..., X_k)$$

First order sensitivity effect for the ***i***-th parameter:

$$S_i = \frac{V_{X_i}(E_{X_{\sim i}}(Y|X_i))}{V(Y)} \leq 1$$

Reduction of V(Y) if fixing X_i
if $\mathbf{S_i}$ **-> 1** then $\mathbf{X_i}$ is influential

Second order sensitivity effect:

$$S_{ij} = \frac{V_{X_i,X_j}(E_{X_{\sim ij}}(Y|X_i, X_j))}{V(Y)}$$

if $\mathbf{S_{ij} >> S_i + S_j}$ then combination of $\mathbf{X_i}$ **and** $\mathbf{X_j}$ is influential

Total sensitivity effect for ***i-th*** input $\mathbf{S_{Ti} = S_i + S_{ij} + S_{im} + S_{ijm} + \ldots}$

if $$\boxed{S_{Ti} = \frac{E(V(Y|X_{\sim i}))}{V(Y)} = 0}$$

then $\mathbf{X_i}$ non influential (necessary and sufficient condition)

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S_{Ti} often unaffordable to calculate!

Elementary effect (Morris) method:
- One-at-a-time Global Sensitivity Analysis method
- Discrete sampling: ***r*** “trajectories” in which at every step only one of the ***k*** input varies of **±Δ**
- Elementary Effect of the ***i***-th input:

$$EE_i = \frac{[Y(X_1, X_2, ..., X_{i-1}, X_i + \Delta, ..., X_k) - Y(X_1, X_2, ..., X_k)]}{\Delta}$$

$$\mu_i^* = \frac{1}{r}\sum_{j=1}^{r} |EE_i^j| \longrightarrow \text{Good proxy for } \mathbf{S_{Ti}}$$

Idea: Application of Morris method to the optimization model in order to quantitatively classify uncertainty and distinguish between relevant and non-influential input parameters -> **factor fixing**

Y → Objective function

Y → Choice/Size of the different technologies

UNCERTAINTY CLASSIFICATION

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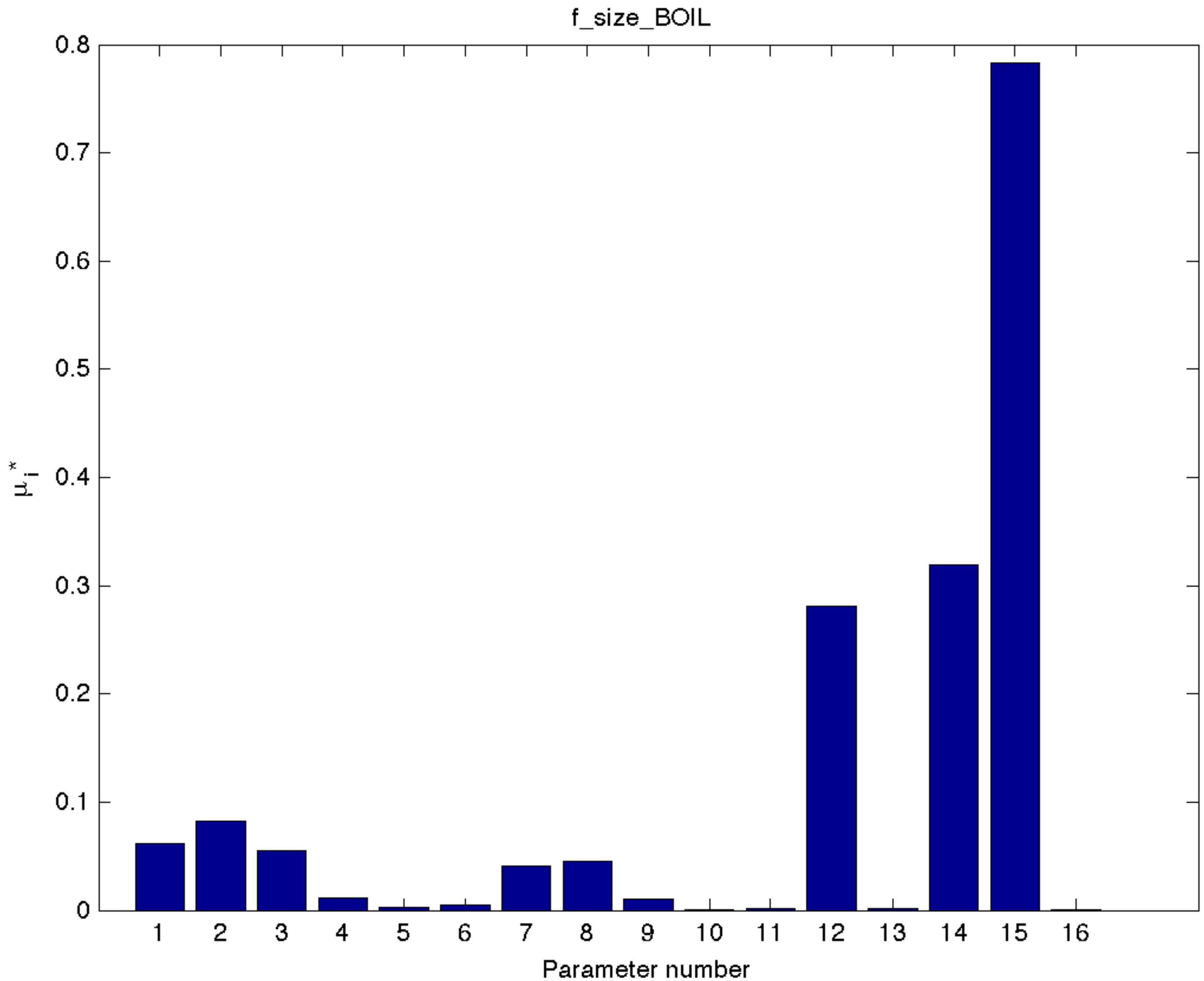

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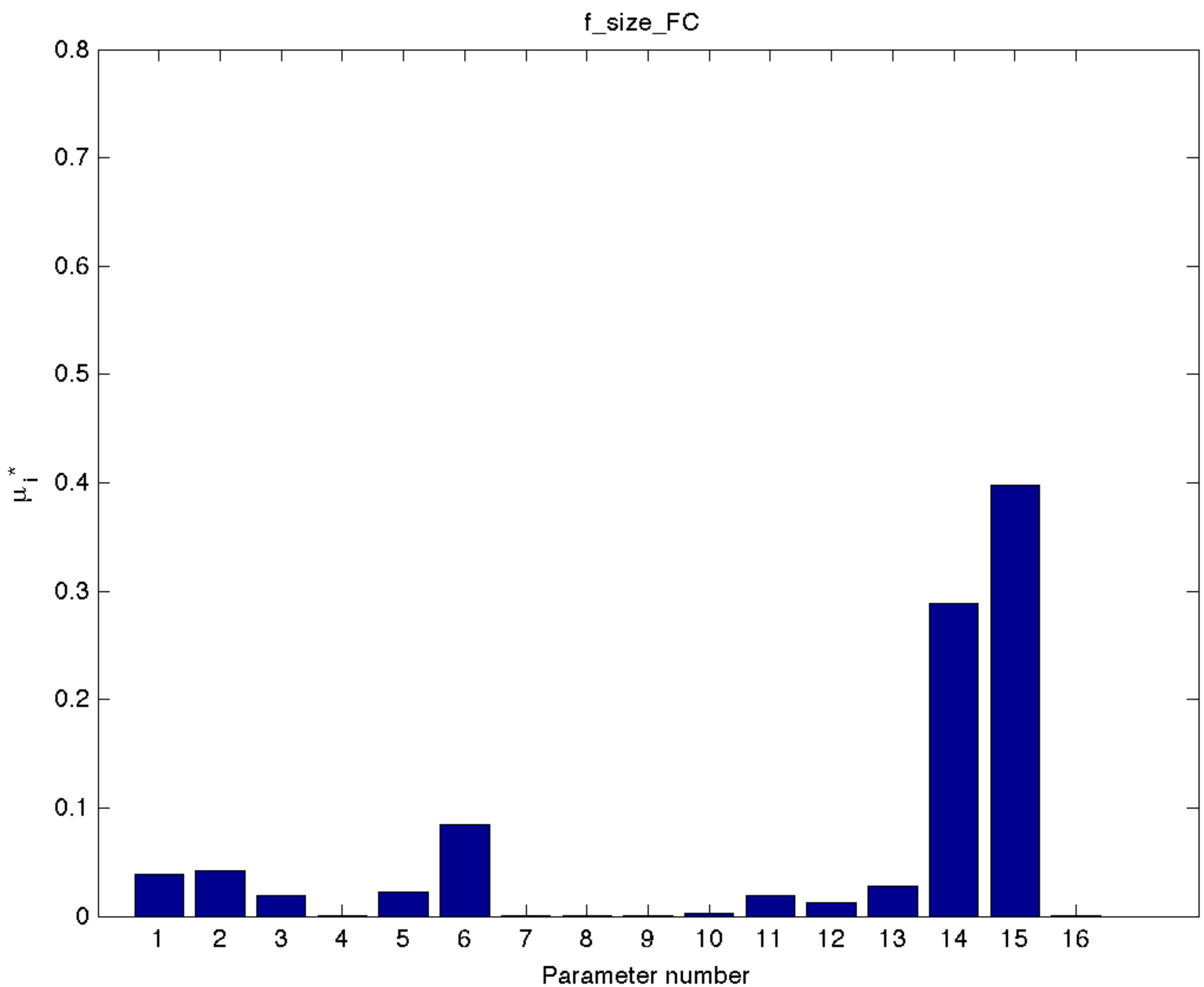

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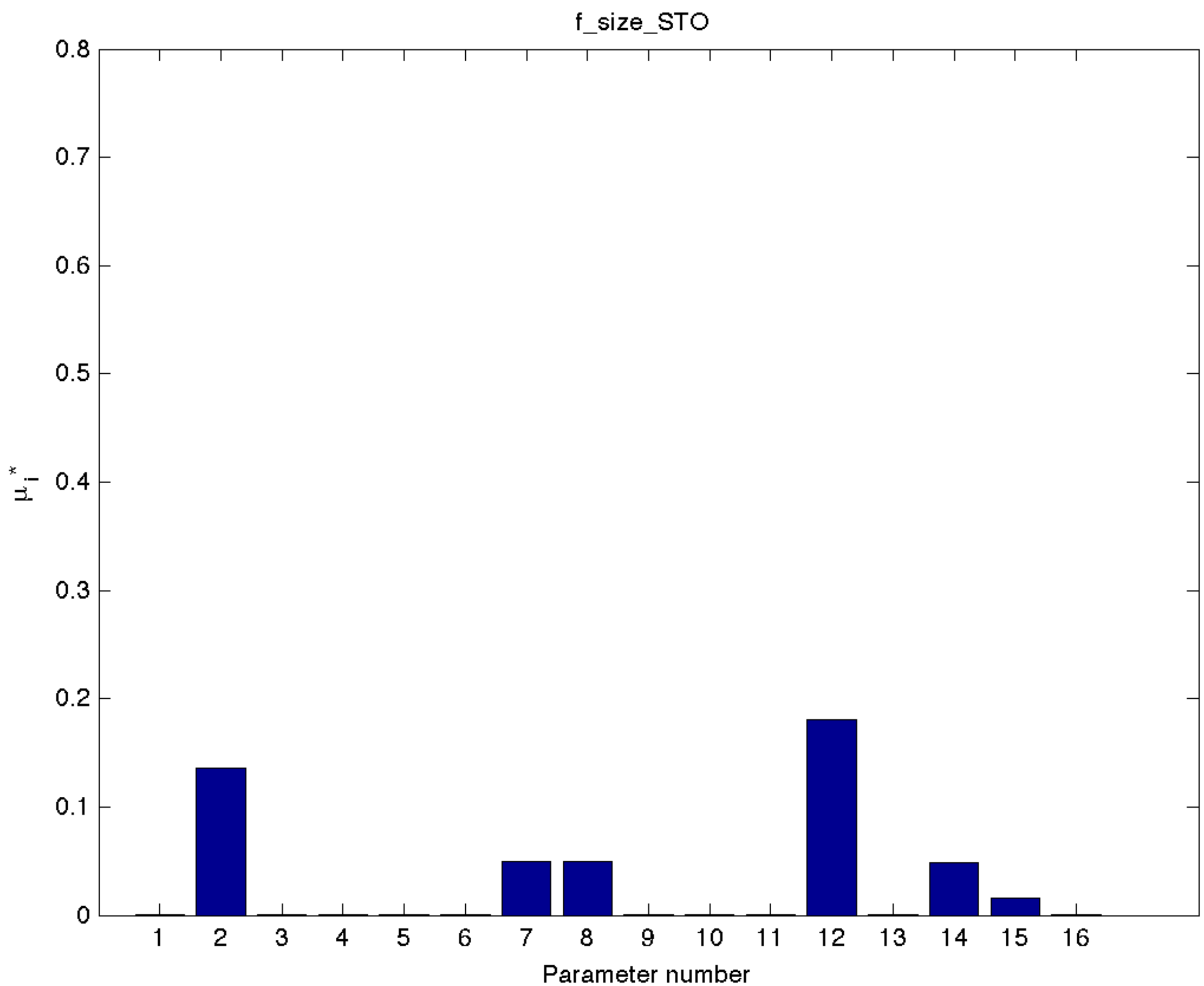

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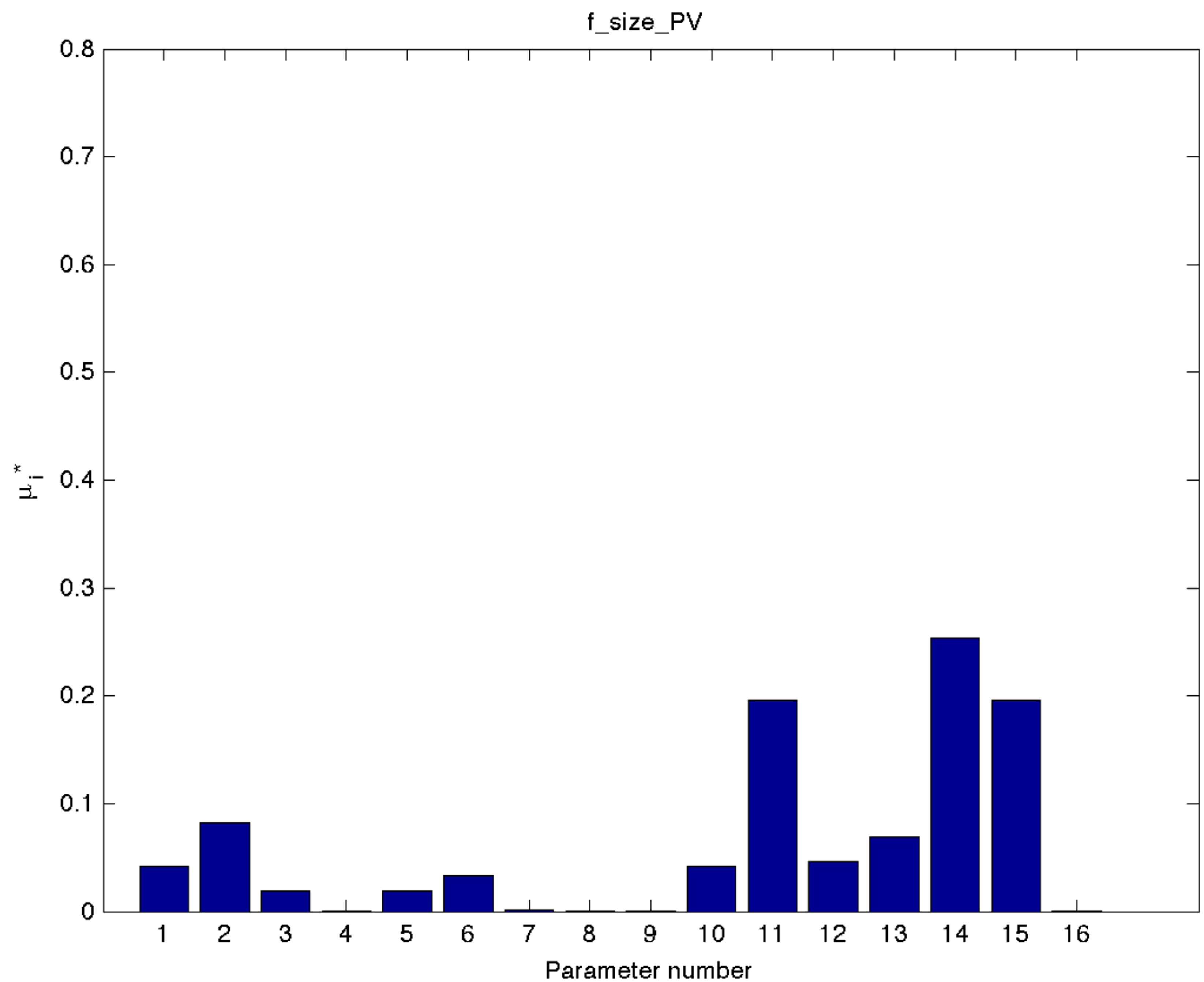

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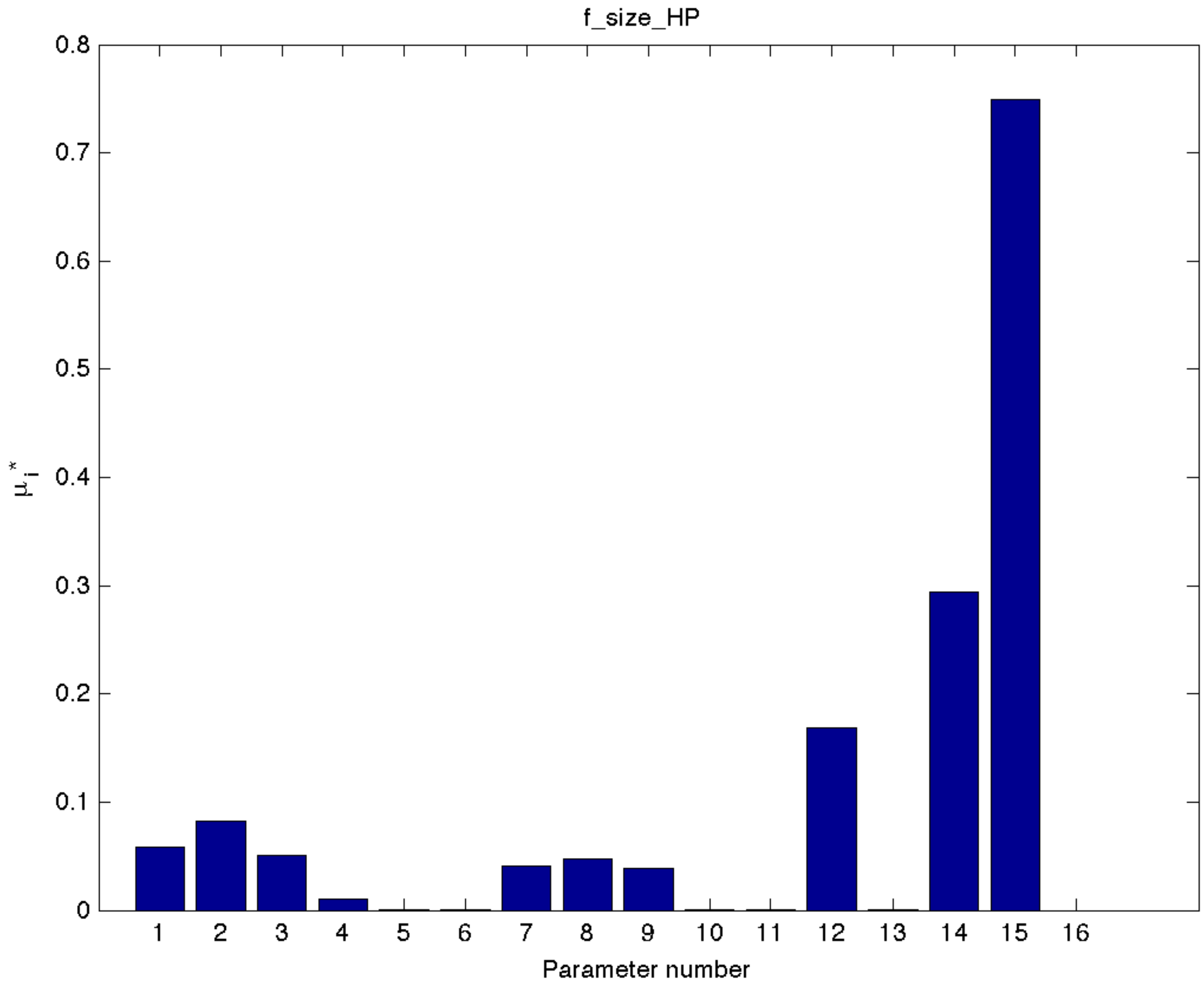

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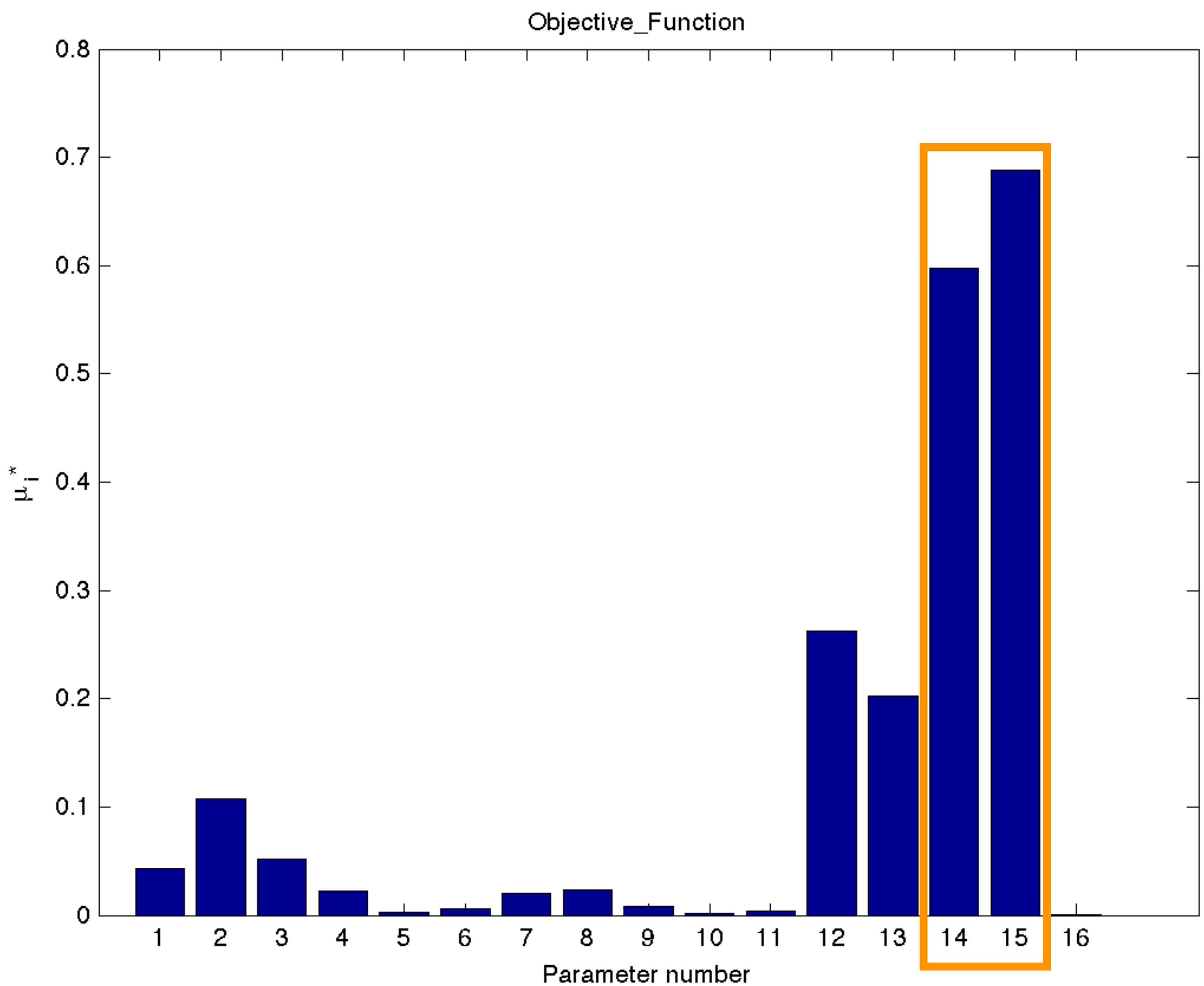


$C_{el,buy}$

C_{ng}

Most influential parameters

Sources:

- Dimitris Bertsimas and Melvyn Sim. The price of robustness. 2004.
- Convex Programming with Set-Inclusive Constraints and Applications to Inexact Linear Programming. 1973

ROBUST OPTIMIZATION
Problem formulation

Soyster (1973): Protection against all uncertain parameters at worst case. Very conservative
Bertsimas and Sim (2004): 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 $\boldsymbol{d_j}$

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

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)

26 uncertain parameters: $c_{el,buy}(t), c_{ng}(t) \qquad \forall t$

Sources:

- Dimitris Bertsimas and Melvyn Sim. The price of robustness. 2004.
- Convex Programming with Set-Inclusive Constraints and Applications to Inexact Linear Programming. 1973

ROBUST OPTIMIZATION
Problem formulation

Robust formulation of our energy planning MILP

New parameters

Γ_0: protection parameter

$d_{el} = [0.05, 0.5], d_{ng} = \frac{1}{2} d_{el}$: variation from the nominal value of the cost

New Variables

$z_0, p_{0,1}(t), p_{0,2}(t), y_1(t), y_2(t)$: variables of the robust counterpart

New Constraints

$$z_0 + p_{0,1}(t) \geq d_{el} y_1(t) \qquad \forall t$$

$$z_0 + p_{0,2}(t) \geq d_{ng} y_2(t) \qquad \forall t$$

$$-y_1(t) \leq \sum_u \dot{Q}_{NG}(u,t) \cdot t_{op}(t) \leq y_1(t) \qquad \forall t$$

$$-y_2(t) \leq \dot{E}_{buy}(t) \cdot t_{op}(t) \leq y_2(t) \qquad \forall t$$

New Objective

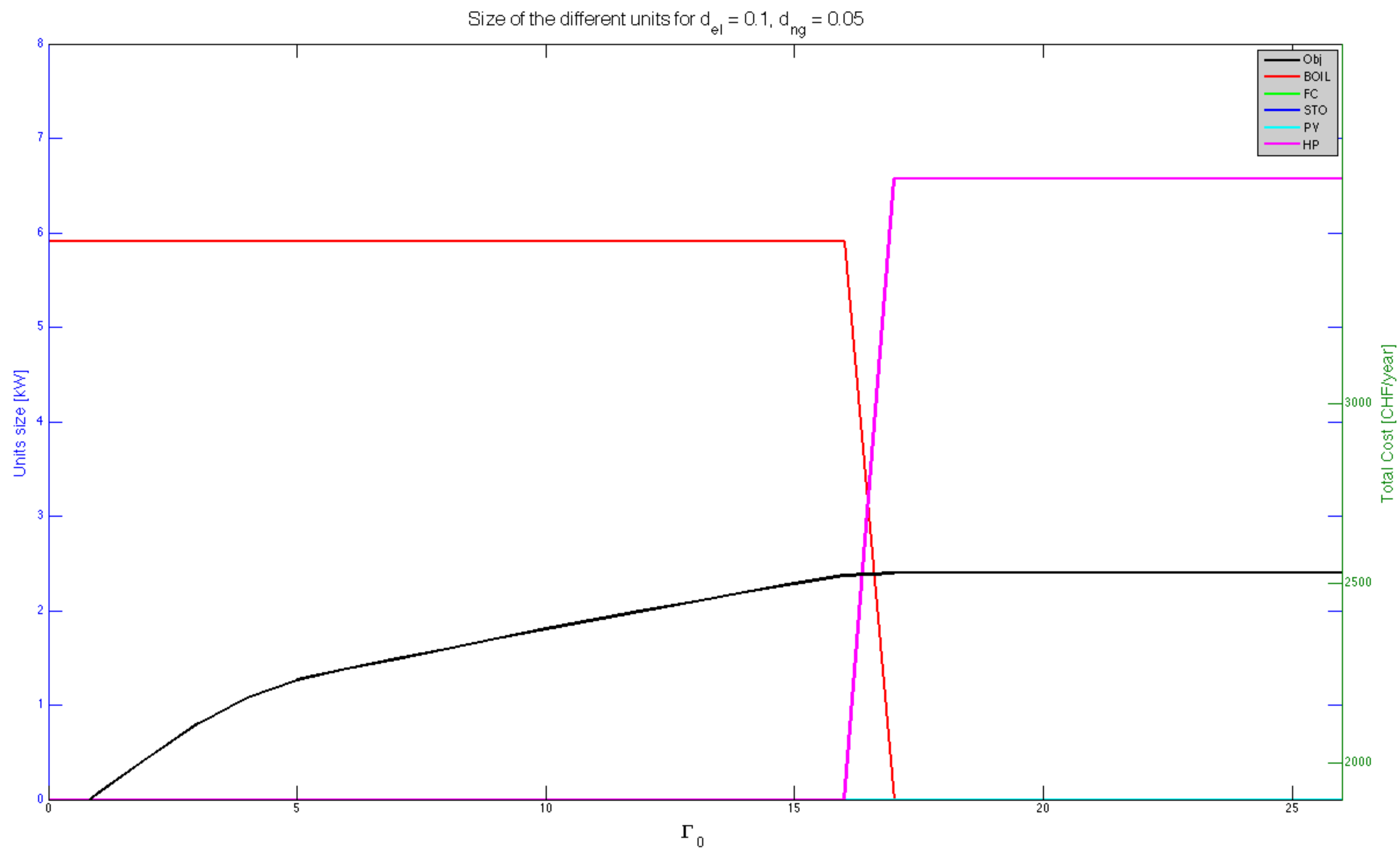
$$\min \ (\tau \sum_u C_{inv}(u) + \sum_t (\sum_u c_{ng}(t) \dot{Q}_{NG}(u,t) + c_{el,buy}(t) \dot{E}_{buy}(t) - p_{el,sell}(t) \dot{E}_{sell}(t)) \cdot t_{op}(t))$$

$$+ z_0 \Gamma_0 + \sum_t p_{0,1}(t) + \sum_t p_{0,2}(t)$$

- Intro & Literature
- Model
- Uncertainty Classification
- Robust Optimization
- Post-sensitvity
- Conclusions

ROBUST OPTIMIZATION

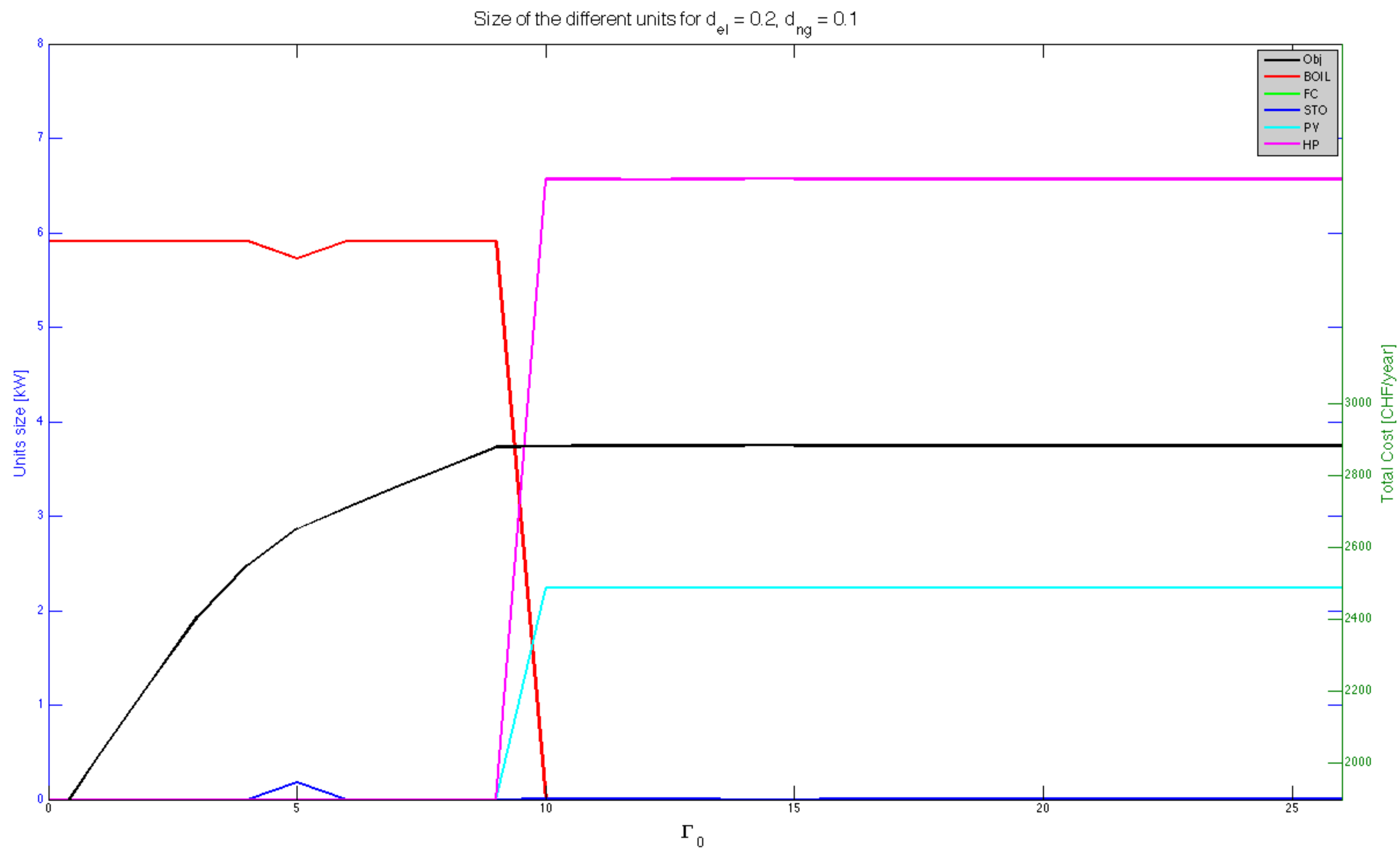
Results (d_{el} = 0.10)



Intro & Literature | Model | Uncertainty Classification | Robust Optimization | Post-sensitvity | Conclusions

ROBUST OPTIMIZATION

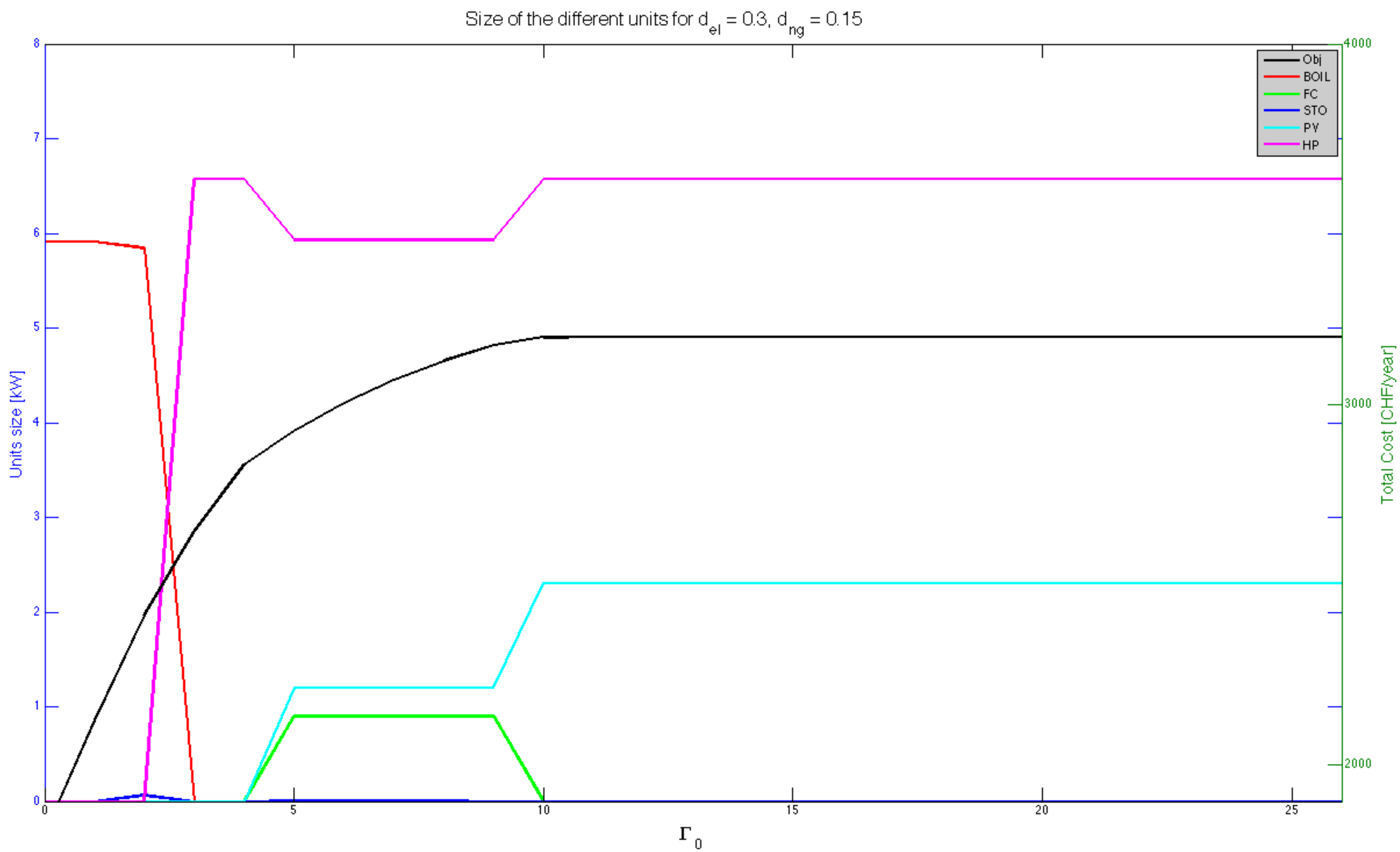
Results (d_{el} = 0.20)



Intro & Literature | Model | Uncertainty Classification | Robust Optimization | Post-sensitvity | Conclusions

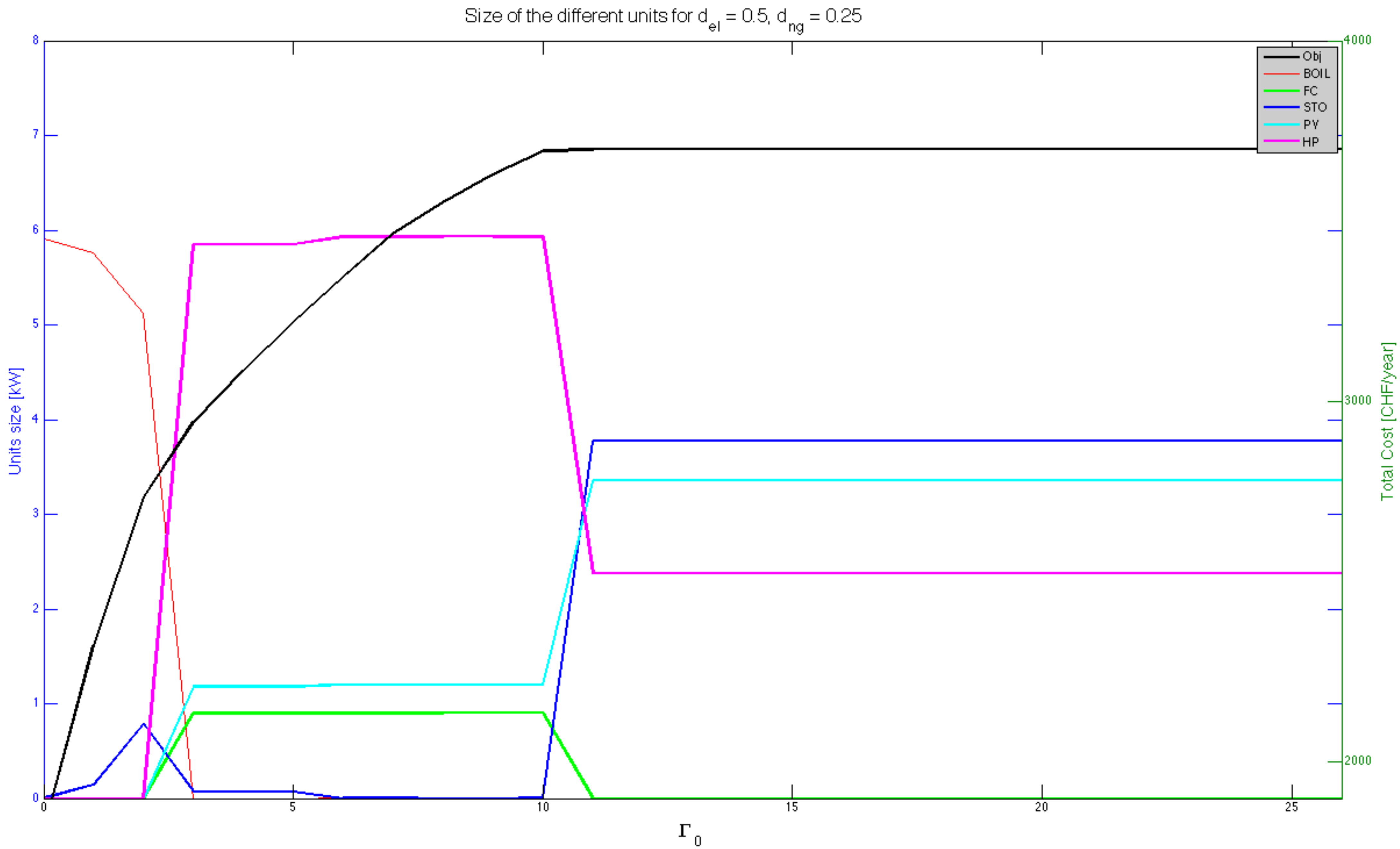
ROBUST OPTIMIZATION

Results (d_{el} = 0.30)



ROBUST OPTIMIZATION

Results (d_{el} = 0.50)



Intro & Literature | Model | Uncertainty Classification | Robust Optimization | Post-sensitvity | Conclusions

ROBUST OPTIMIZATION
Results

Choice and size of the technologies:

- **Boiler**: deterministic case, when $\boldsymbol{d}$ increases is discarded even for low values of $\boldsymbol{\Gamma_0}$
- **Fuel Cell**: chosen if $\boldsymbol{d_{el}}$ >= 0.25, for medium values of $\boldsymbol{\Gamma_0}$
- **Storage**: chosen if $\boldsymbol{\Gamma_0}$ is either low (oscillations) either uncertainty is very high
- **PV**: natural replacement of E_{import}, size increases with increasing $\boldsymbol{d}$ and $\boldsymbol{\Gamma_0}$
- **HP**: natural replacement of boiler, size increases with increasing $\boldsymbol{d}$ and $\boldsymbol{\Gamma_0}$

Key preliminary conclusions:

- Model is very simple -> results should be taken as proof of concept
- Robust optimization implementation works correctly and shows interesting trade-offs
- Deterministic solution (Boiler + E_{import}) tends to be replaced by other technologies even with low $\boldsymbol{\Gamma_0}$ (most parameters at their deterministic values)
- In the uncertain domain, investing on more efficient and renewable technologies can be **economically optimal**

POST-SENSITIVITY
Methodology

Idea: how do the found robust solutions perform in the uncertain domain?

Investment decision is taken
- ***y*** (technlogy choice) and $\boldsymbol{f_{size}}$ are now **parameters**
- ***f*** (use, operation of the technology) is still a **variable**

Identification of key solutions/configuration

↓

Simulation in the uncertain domain

↓

Statistical analysis of results

Each solution is evaluated 2000 times
Parameters drawn from uniform distribution

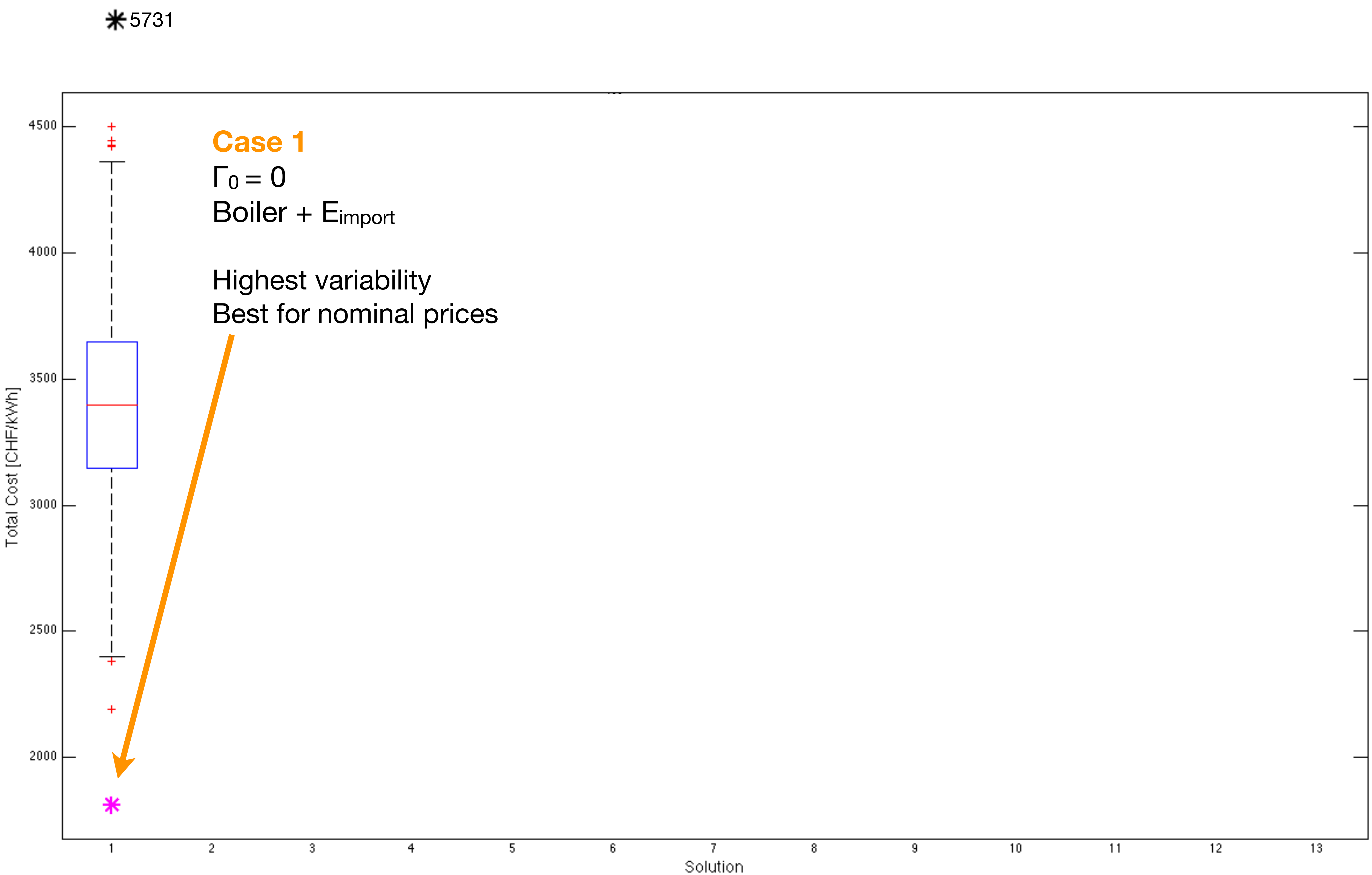
$$c_{ng} \in [-0.0485, 0.25]$$
$$c_{el,buy} \in [-0.09, 0.5]$$

POST-SENSITIVITY
Results

Legend

✱ All prices at worst case

✱ All prices at nominal value



Case 1

$\Gamma_0 = 0$

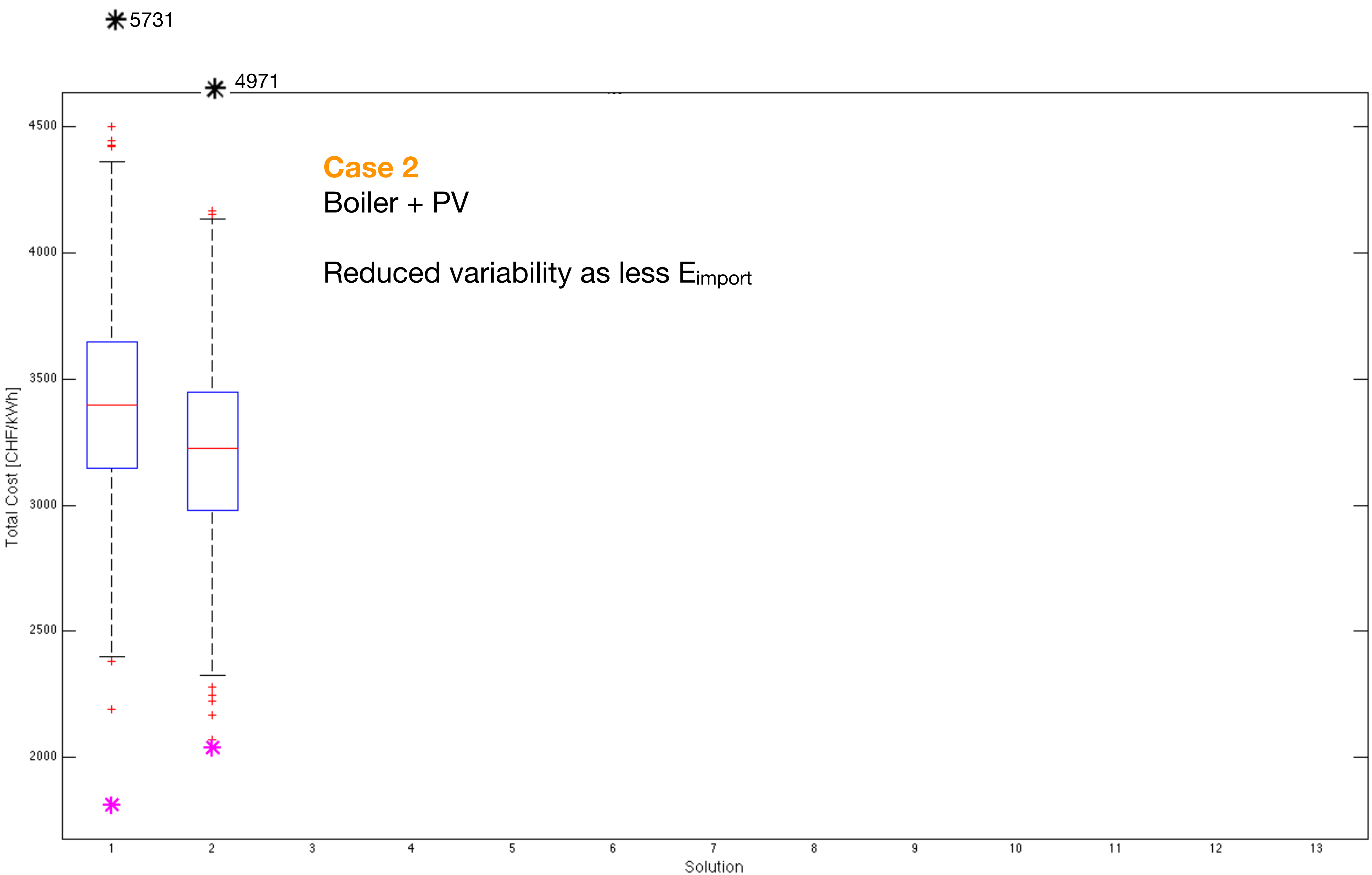
Boiler + E_{import}

Highest variability

Best for nominal prices

POST-SENSITIVITY
Results

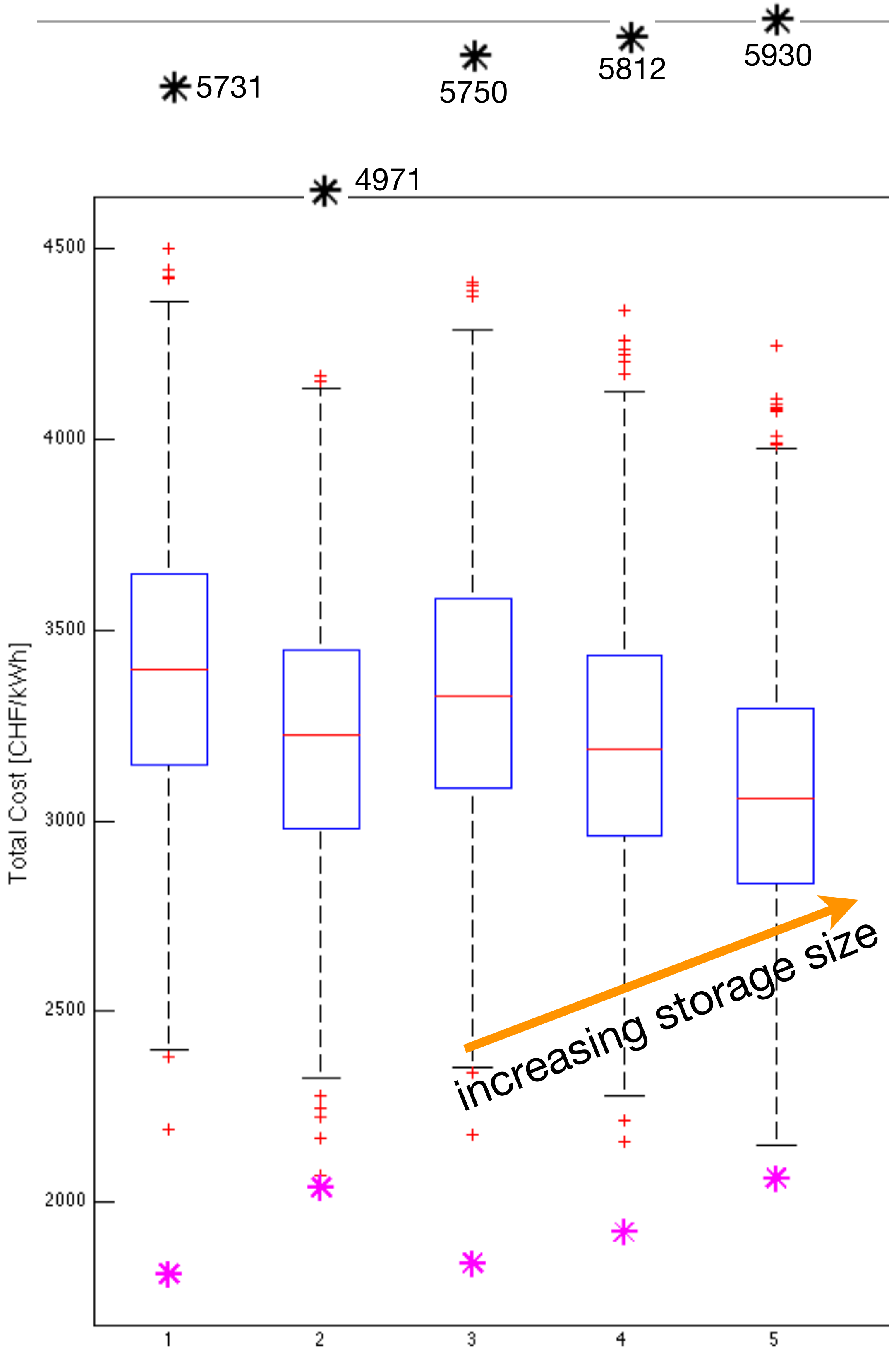
Legend
All prices at worst case
All prices at nominal value



POST-SENSITIVITY

Results

Legend
All prices at worst case
All prices at nominal value



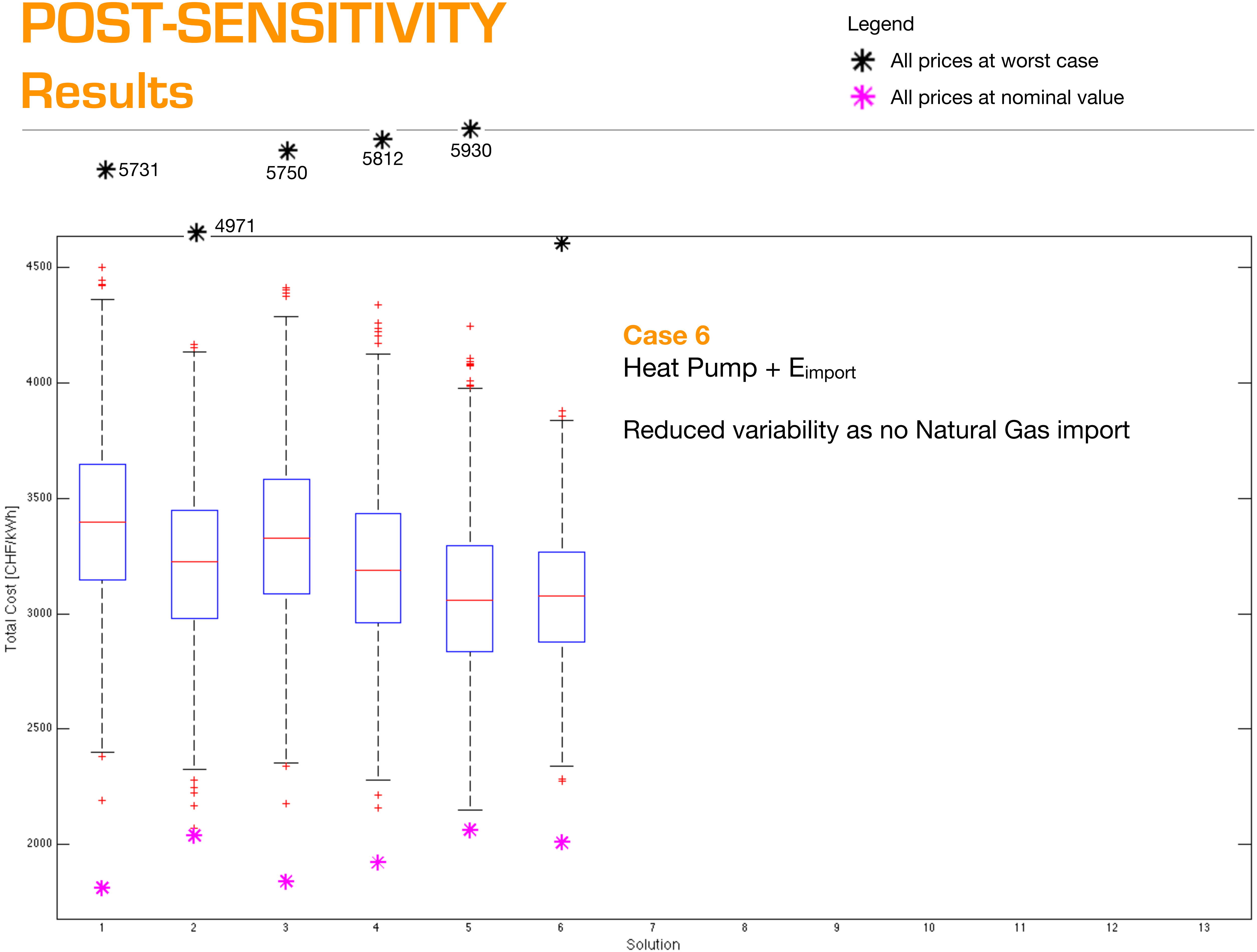
Cases 3,4,5

Boiler + Storage (increasing size)

Range gradually reduced and better objective
Storage acts as a damper of uncertainty

POST-SENSITIVITY

Results



Case 6

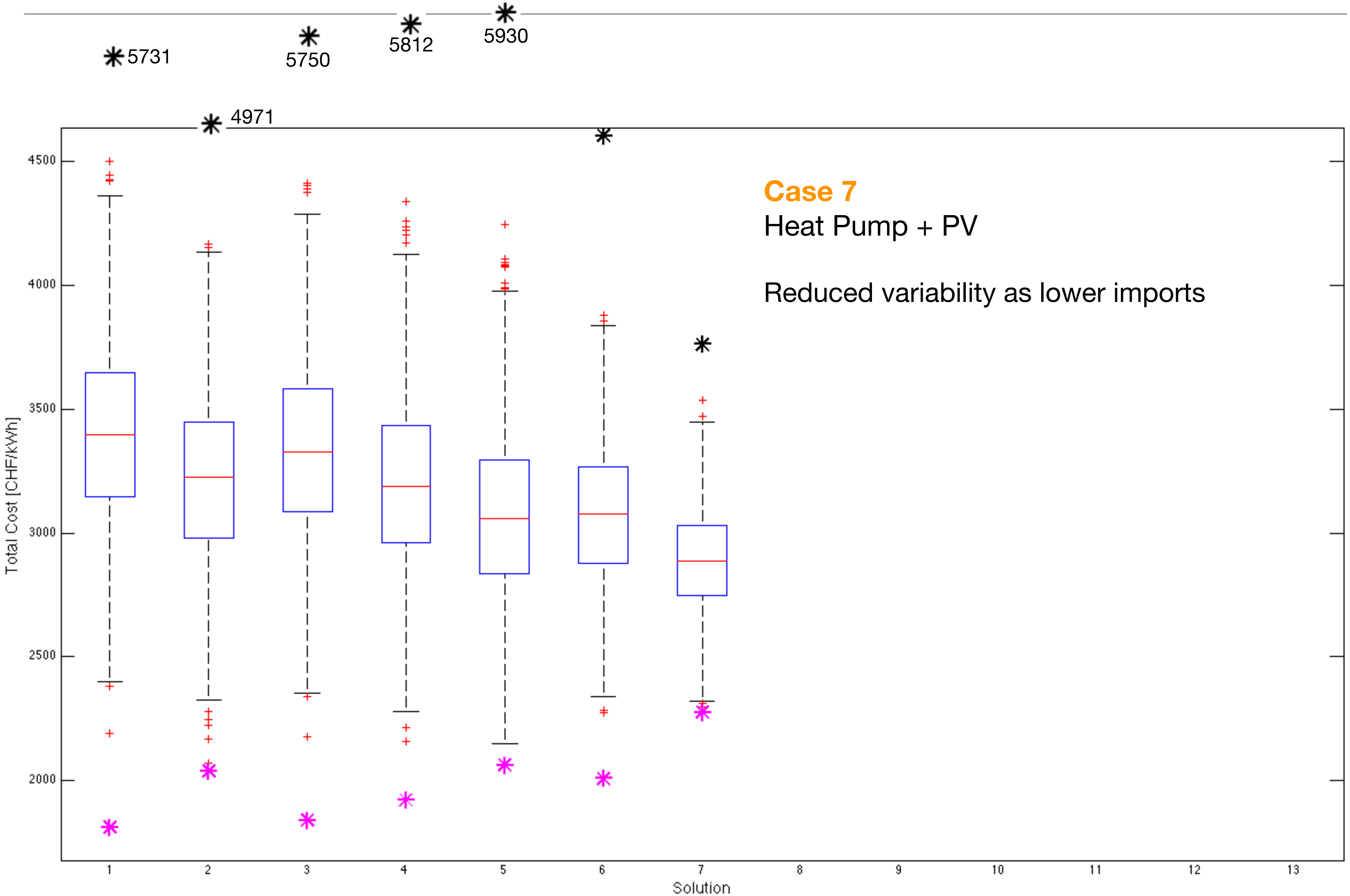
Heat Pump + E_{import}

Reduced variability as no Natural Gas import

POST-SENSITIVITY

Results

Legend
All prices at worst case
All prices at nominal value



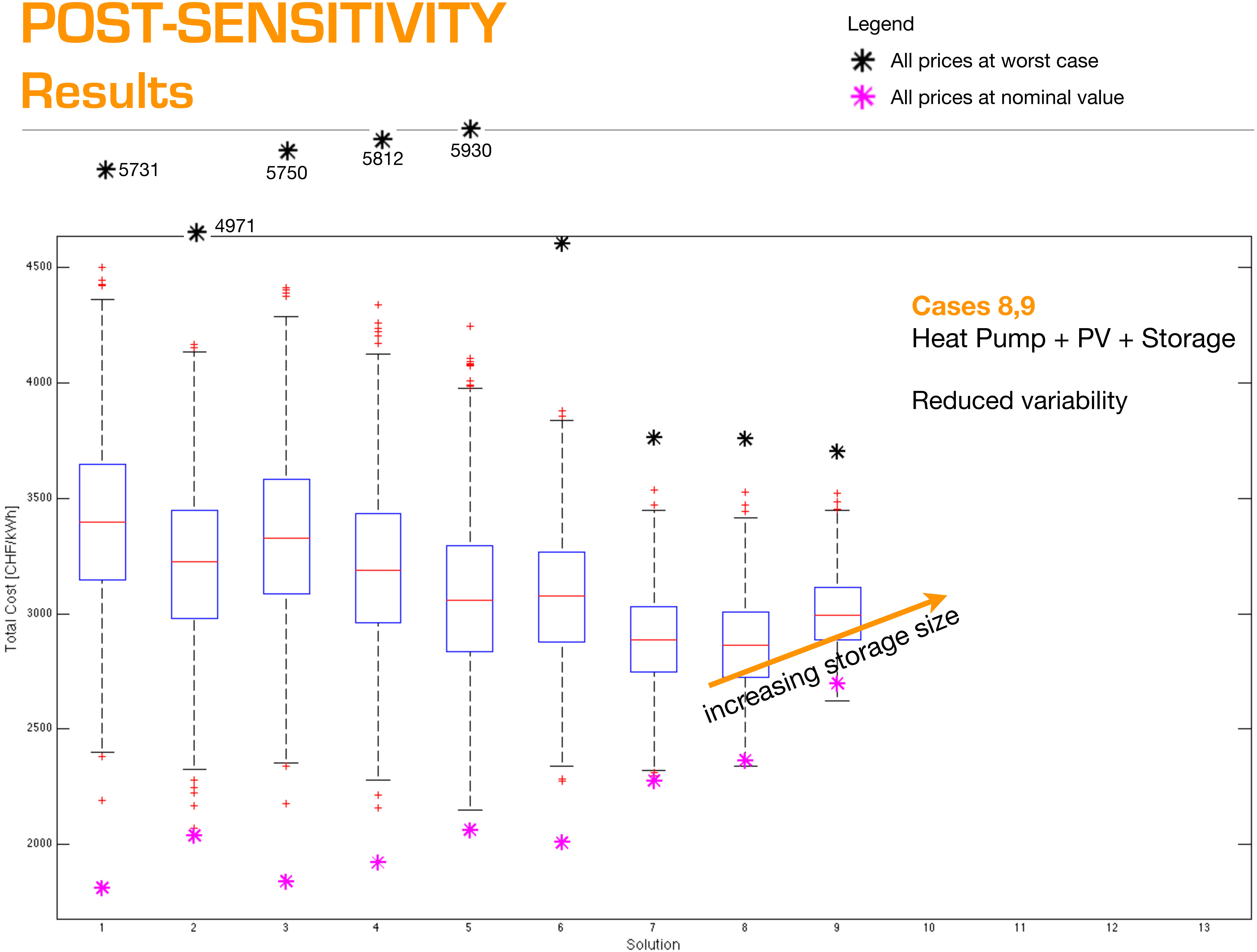
Case 7

Heat Pump + PV

Reduced variability as lower imports

POST-SENSITIVITY

Results



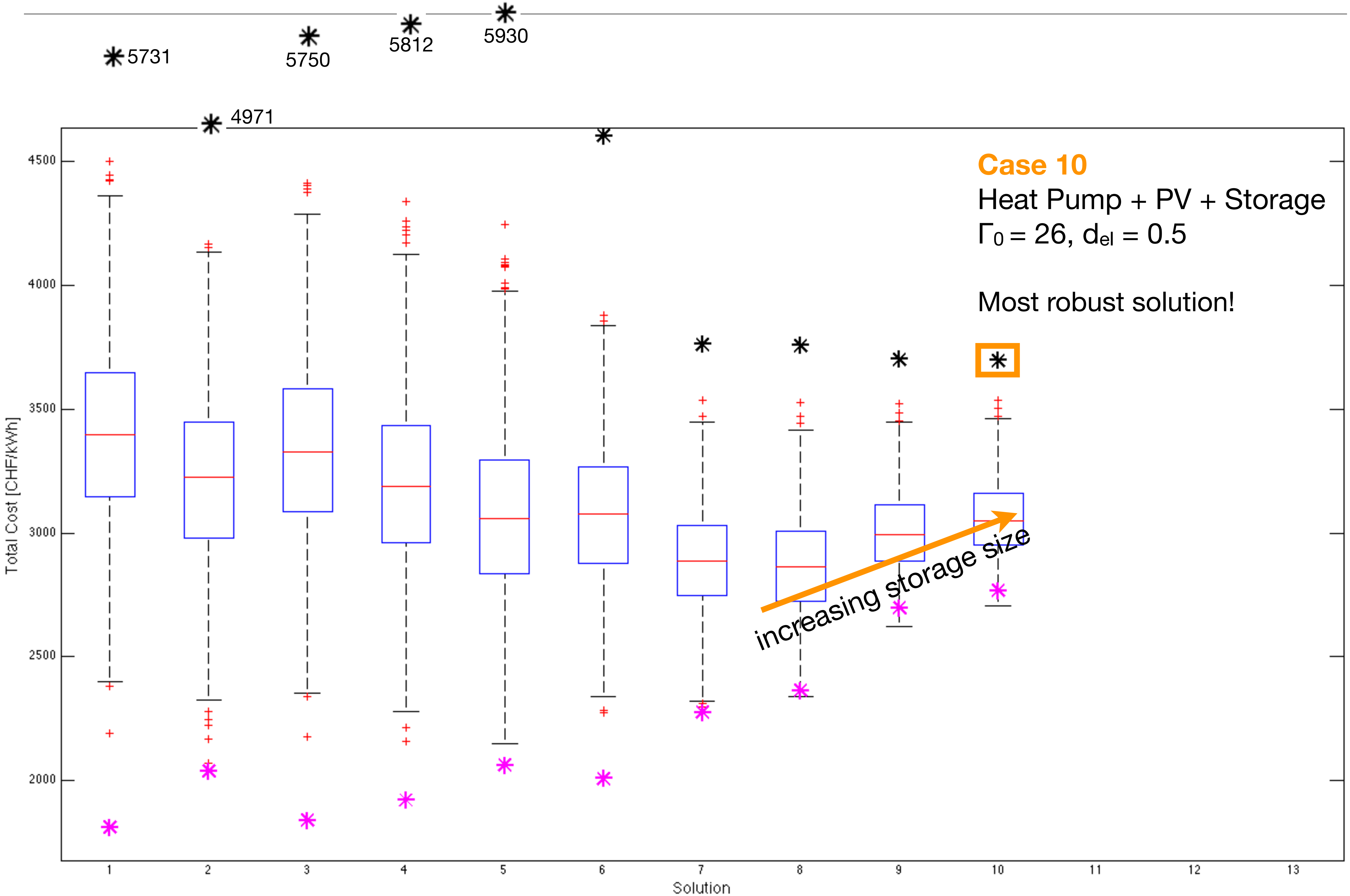
POST-SENSITIVITY

Results

Legend

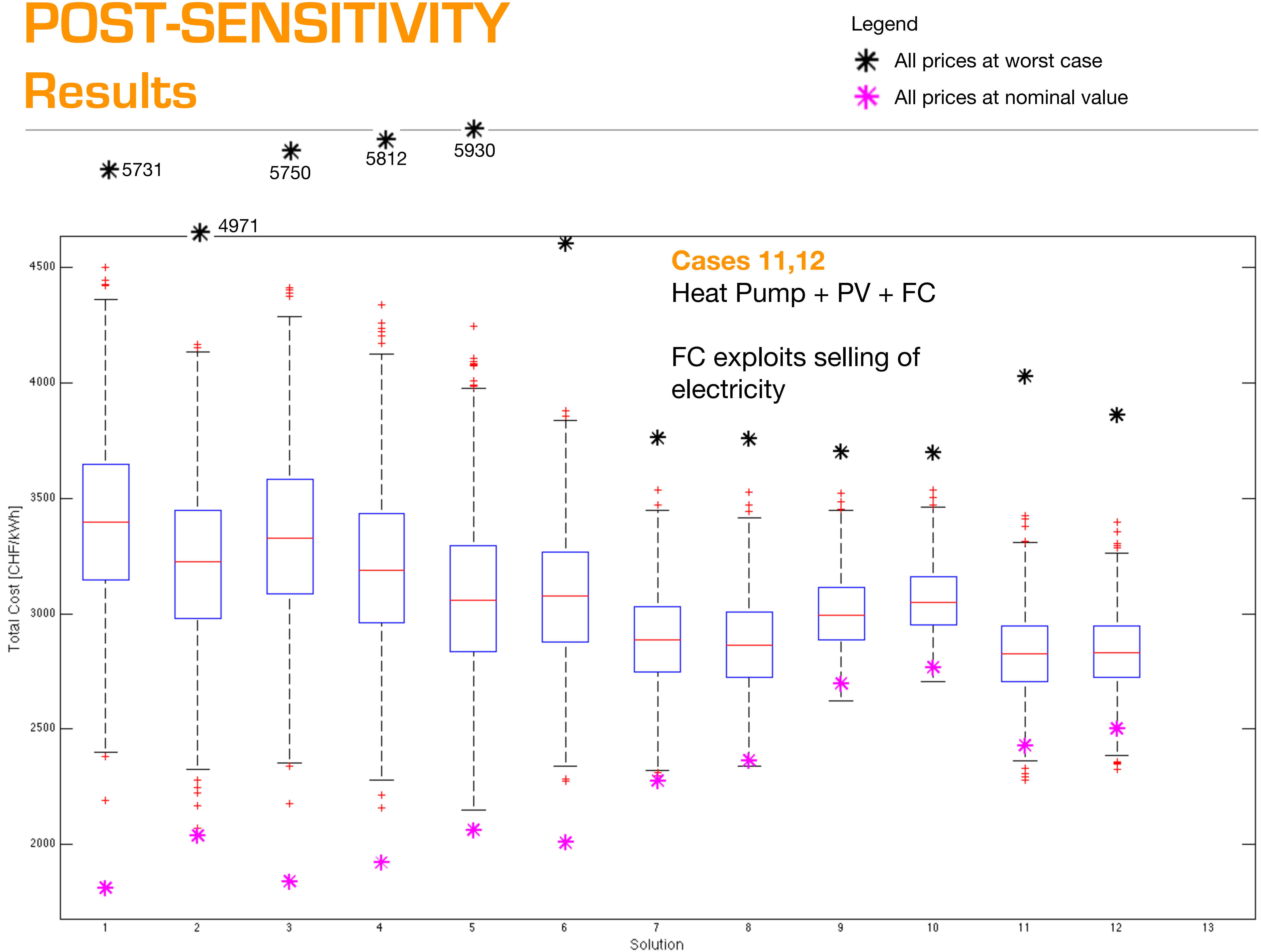
All prices at worst case

All prices at nominal value



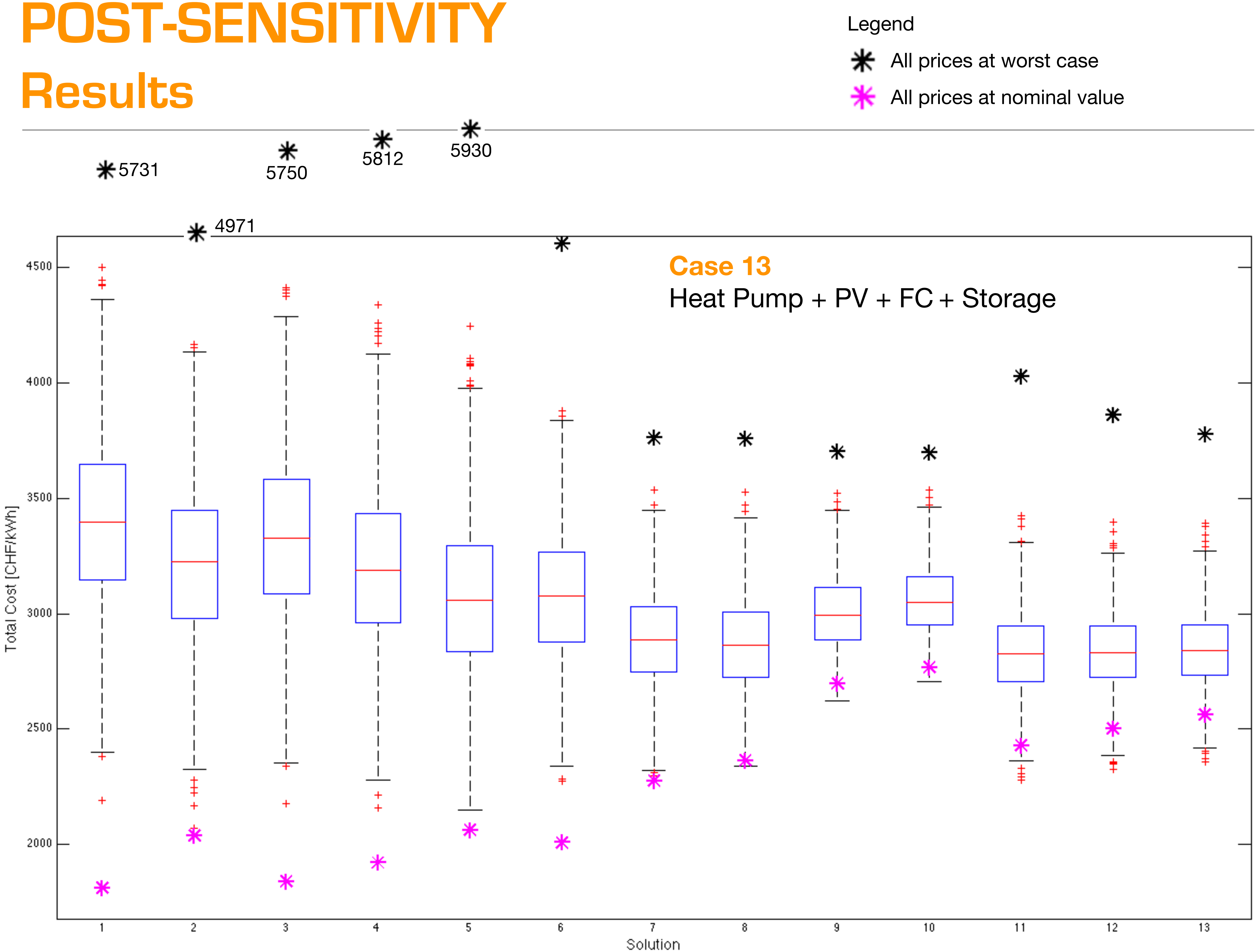
POST-SENSITIVITY

Results



POST-SENSITIVITY

Results



CONCLUSIONS

Key outcomes

- Efficient/renewable technologies (and Storage) can be uncertainty "dampers"
- Investment-intensive technologies reduce future cost oscillations
- Local, decentralised production (FC) can open room for profit
- Uncertainty is not the same for all parameters in a model
- Taking uncertainty into account highly impacts strategic energy planning (even with low Γ_0)

In the uncertain domain, investing on more efficient and renewable technologies can be **economically optimal**

Intro & Literature — Model — Uncertainty Classification — Robust Optimization — Post-sensitivty — Conclusions

CONCLUSIONS
Next steps

Already achieved:

- Simple MILP showing typical trade-offs in strategic energy planning
- Qualitative/quantitative method to classify uncertainty
- First implementation of robust optimisation (no PDF needed!)
- Promising preliminary results, proof-of-concept

Next steps:

- More detailed model -> application to national energy system
- Rigorous methodology to classify uncertainty for strategic energy planning
- Application of two-stage programming -> uncertainty unfolding in the future
- Comparison with other decision-making approaches

THANK YOU!

Thank you for your attention!

Question/remarks?