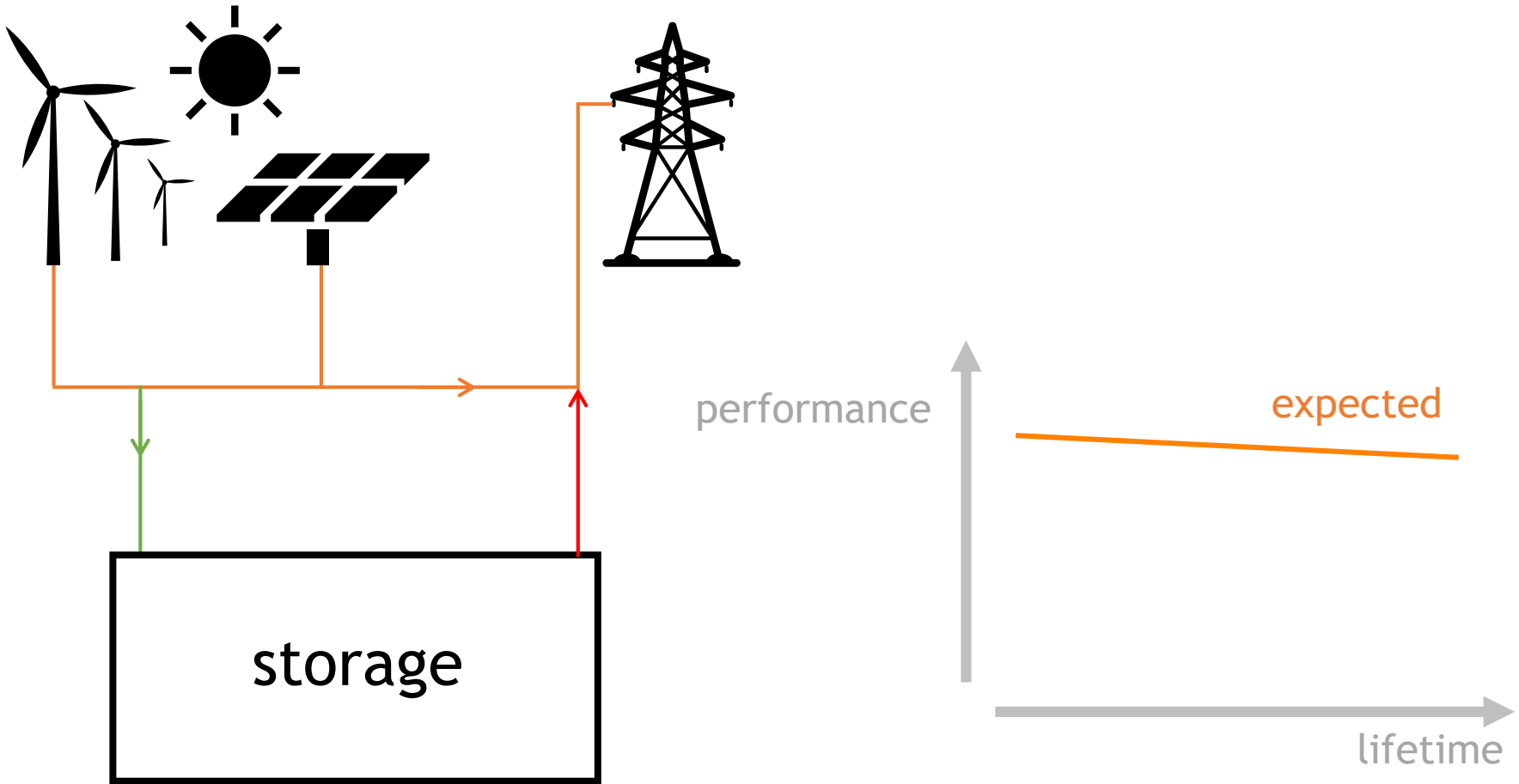# Epistemic and aleatory uncertainty quantification of a grid-connected photovoltaic system with battery storage and hydrogen storage
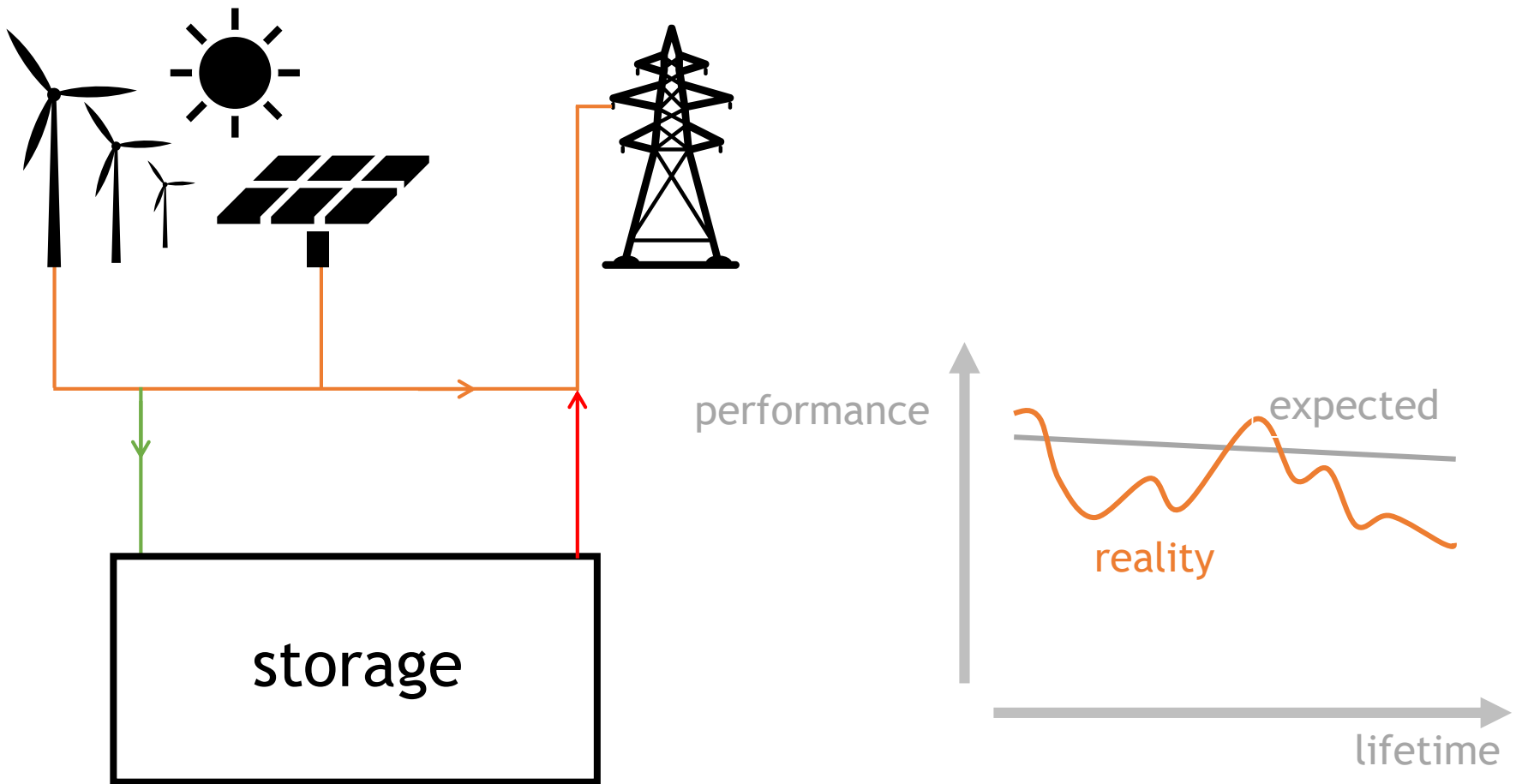
Diederik Coppitters

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During system design, the performance is predicted based on fixed system parameters

storage

performance

expected

lifetime

Uncertainties on these system parameters can have drastic consequences on the performance

Uncertainties are characterized, propagated and analysed, to determine efficient measures for robustness

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┌─────────────────┐      ┌─────────────────┐      ┌─────────────────┐
│                 │      │                 │      │                 │
│   uncertainty   │ ───> │   uncertainty   │ ───> │   sensitivity   │
│ characterization│      │   propagation   │      │    analysis     │
│                 │      │                 │      │                 │
└─────────────────┘      └─────────────────┘      └─────────────────┘
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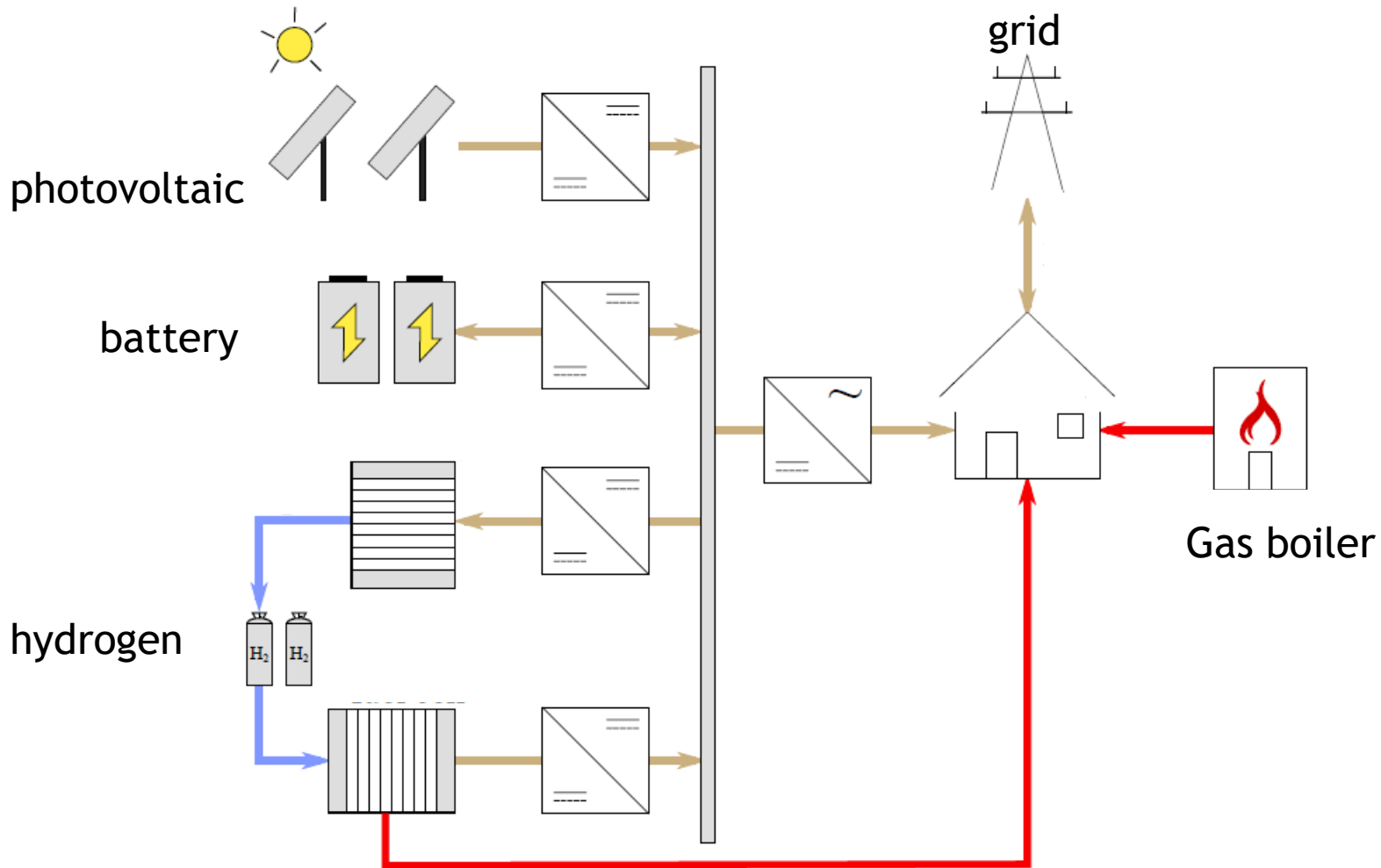
Uncertainties are characterized, propagated and analysed, to determine efficient measures for robustness
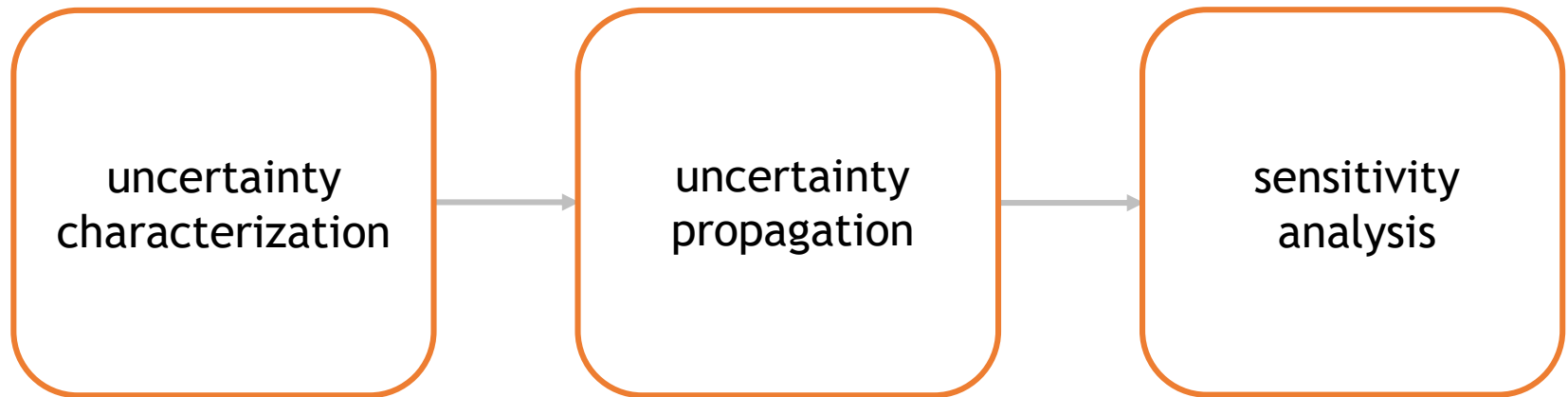
```
uncertainty          uncertainty          sensitivity
characterization  →  propagation     →    analysis
```
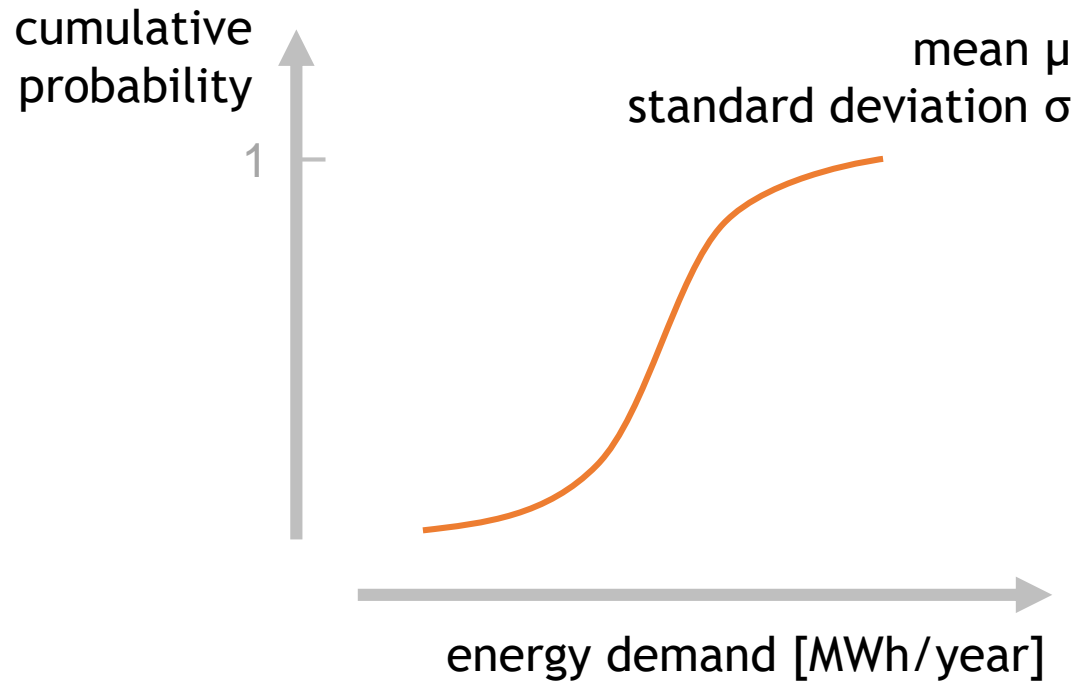
Belgian household, connected to gas and electricity grid, is supported by solar energy, battery + hydrogen storage

photovoltaic

battery

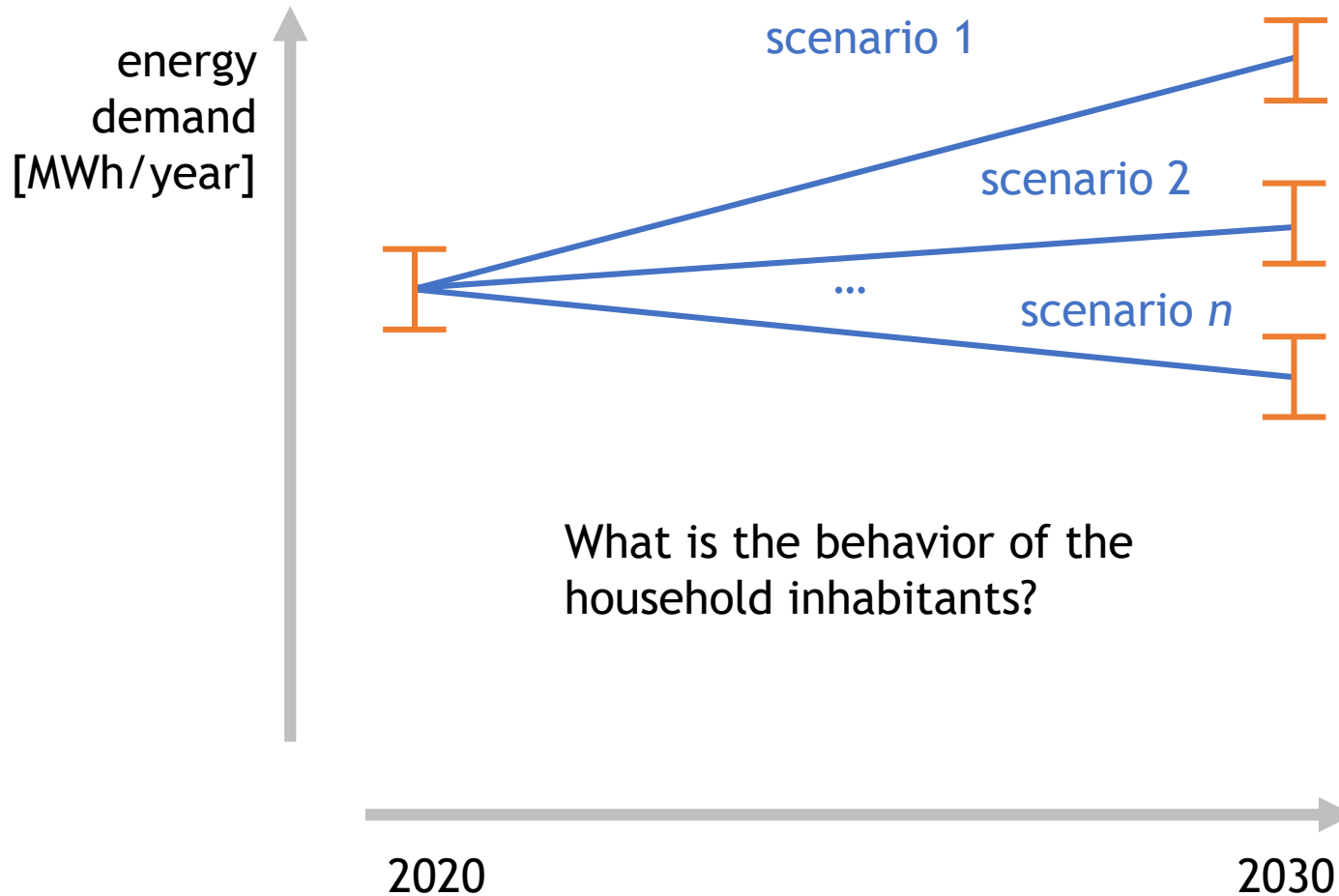hydrogen

grid

Gas boiler

The natural variability (i.e. evolution over time) illustrates the aleatory (i.e. future) uncertainty

energy demand [MWh/year]

scenario 1

scenario 2

...

scenario *n*

How will the demand evolve over time?
increase in electric applications
Increase in insulation
Increase in energy efficiency

2020

2030
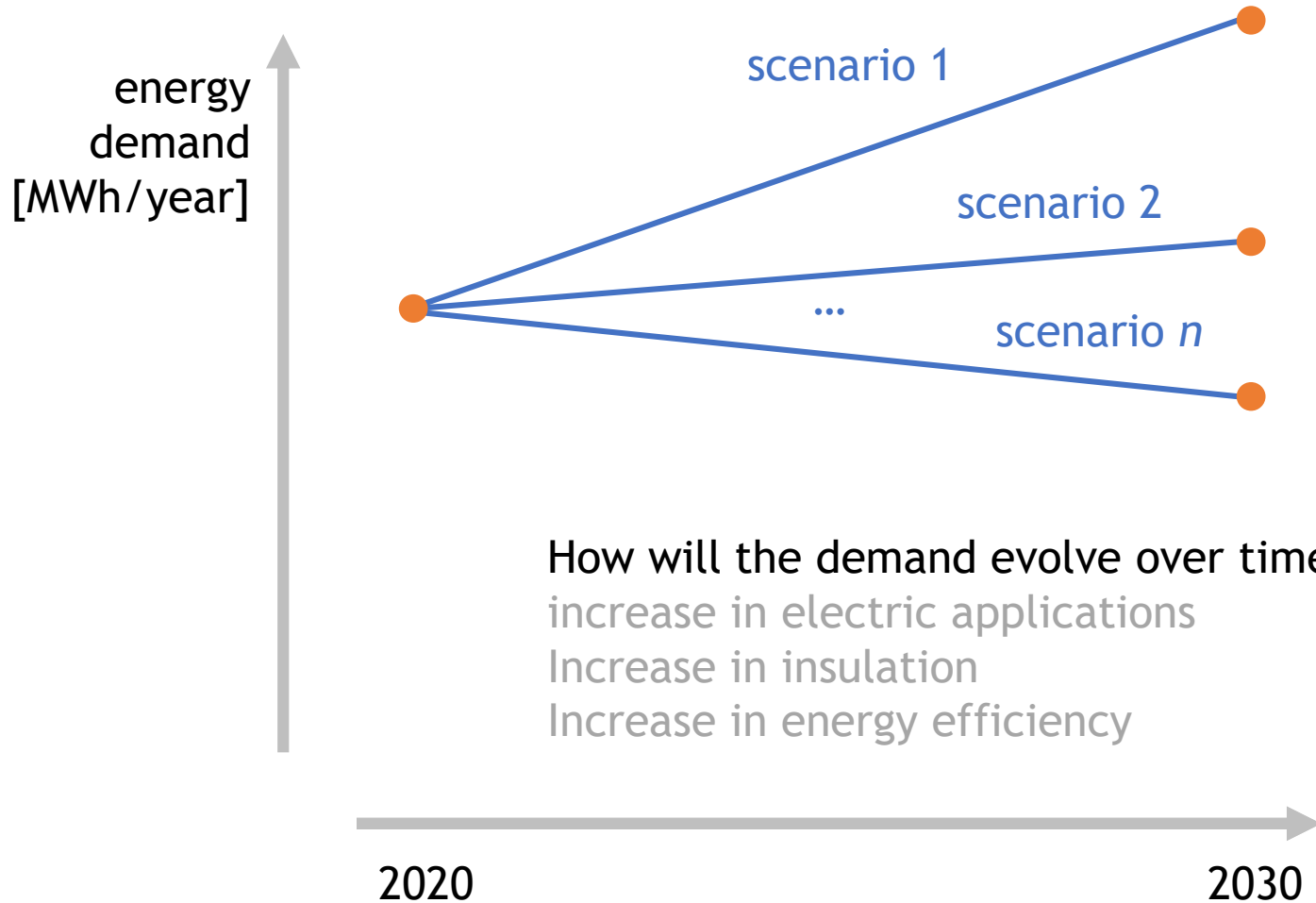
The aleatory uncertainty can be captured in a Cumulative Density Function (CDF)

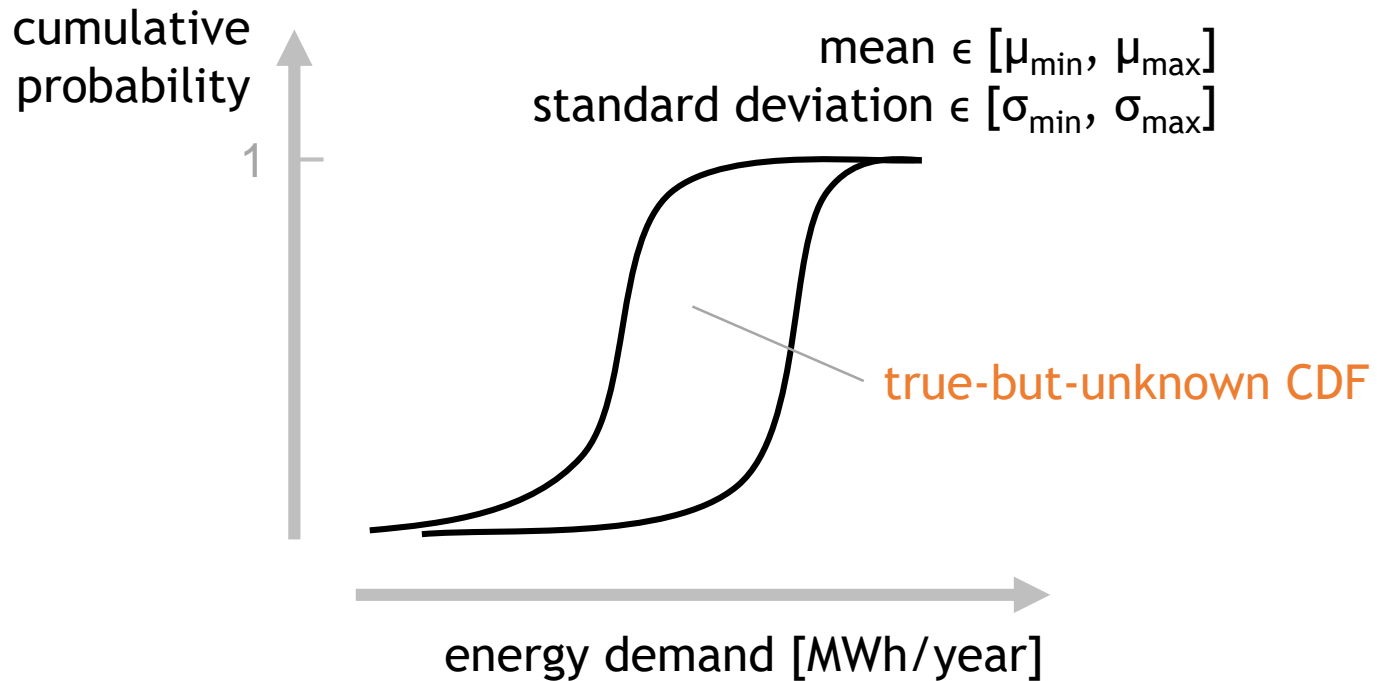

cumulative probability

1

mean μ
standard deviation σ

energy demand [MWh/year]

The lack of confidence (i.e. lack of data/information) illustrates the epistemic (i.e. present) uncertainty

energy demand [MWh/year]

scenario 1

scenario 2

...

scenario *n*

What is the behavior of the household inhabitants?

2020

2030

The epistemic uncertainty makes the CDF uncertain

cumulative probability

mean ϵ [μ_{min}, μ_{max}]
standard deviation ϵ [σ_{min}, σ_{max}]

1

energy demand [MWh/year]
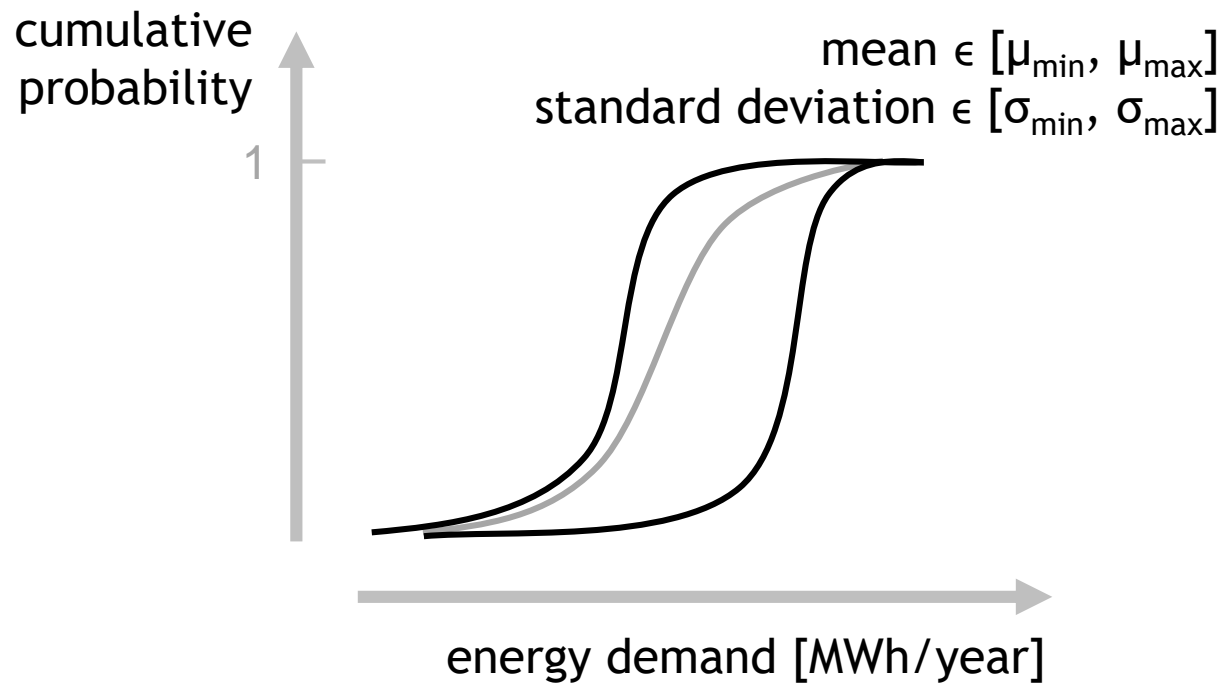
In between the CDF bounds, the true-but-unknown CDF is situated, representing the real aleatory uncertainty

cumulative probability

mean $\in [\mu_{min}, \mu_{max}]$
standard deviation $\in [\sigma_{min}, \sigma_{max}]$

1

true-but-unknown CDF

energy demand [MWh/year]

Uncertainty characterization based on literature

Electricity/heat demand
epistemic: behavior
aleatory: evolution over time

mean ϵ [80, 120] % of average demand
standard deviation = 6.7 % of average demand

Uncertainty characterization based on literature

Electricity/gas cost
epistemic: contract/energy supplier
aleatory: evolution over time

electricity cost
mean $\in$ [69, 77] €/MWh
standard deviation = 5.4 €/MWh

gas cost
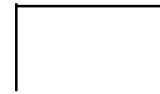mean $\in$ [34, 36.6] €/MWh
standard deviation = 3.9 €/MWh

Uncertainty characterization based on literature

Investment cost
PV, battery, electrolyzer, tank, fuel cell
epistemic: market

Investment cost
photovoltaic ϵ [430, 780] €/kWp
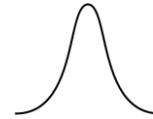battery ϵ [102, 354] €/kWh
electrolyzer ϵ [1400, 2100] €/kW
tank ϵ [12, 16] €/kWh
fuel cell ϵ [1500, 2400] €/kW
discount rate ϵ [4, 8] %

Uncertainty characterization based on literature

Solar irradiance and ambient temperature
aleatory: interannual variability
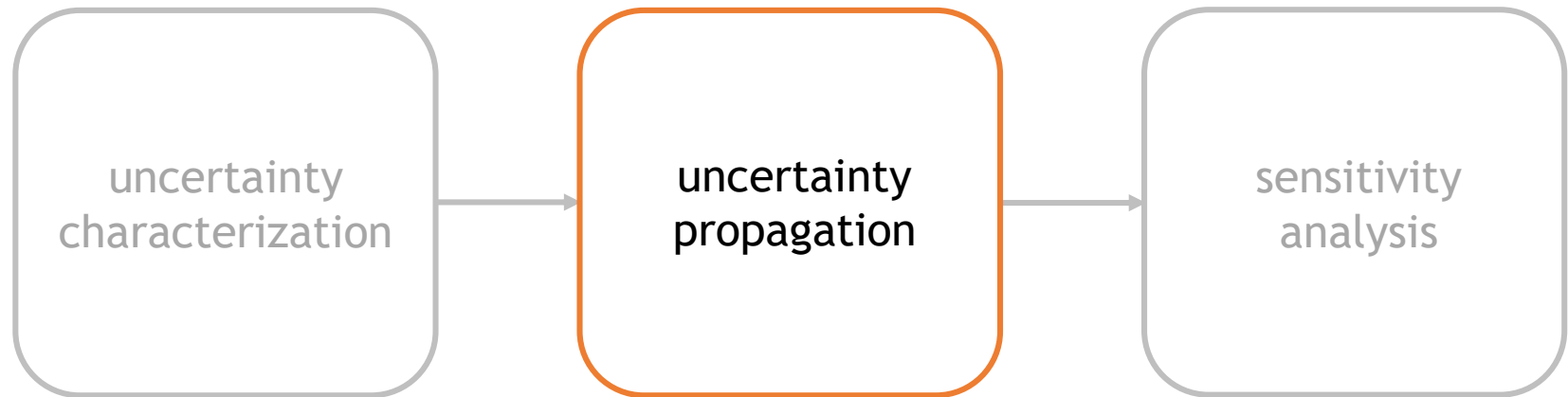
solar irradiance
mean = 1102 W/m^2
standard deviation = 2.9% of average annual solar irradiance

Ambient temperature
mean = 10.8 °C
standard deviation = 0.4 °C

How to characterize the uncertainty related to model parameters?

Polynomial Chaos Expansion on the system model to ensure computational tractability

$$\sum_{i=0}^{P} y_i \psi_i(\xi) \approx \text{model}(\xi)$$

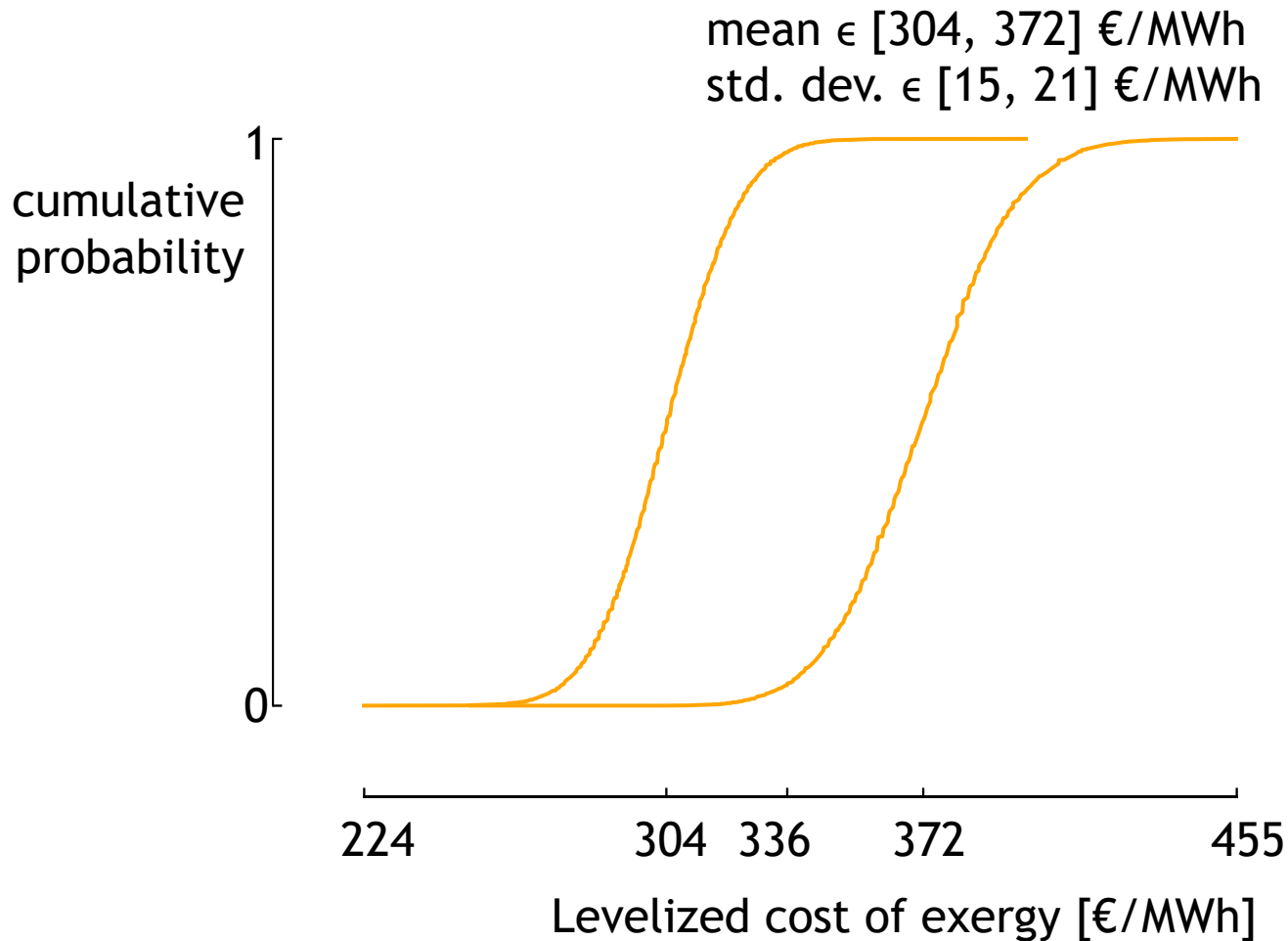Orthogonal polynomials

Vector uncertain parameters

Unknown coefficients
Found with real model evaluations

Schöbi, R. et al. "Global sensitivity analysis in the context of imprecise probabilities (p-boxes) using sparse polynomial chaos expansions." *Reliability Engineering & System Safety* 187 (2019): 129-141.
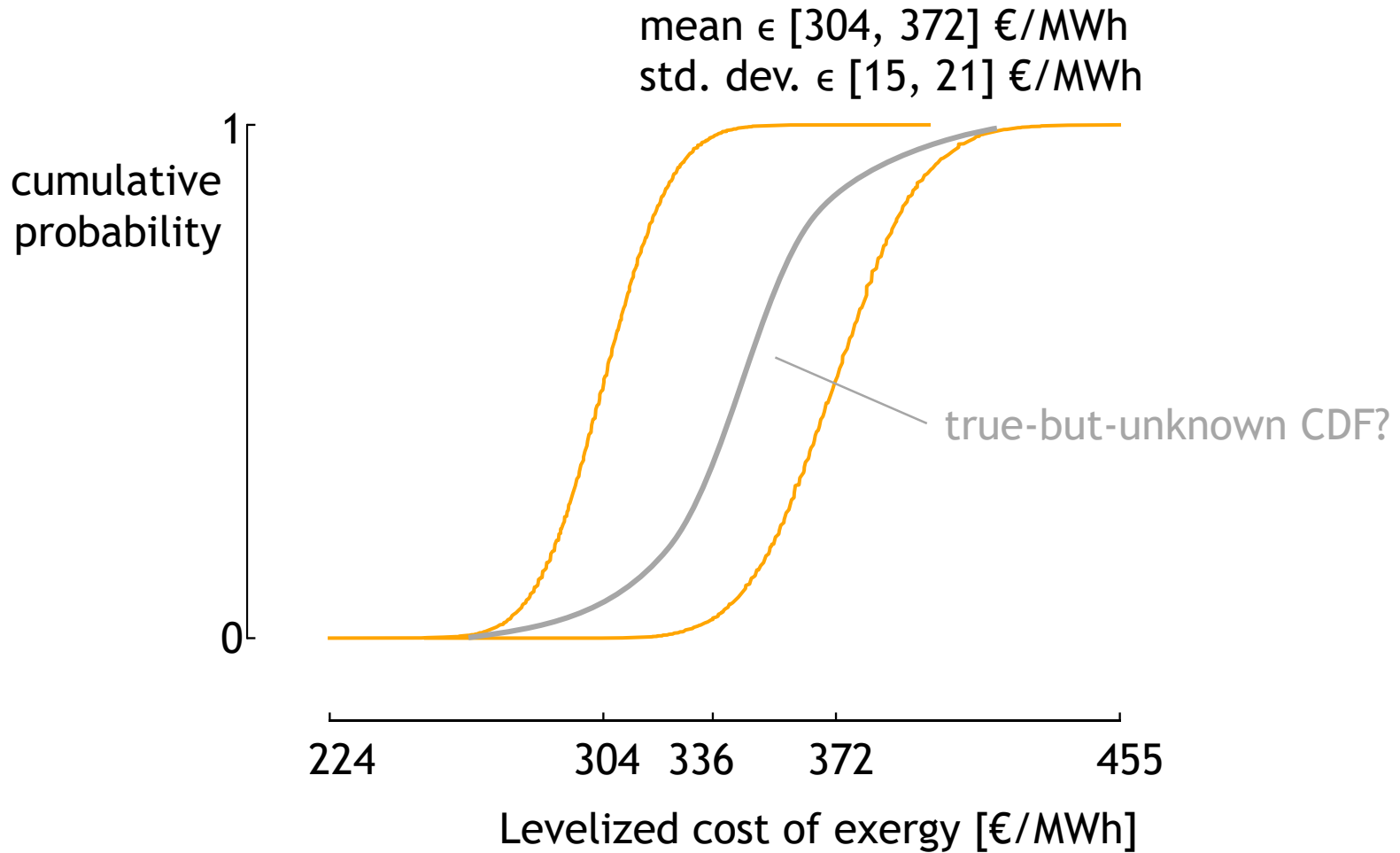
How to characterize the uncertainty related to model parameters?

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┌─────────────────┐      ┌─────────────────┐      ┌─────────────────┐
│                 │      │                 │      │                 │
│   uncertainty   │ ───▶ │   uncertainty   │ ───▶ │   sensitivity   │
│ characterization│      │   propagation   │      │    analysis     │
│                 │      │                 │      │                 │
└─────────────────┘      └─────────────────┘      └─────────────────┘
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The probability box of the Levelized Cost of Exergy for the photovoltaic design (2.7 kWp)

mean ∈ [304, 372] €/MWh
std. dev. ∈ [15, 21] €/MWh

cumulative probability

Levelized cost of exergy [€/MWh]

Epistemic uncertainty hides the true-but-unknown CDF

mean ∈ [304, 372] €/MWh
std. dev. ∈ [15, 21] €/MWh

cumulative probability

true-but-unknown CDF?

Levelized cost of exergy [€/MWh]

224   304 336   372   455

Sensitivity analysis on epistemic part indicates the main drivers

cumulative probability

electricity cost: 25%
heat demand: 20%
investment cost PV: 18%

224   304 336   372   455
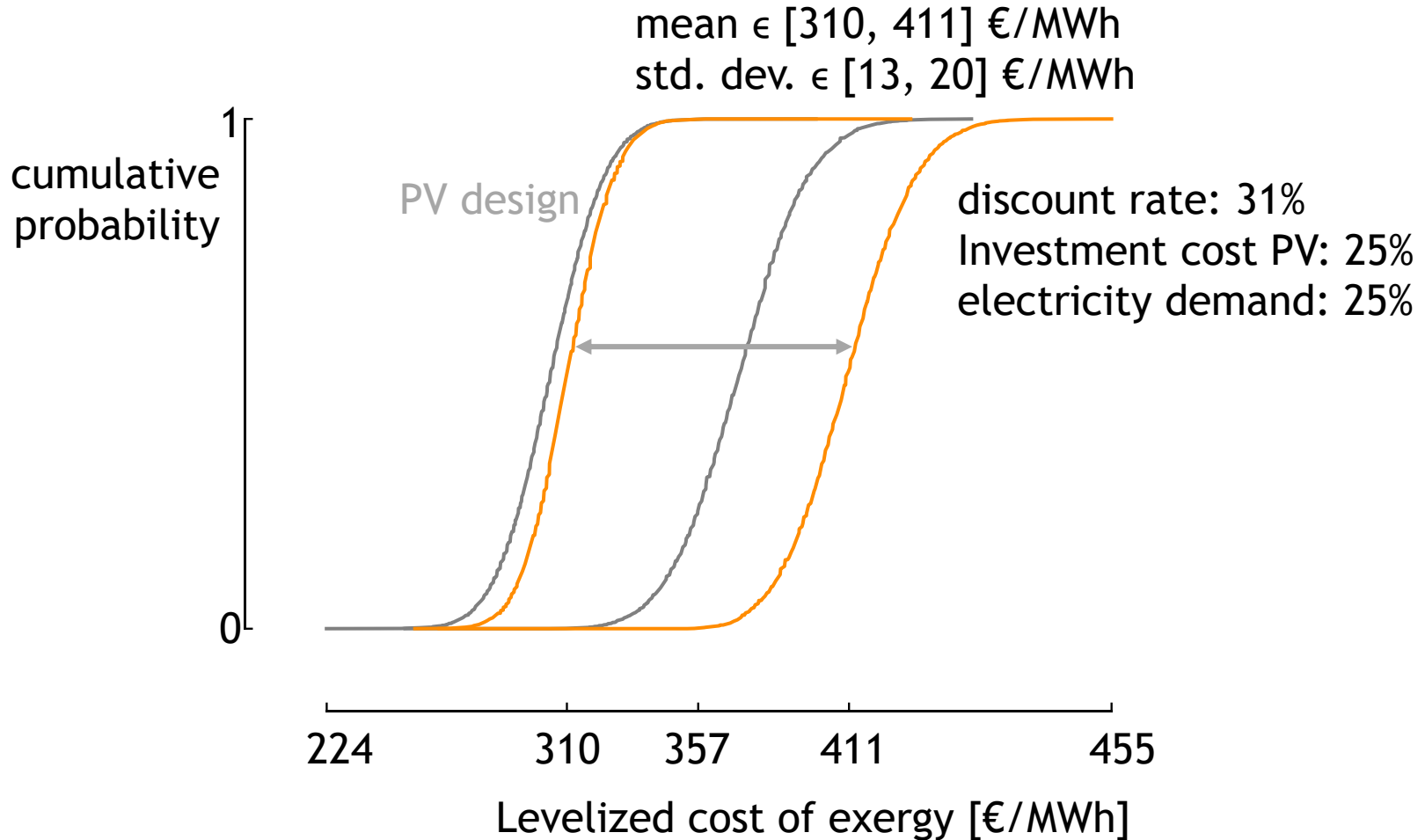
Levelized cost of exergy [€/MWh]
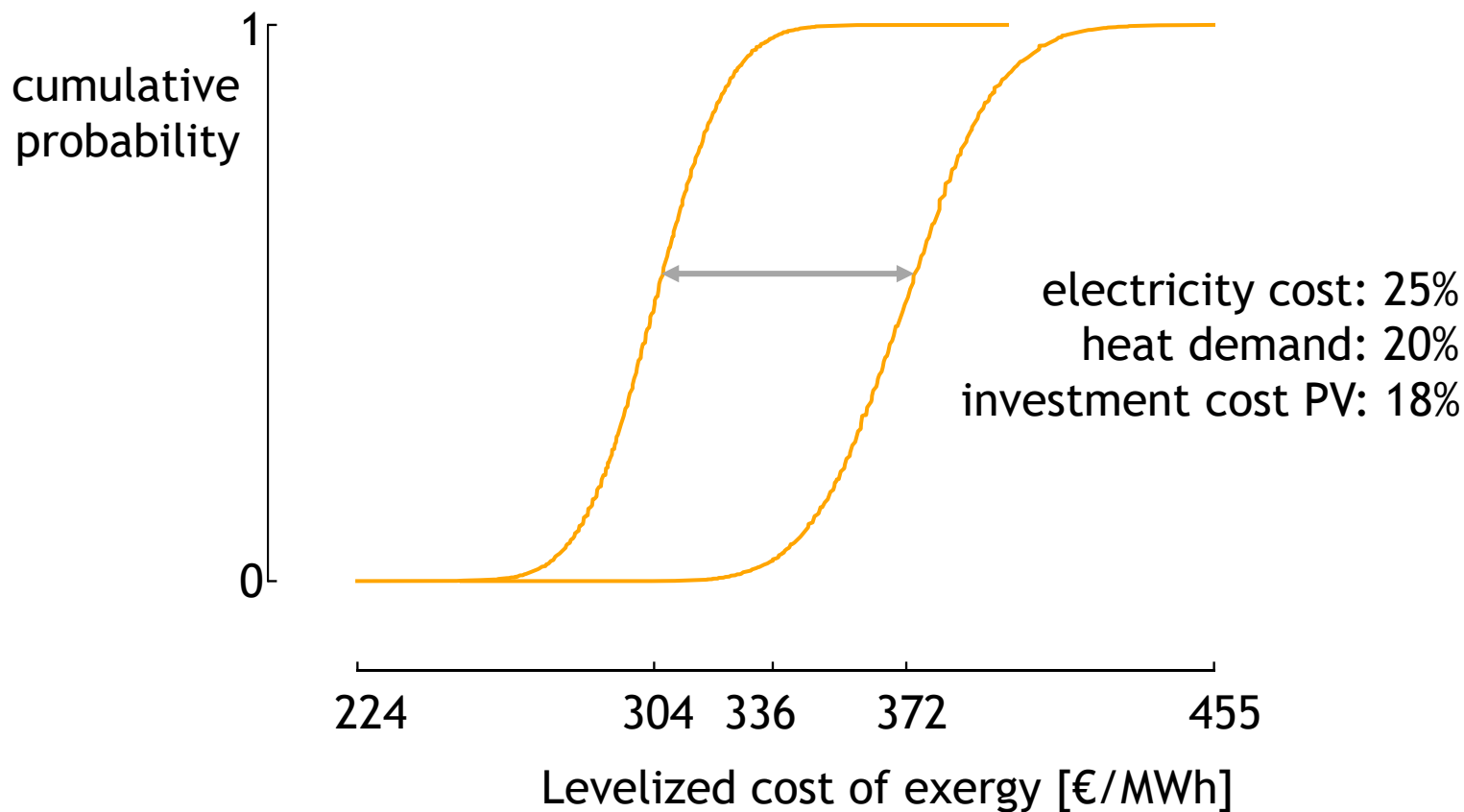
The standard deviation is mainly driven by the gas cost
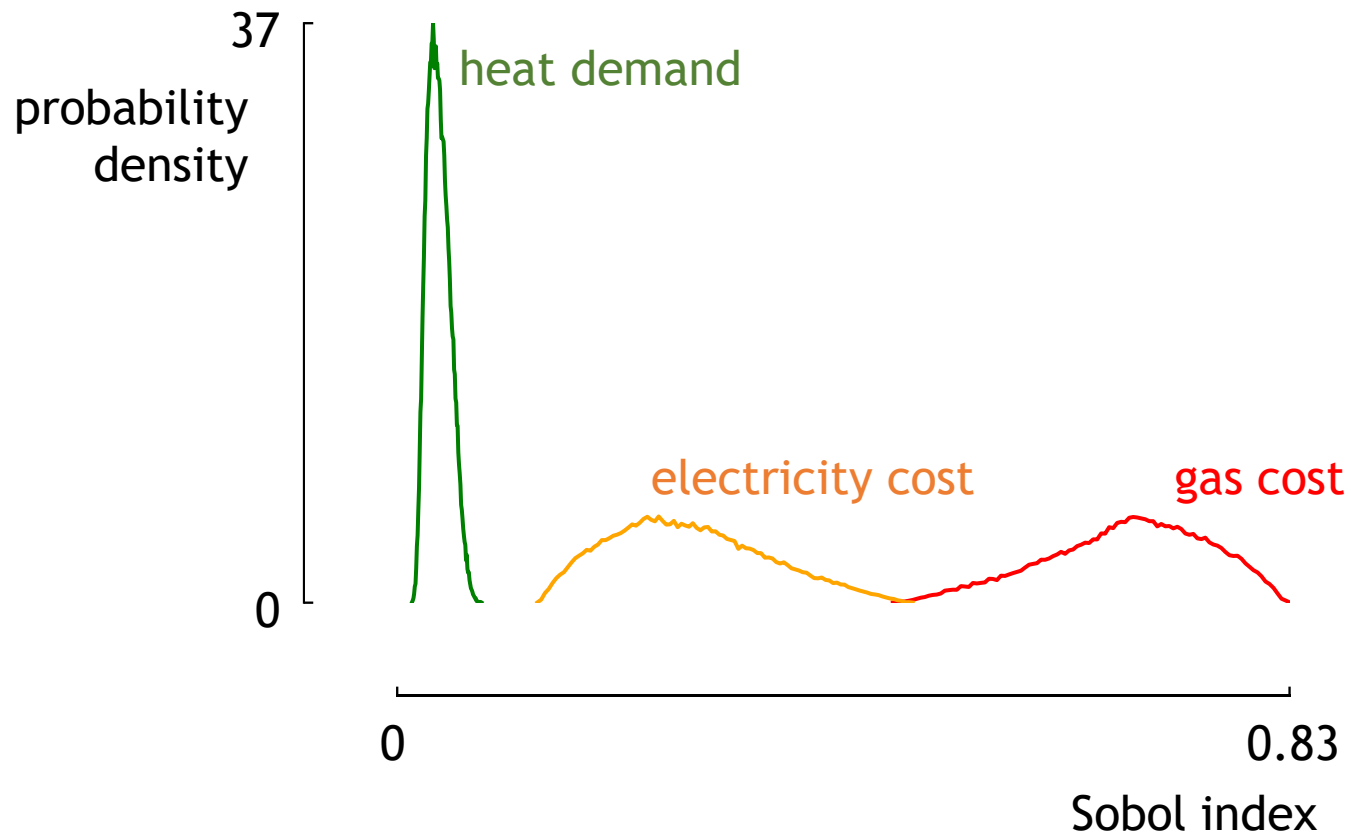
The probability box for the photovoltaic-battery design is subject to larger epistemic uncertainty
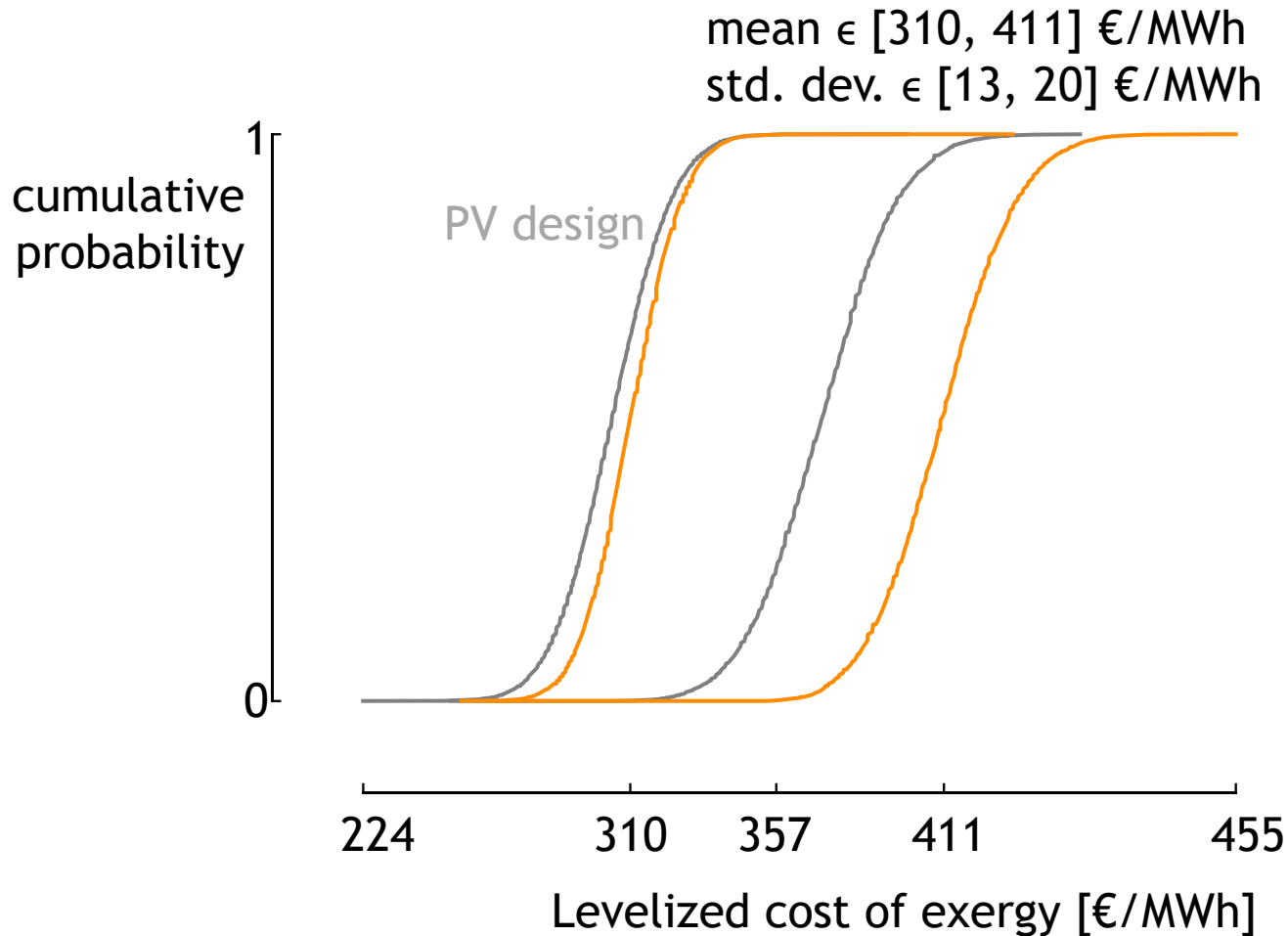
mean ∈ [310, 411] €/MWh
std. dev. ∈ [13, 20] €/MWh

cumulative probability

PV design

1

0

224   310   357   411   455

Levelized cost of exergy [€/MWh]

Epistemic uncertainty is dominated by discount rate, photovoltaic investment cost and electricity demand

mean ϵ [310, 411] €/MWh
std. dev. ϵ [13, 20] €/MWh

cumulative probability

PV design

discount rate: 31%
Investment cost PV: 25%
electricity demand: 25%

224   310   357   411   455

Levelized cost of exergy [€/MWh]

Standard deviation is dominated by the gas cost

probability density

37

0

heat demand

electricity demand

electricity cost

gas cost

0

0.89

Sobol index
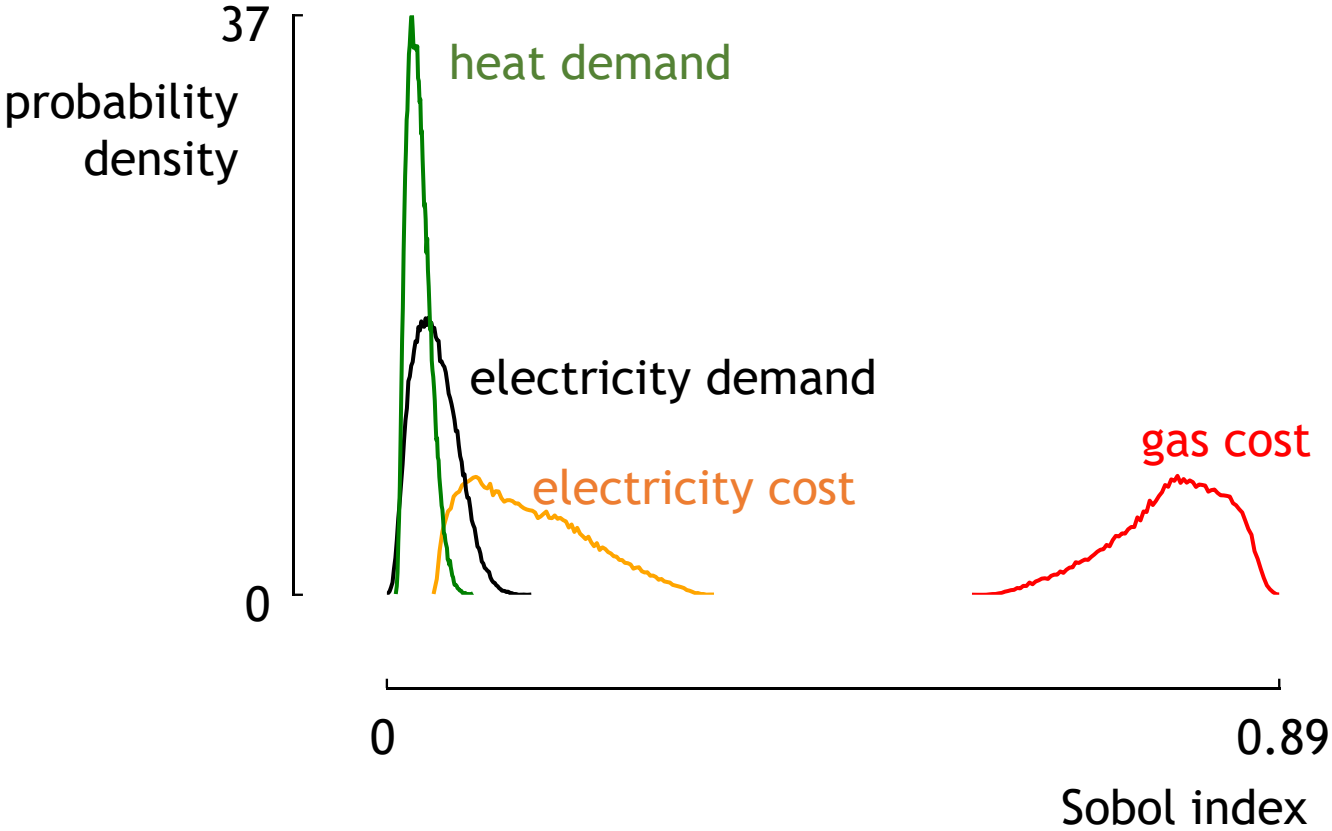
The probability box for the photovoltaic-battery-hydrogen design

mean $\in$ [446, 1149] €/MWh
std. dev. $\in$ [30, 68] €/MWh
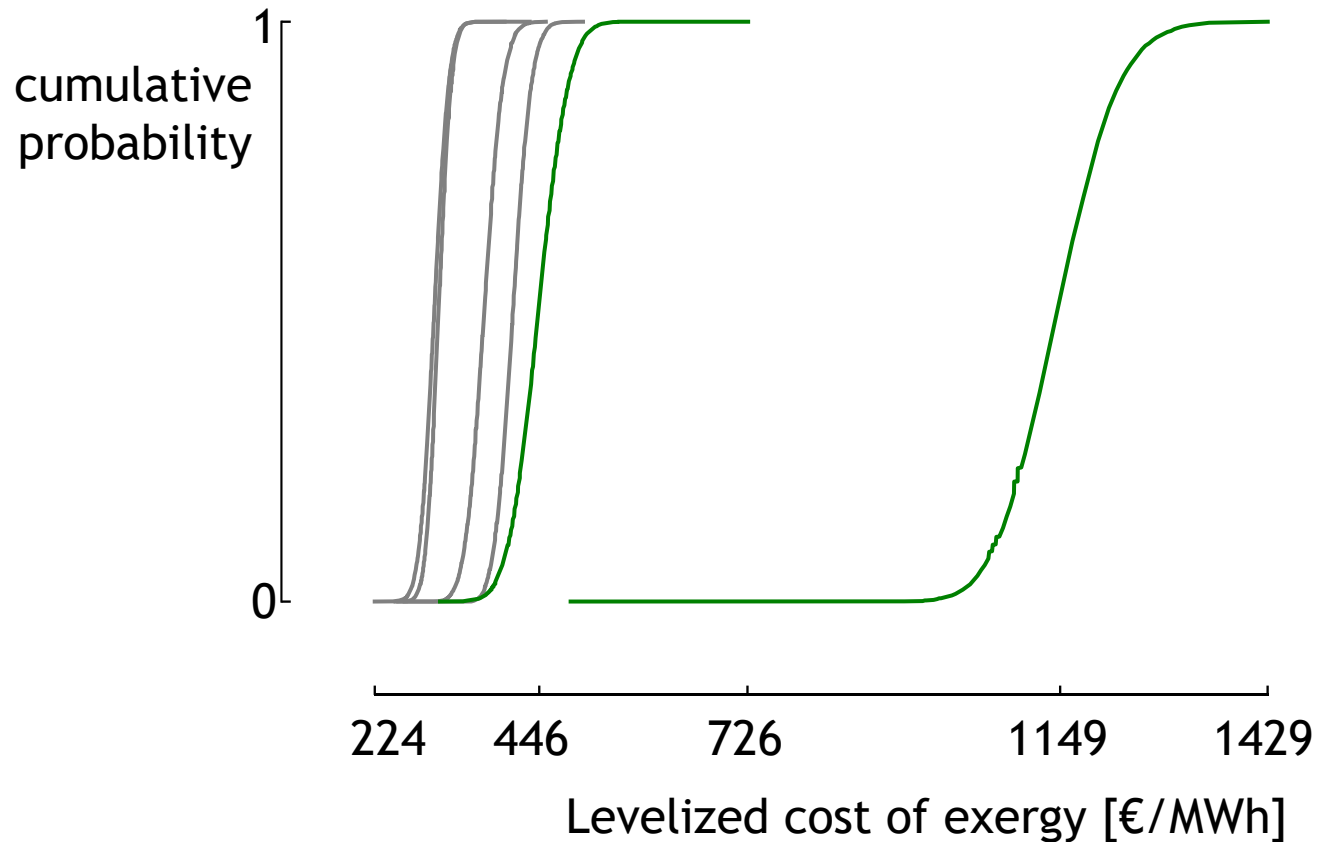
cumulative probability

1

0

224   446   726   1149   1429

Levelized cost of exergy [€/MWh]

Epistemic uncertainty is dominated by discount rate, photovoltaic investment cost and electricity demand

mean ∈ [446, 1149] €/MWh
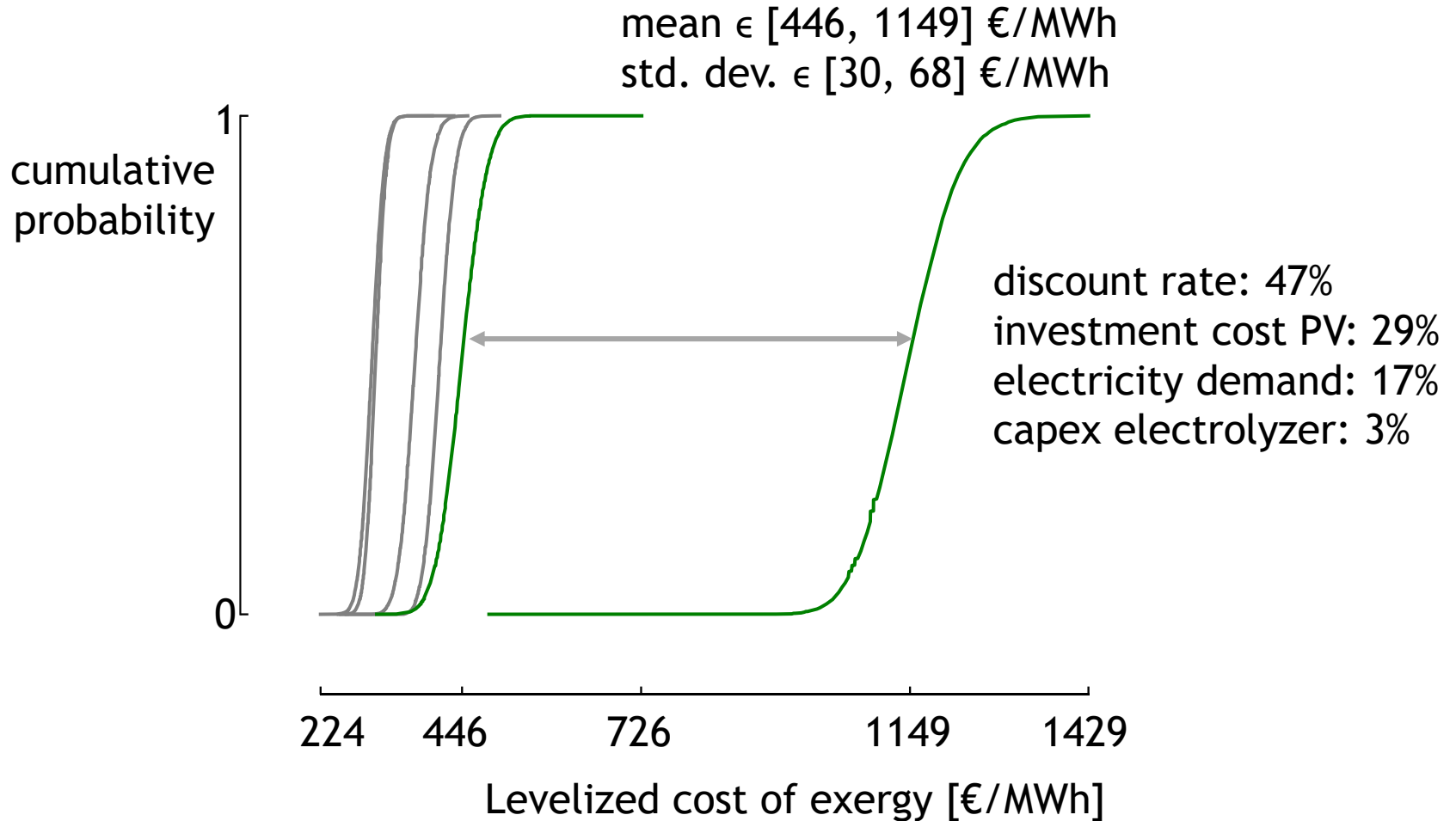std. dev. ∈ [30, 68] €/MWh

discount rate: 47%
investment cost PV: 29%
electricity demand: 17%
capex electrolyzer: 3%

cumulative probability

1

0

224   446   726   1149   1429

Levelized cost of exergy [€/MWh]

Standard deviation is dominated by the electricity cost and electricity demand
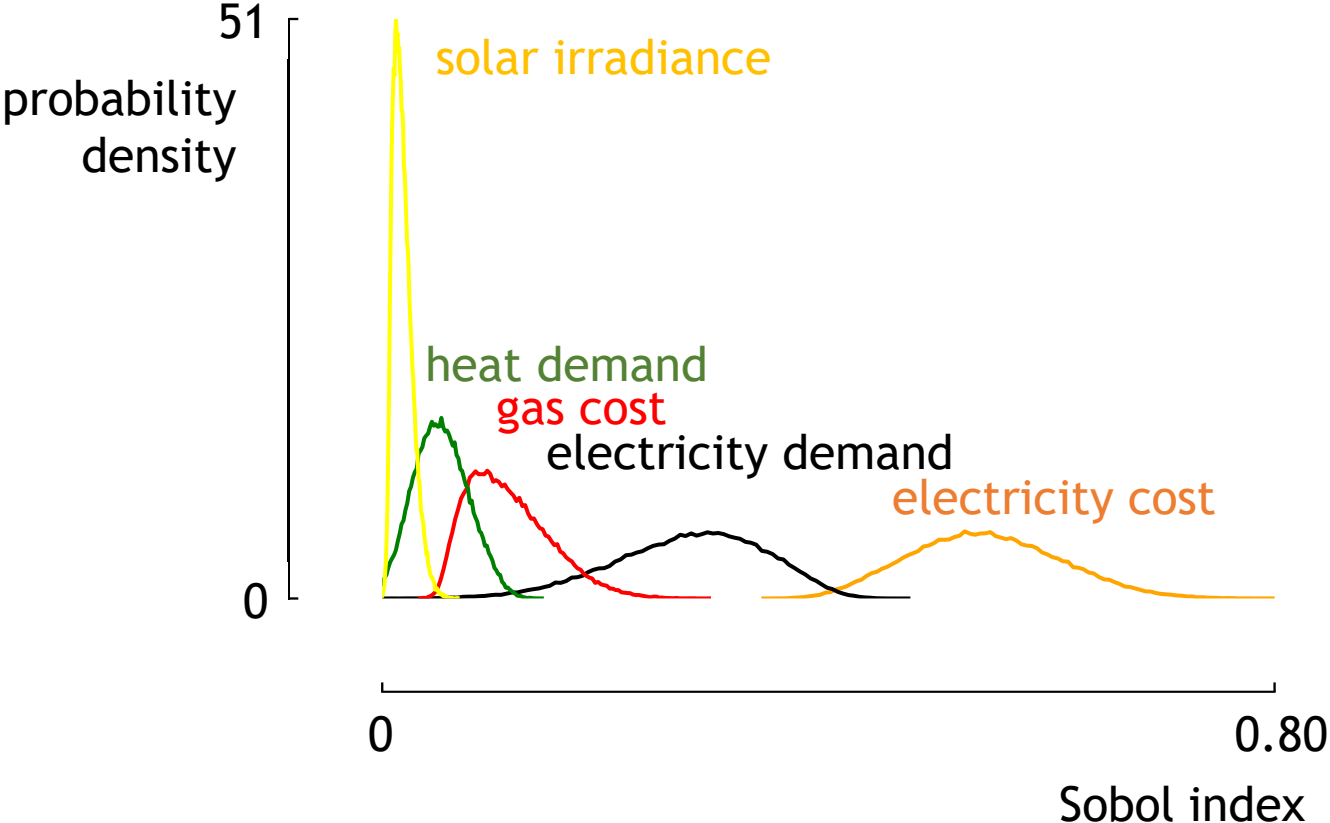
The framework will consider uncertainties in the design and highlight the industrial advantages of robust designs

uncertainty characterization → uncertainty propagation → sensitivity analysis
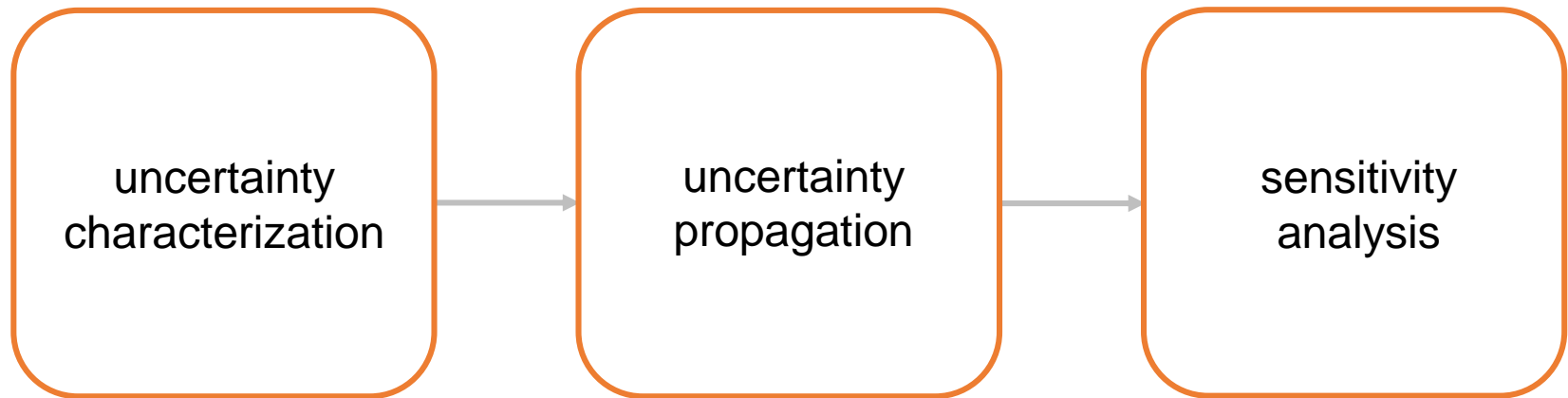
Conlusions and future opportunities

PV-battery design likely to be the most robust towards future uncertainty, however epistemic uncertainty makes this inconclusive

Gaining information on discount rate, PV investment cost, electricity cost and heat demand will reduce epistemic uncertainty efficiently

Both PV and PV-battery design are most sensitive to gas cost and electricity cost evolution in their levelized cost of exergy

Framework released open-source
and published in Journal of Open Source Software (2021)

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