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ASSESSMENT OF CLIMATE UNCERTAINTY IN AN INTEGRATED EUROPEAN POWER AND HEATING SYSTEM

GOR 2024, Leonie Sara Plaga, David Huckebrink, Valentin Bertsch

Chair of Energy Systems & Energy Economics

Overview

1 Motivation

2 Integrated power and heat system

3 Climate uncertainty assessment

4 Results

5 Conclusion and outlook

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Overview

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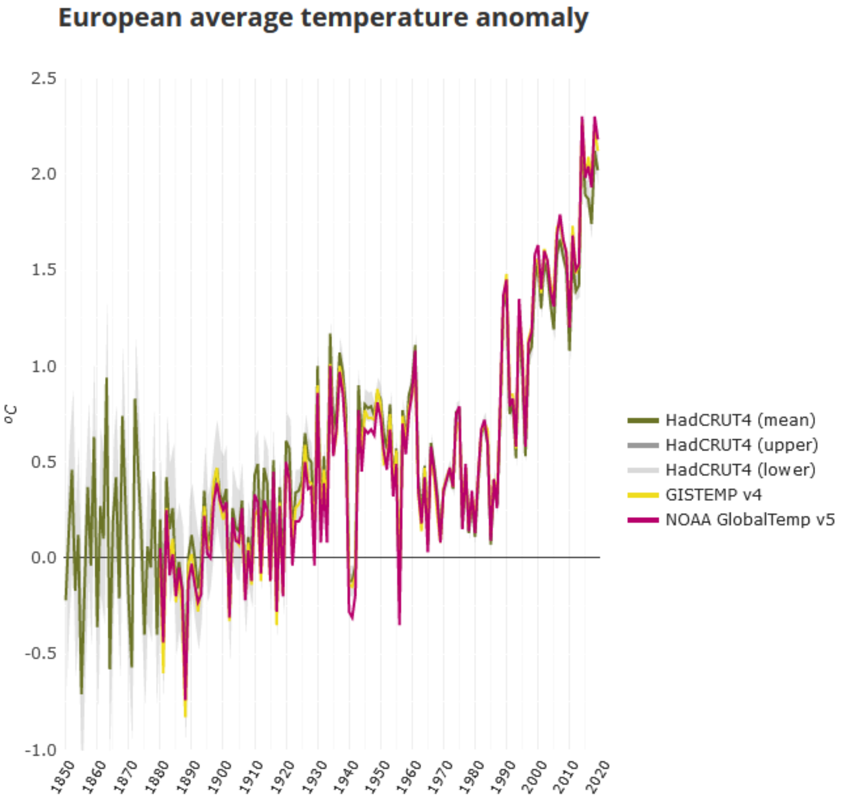
Motivation

- Climate change impacts already visible
- Energy systems depend on climate variables



Source: https://www.eea.europa.eu/data-and-maps/indicators/global-and-european-temperature-10/assessment

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Motivation

- Climate change impacts already visible
- Energy systems depend on climate variables
- Climate projections are highly uncertain
  - different models
  - different years
  - different RCPs

Source: https://www.eea.europa.eu/data-and-maps/indicators/global-and-european-temperature-10/assessment

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Motivation

- How can we plan an energy system, that is robust to different climate developments?
- How can we model influence of changing temperatures on heating and cooling demand?

→ **Robust optimization of integrated power and heat system**

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Overview

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Integrated power and heat system

Overview

- Least-cost energy system optimization
- Target year 2050
- Zero CO_2 emissions

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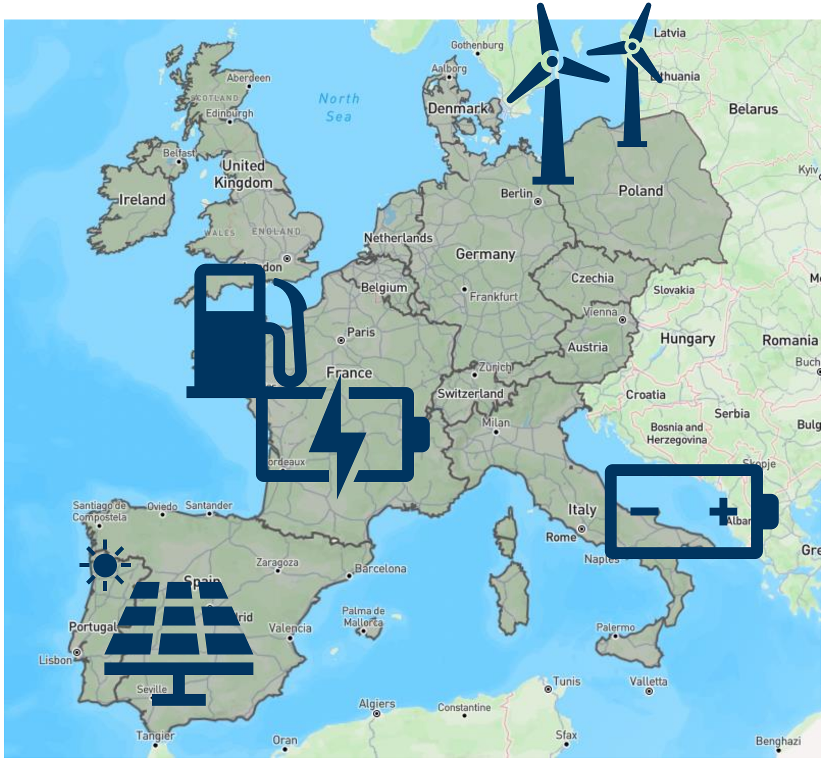
Integrated power and heat system

Power

- Green field modelling except for hydro power
- Investment possibilities
- Analysis in energy system model backbone[1]
- Most power system data from pypsa-eur[2]



[1] Helistö et. al, 2019, doi.org/10.3390/en12173388
[2] Hörsch et. al, 2018, doi.org/10.1016/j.esr.2018.08.012

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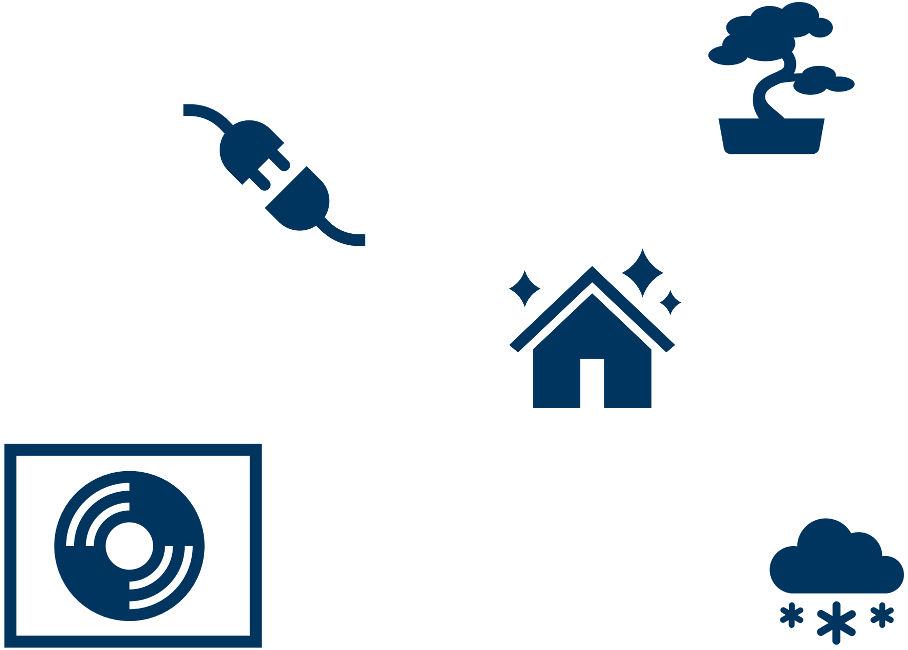
Integrated power and heat system

Heat

- Investments possibilities
- Retrofits possible



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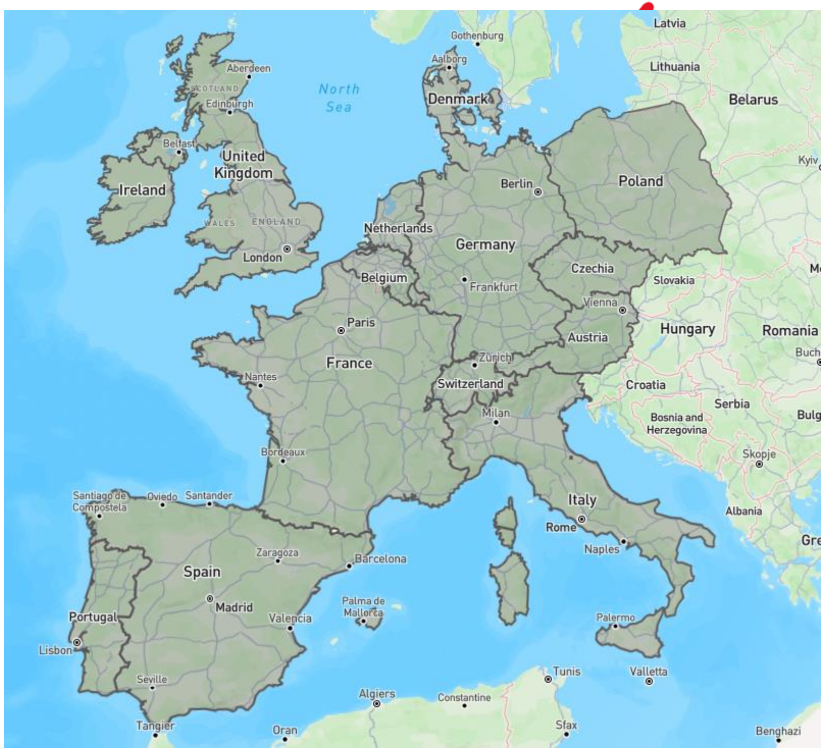
Integrated power and heat system

Climate data

Heat

- Simplified representation of buildings
- Aggregated per country
- U-values via regression with Hotmaps data[1]
- 20° C temperature indoor



[1] Pezzutto et al. Hotmaps, D2.3 WP2 Report – Open Data Set for the EU28, 2019

Overview

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Assessment of climate uncertainty

Climate data and uncertainty

- Climate projections from Euro-Cordex
- Processed with tool *cd2es* (https://gitlab.ruhr-uni-bochum.de/ee/cd2es)
- Bias-adopted temperature data
  - Two climate models
  - 5 years (2045 – 2050)
  - Two RCPs (2.6, 8.5)
- Only for temperature

(Sun et al., 2019)

Assessment of climate uncertainty

Compared methods

- Base case: choose average year for planning of investments
- Two-stage robust optimization (column and constraint generation algorithm)
- Time series aggregation method *obpc*

(Sun et al., 2019)

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Assessment of climate uncertainty

Two-stage robust optimization

- Uncertainty set U
- Optimization problem:

First stage decision (e.g. investment)

$$\min_{y} \boldsymbol{c}^T \boldsymbol{y} + \max_{u \in U} \min_{x \in F(\boldsymbol{y}, u)} \boldsymbol{b}^T \boldsymbol{x}$$

Second stage decision (e.g. dispatch)

$$\text{s.t.} \, \boldsymbol{Ay} \leq \boldsymbol{d}, \boldsymbol{y} \in \boldsymbol{S_y}$$

$$\boldsymbol{F}(\boldsymbol{y}, u) = \{\boldsymbol{x} \in \boldsymbol{S_x} : \boldsymbol{Gx} \geq \boldsymbol{h} - \boldsymbol{Ey} - \boldsymbol{M}u\}$$

- Uncertainty set $U = \{all\ scenarios\}$

(Zheng, Zhao, 2013)

Assessment of climate uncertainty

Two-stage robust optimization – column and constraint generation algorithm

$$\min_{y} \boldsymbol{c}^T \boldsymbol{y} + \max_{u \in U} \min_{x \in F(\boldsymbol{y},u)} \boldsymbol{b}^T \boldsymbol{x}$$

1. Solve master problem for one scenario:

$$\Rightarrow \min_{y,x} \boldsymbol{c}^T \boldsymbol{y} + \boldsymbol{b}^T \boldsymbol{x}$$

2. Solve sub problems for all scenarios with solution $\boldsymbol{y}$:

$$\Rightarrow \max_{u \in U} \min_{x \in F(\boldsymbol{y},u)} \boldsymbol{b}^T \boldsymbol{x}$$

(Zheng, Zhao, 2013)

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Assessment of climate uncertainty

Two-stage robust optimization – column and constraint generation algorithm

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2. Solve sub problems for all scenarios with solution $\boldsymbol{y}$:

$$\Rightarrow \max_{u \in U} \min_{x \in F(\boldsymbol{y},u)} \boldsymbol{b}^T \boldsymbol{x}$$

3. Add constraints to master problem:
   investment may never be smaller than in solution $\boldsymbol{y}$
4. Return to 1., use worst scenario in master problem

Exit loop, if all sub problem solutions are below threshhold

(Zheng, Zhao, 2013)

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Assessment of climate uncertainty

Robustness via time series aggregation

Day 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

⬇

Day 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

⬇

System optimization

(Sun et al., 2019)

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Assessment of climate uncertainty

Robustness via time series aggregation – *obpc*

- *O*ptimization *b*ased: Clusters in result space
  - Run every day individually
  - Use results for clustering
- Possibility to assign *p*riority to days in the *c*lustering process

Traditional
Demand timeseries
Capacity factors
Hydro inflows

→

Based on optimization results
Investment decisions
Generated energy
Costs

(Sun et al., 2019)

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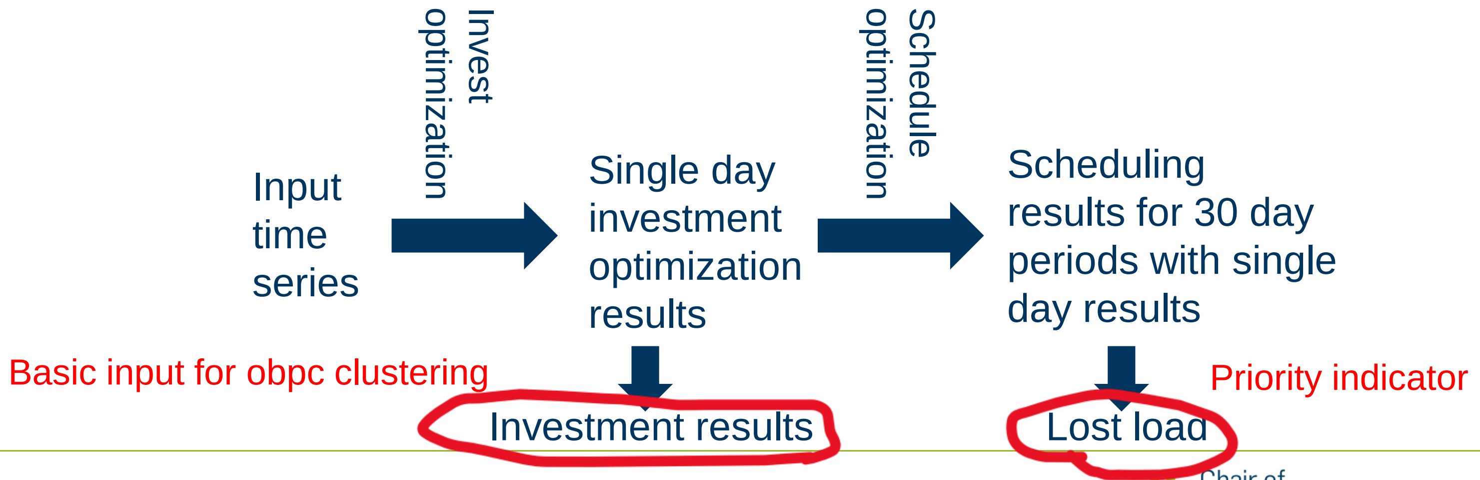
Assessment of climate uncertainty

Lost load as priority indicator

- Robust system: avoid lost load
- Lost load: no result from single day investment optimization
- Perform a schedule run with the single day results on a 30-day sample



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Assessment of climate uncertainty

Lost load as priority indicator

- Robust system: avoid lost load
- Lost load: no result from single day investment optimization
- Perform a schedule run with the single day results on a 30-day sample

→ Only solve 1 365-day optimization model

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Overview

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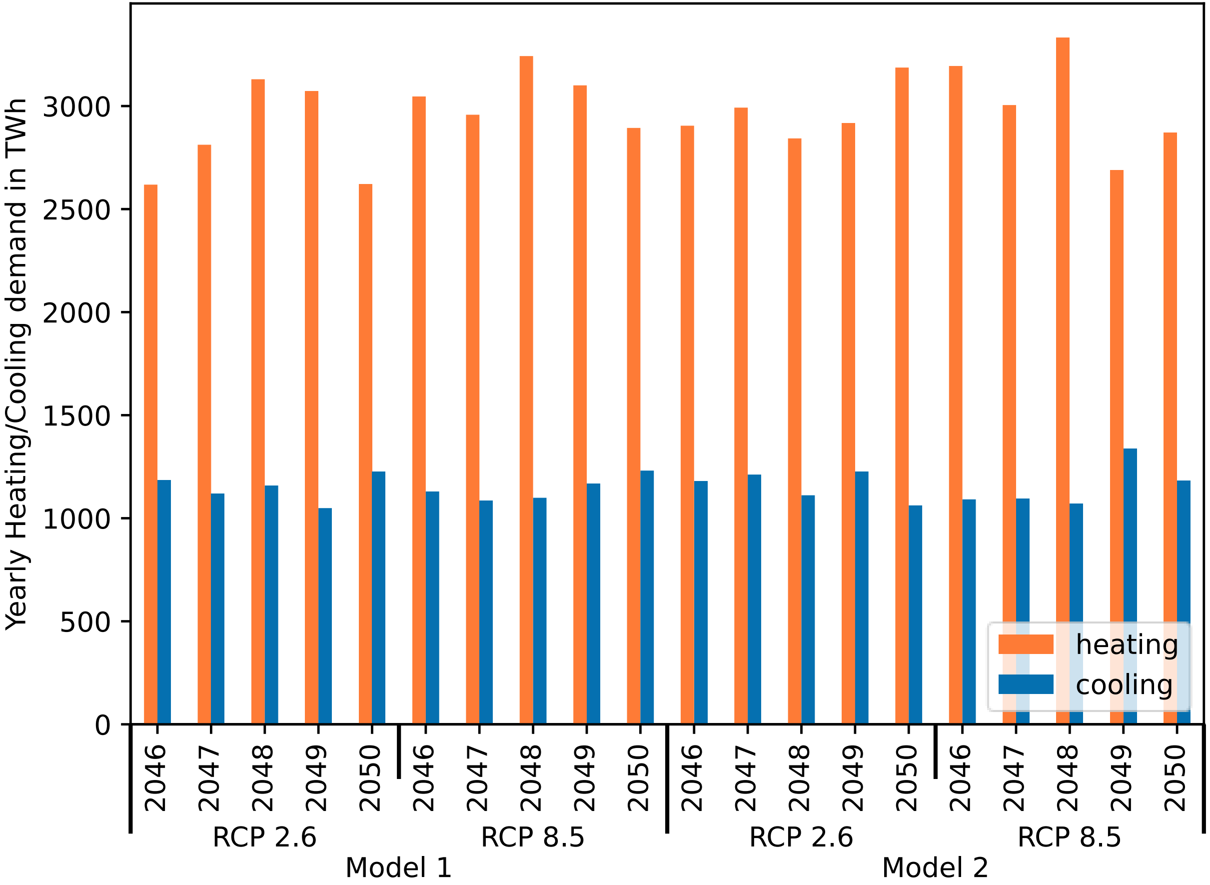
Results

Changes in heating and cooling demand



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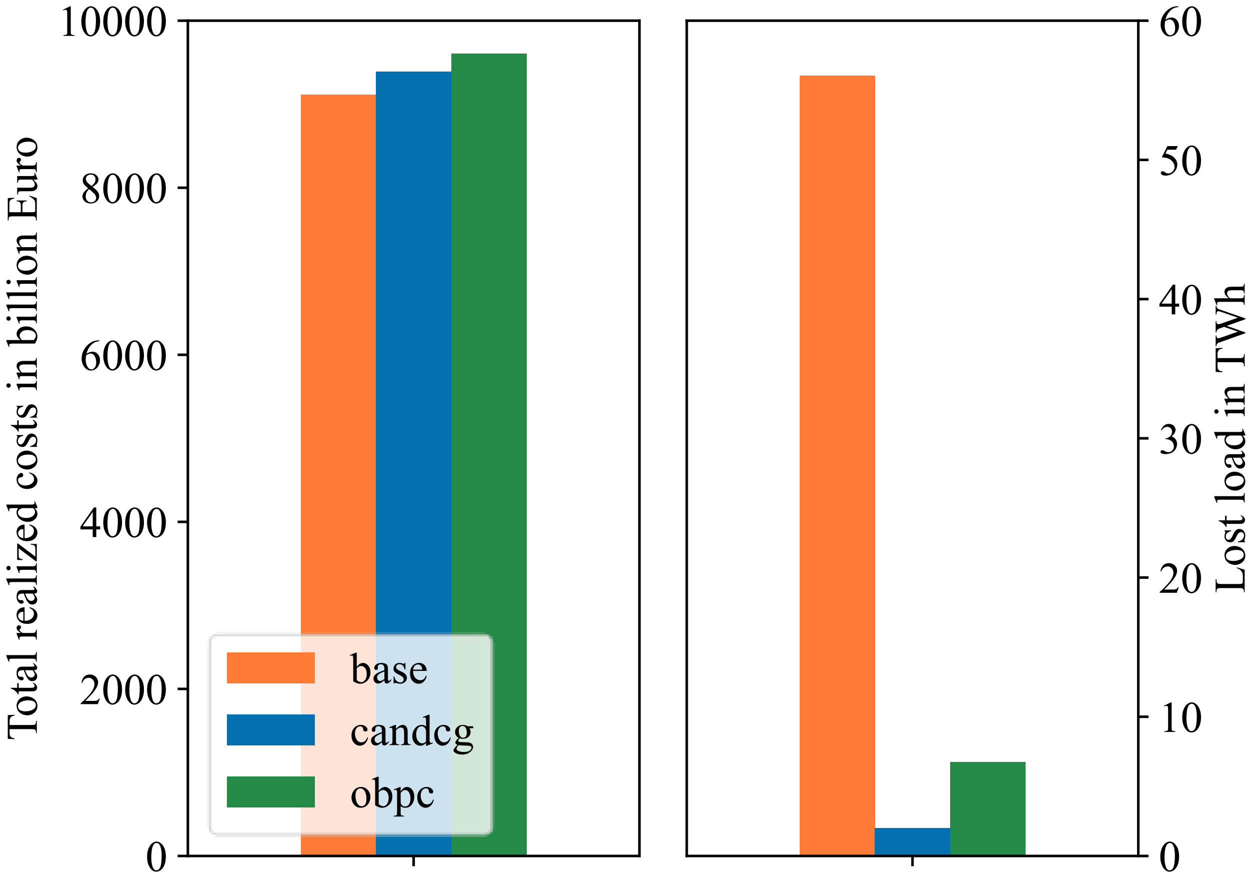
Results

Costs and lost load



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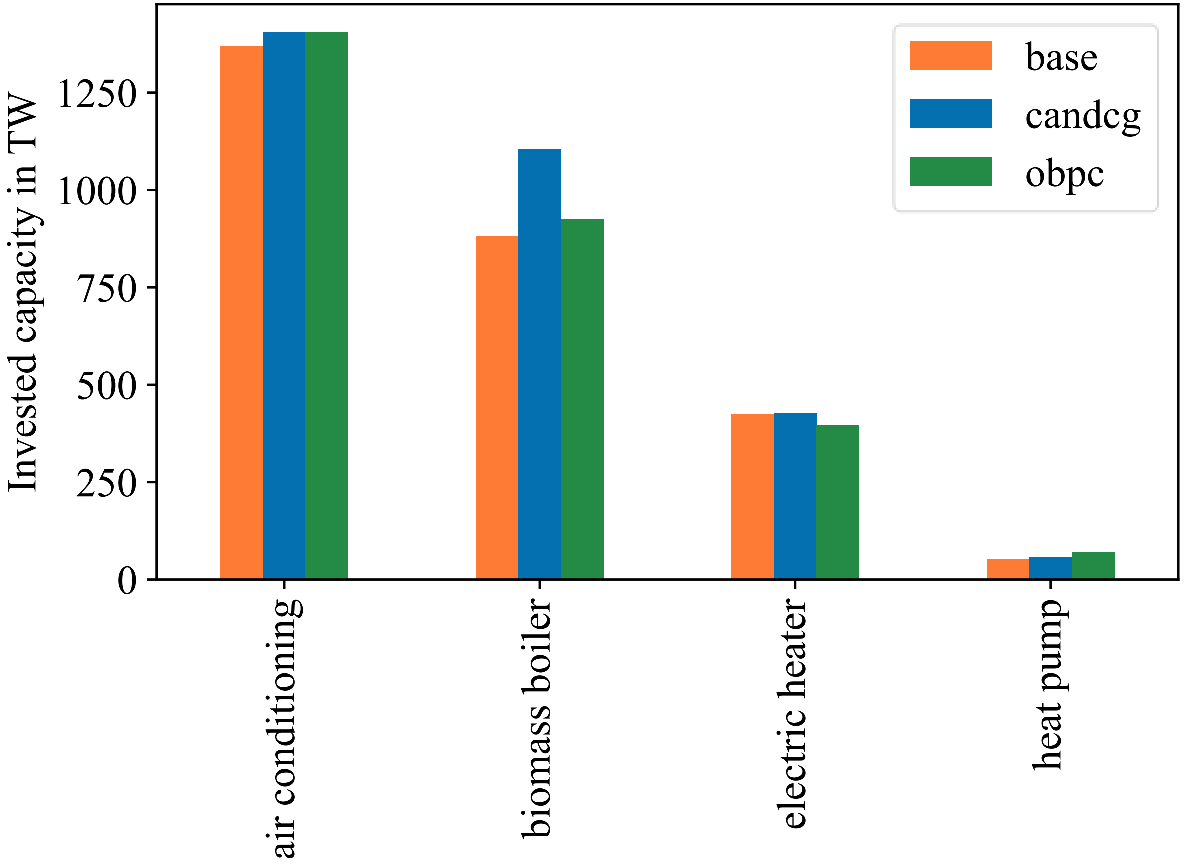
Results

Investment – heat technologies



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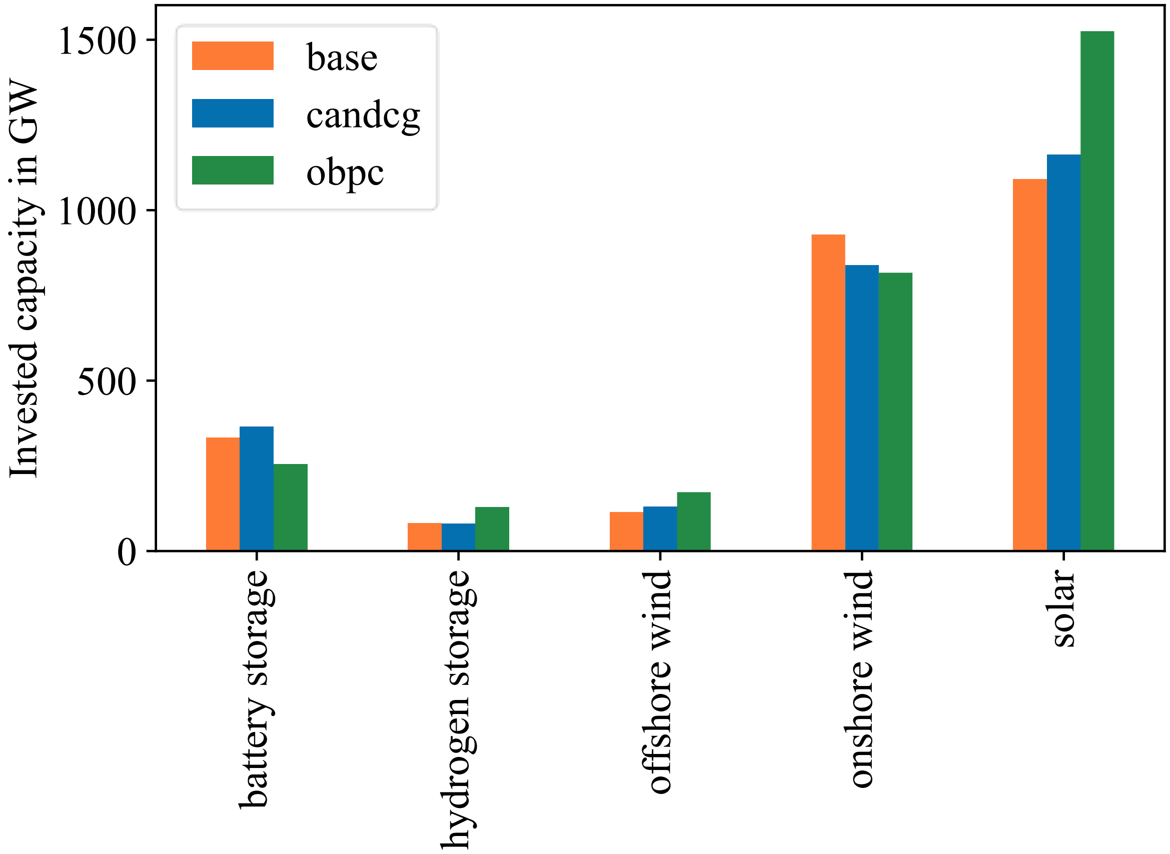
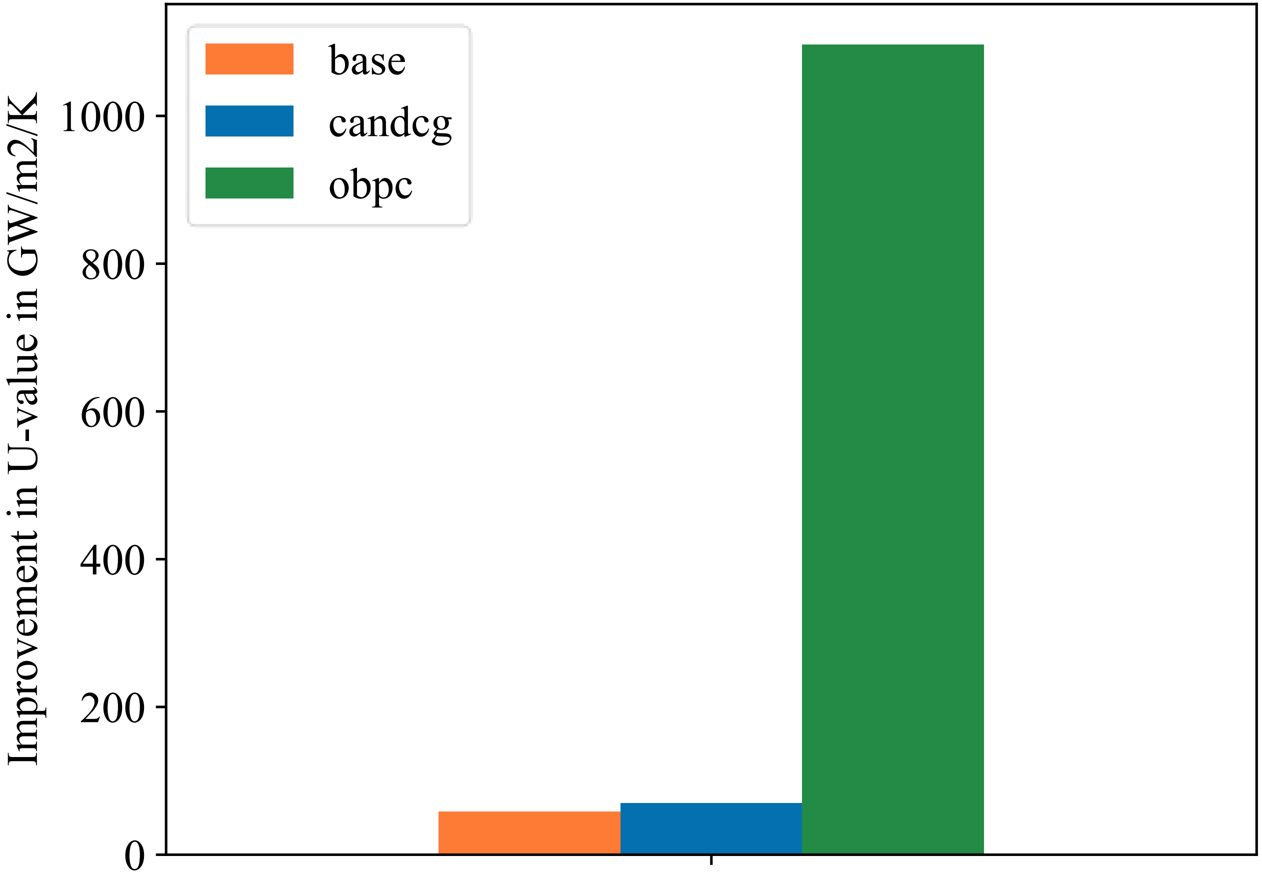
Results

Investment – generation technologies



Results

Investment – retrofit



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Overview

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Conclusion and Outlook

Conclusion

- Climate change impact on integrated heat and power system
- Interyear variability greater than difference between RCPs/models
- C&CG and *obpc* reduce lost load
- *obpc* faster, but higher lost load abatement costs
- Very different solutions in investment space

(Sun et al., 2019)

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Conclusion and Outlook

Outlook

- Improve performance of *obpc*
- Look into more climate imapcts
  - Hydro power
  - Wind power
  - Solar power
  - Efficiency of thermal power plants
- Flexible temperatures in buildings
- Constrain biomass usage

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Thank you for your attention!

CONTACT

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Additional Slides

Influence of climate variables on energy systems

- Demand
- Hydro power
- Wind power
- Solar power
- Efficiency of thermal power plants

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Additional Slides

Influence of climate variables on energy systems

- Demand
  - Temperature influences heating and cooling demand
  - Country-specific regression

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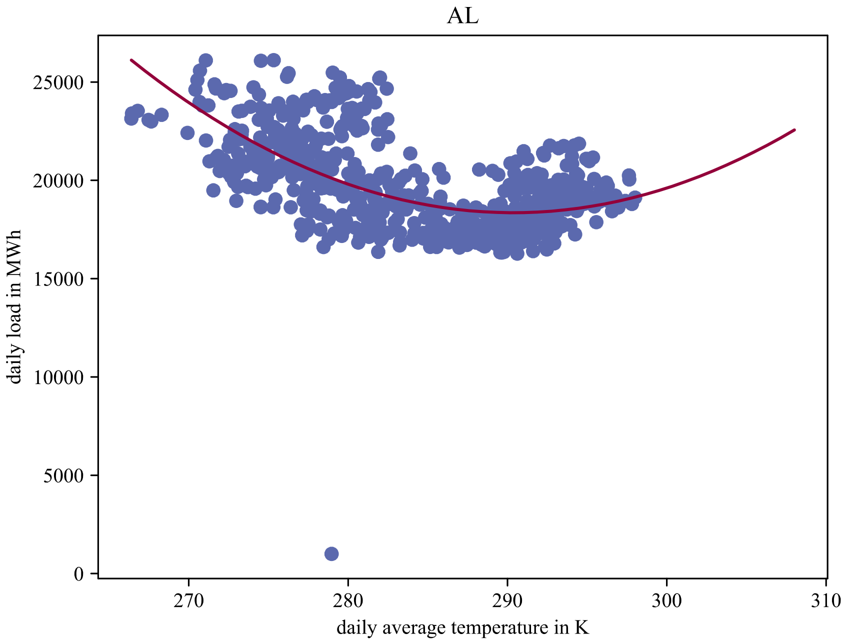
Additional Slides

Influence of climate variables on energy systems



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Additional Slides

Influence of climate variables on energy systems

- Hydro power
  - River-runoff determines production
  - Site-specific evaluation very costly
  - Europe-wide regression
  - Estimating country-specific hydro production based on European trend

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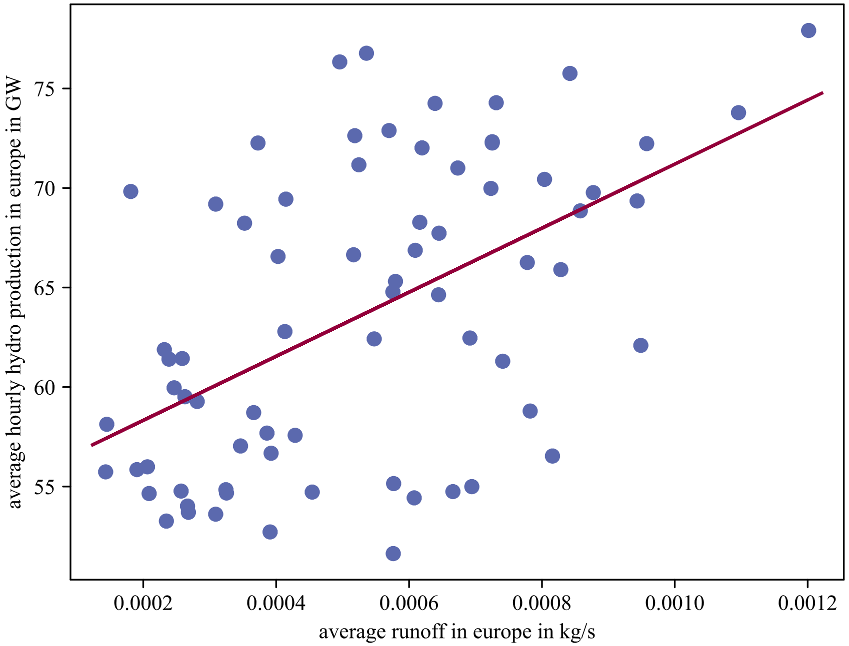
Influence of climate variables on energy systems



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Additional Slides

Influence of climate variables on energy systems

- Wind power
  - Interpolate wind speed to hub height
  - Use standardized production functions
- Solar power
  - Output depends on solar irradiation
  - Rising temperature decreases cell efficiency
  - Temperature of cell rises with outside temperature and irradiation

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Additional Slides

Influence of climate variables on energy systems

- Efficiency of thermal power plants
  - Cooling system is depending on temperature
  - Once-through cooling more vulnerable than closed-loop cooling
  - In this study: only closed-loop

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Additional Slides

Influence of climate variables on energy systems

- Wind power
  - Climate models report wind speeds
  - Interpolate to hub height:

$$v(h) = v(h_0) \cdot \left(\frac{h}{h_0}\right)^{1/7}$$

  - Calculate capacity factor:

$$c_\mathrm{f} = \begin{cases} 0, & v < v_\mathrm{in} \\ \frac{v^3 - v_\mathrm{in}^3}{v_\mathrm{r}^3 - v_\mathrm{in}^3}, & v_\mathrm{in} \leq v < v_\mathrm{r} \\ 1, & v_\mathrm{r} \leq v < v_\mathrm{out} \\ 0, & v > v_\mathrm{out} \end{cases}$$

Additional Slides

Influence of climate variables on energy systems

- Solar power
  - Rising temperature decreases cell efficiency:

$$\eta = \eta_{\mathrm{STC}}\left(1 - \beta(T_{\mathrm{cell}} - T_{\mathrm{STC}})\right)$$

  - Temperature of cell rises with outside temperature and irradiation:

$$T_{\mathrm{cell}} = T_{\mathrm{am}} + c \cdot G$$

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Additional Slides

Influence of climate variables on energy systems

- Efficiency of thermal power plants
  - Cooling system is depending on temperature
  - Once-through cooling more vulnerable than closed-loop cooling
  - In this study, only closed-loop:

$$\eta = \begin{cases} \eta_0, & T \leq T_{\text{health}} \\ \eta_0\left(1 - \rho(T - T_{\text{health}})\right), & T > T_{\text{health}} \end{cases}$$

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State-of-the-art robust optimization

Column and constraint generation algorithm

- Uncertainty set U
- Optimization problem:

$$\min_{y} \boldsymbol{c}^T \boldsymbol{y} + \max_{u \in U} \min_{x \in F(\boldsymbol{y},u)} \boldsymbol{b}^T \boldsymbol{x}$$

$$\text{s.t. } \mathbf{Ay} \leq \boldsymbol{d}, \boldsymbol{y} \in \boldsymbol{S}_{\mathbf{y}}$$

(Zeng., 2013)

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State-of-the-art robust optimization

Column and constraint generation algorithm

- Set $LB = -\infty$, $UB = +\infty$, $k = 0$ and $O = \emptyset$
- Solve the following master problem.

$$MP2: \min_{y,\eta} \boldsymbol{c}^T \boldsymbol{y} + \eta$$

$$\text{s.t. } \mathbf{Ay} \leq \boldsymbol{d}, \boldsymbol{y} \in \mathbf{S_y}$$

$$\eta \geq \boldsymbol{b}^T \boldsymbol{x}_l, \forall l \in O$$

$$Ey$$

- MP2
- : min y,η
- s.t. Ay ≥ d
- η ≥ bTxl
- Ey + Gxl
- y ∈ Sy

(Zeng., 2013)

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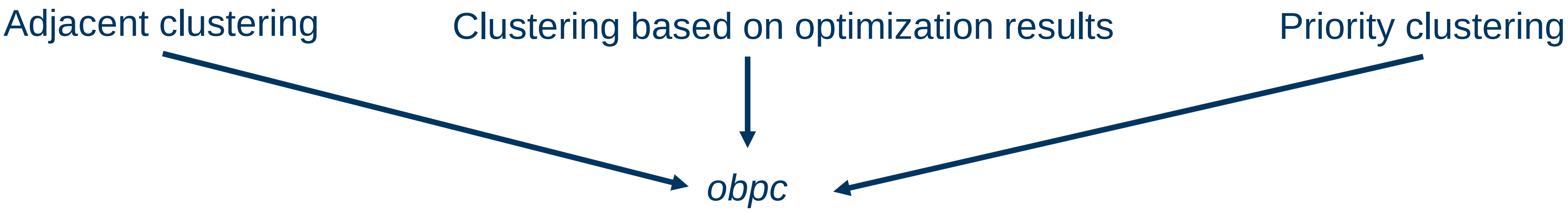
Timeseries aggregation methods

Overview

- Reduce timeseries with length *n* to shorter timeseries with length *n'*
- Aggregation of redundant information
- Many different methods
- No method to improve robustness



(Hoffman et al., 2020)

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Adjacent clustering

Basic method

- Combine vectors with lowest Euclidean distance
- Only neighbouring vectors can form clusters → conserves temporal order

$$\overset{1}{\begin{pmatrix}1\\1\end{pmatrix}}\overset{2}{\begin{pmatrix}0.7\\0.5\end{pmatrix}}\overset{3}{\begin{pmatrix}1\\1.1\end{pmatrix}}\overset{4}{\begin{pmatrix}0\\0\end{pmatrix}}\overset{5}{\begin{pmatrix}0.3\\0.4\end{pmatrix}}$$

$$\overset{1}{\begin{pmatrix}1\\1\end{pmatrix}}\overset{2}{\begin{pmatrix}0.7\\0.5\end{pmatrix}}\overset{3}{\begin{pmatrix}1\\1.1\end{pmatrix}}\overset{4}{\left[\begin{pmatrix}0.15\\0.2\end{pmatrix}\right]}$$

(Hoffman et al., 2020)

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Clustering based on optimization results

Original Method

- Divide timeseries in smaller timeslices (e.g. days)
- Optimize the smaller timesclies individually
- Cluster based on optimization results

Traditional
Demand timeseries
Capacity factors
Hydro inflows

→

Based on optimization results
Investment decisions
Generated energy
Costs

(Sun et al., 2019)

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Priority clustering

Original Method

- Three groups:
  1. Very important timesteps
  2. Important timesteps
  3. Normal timesteps

(García-Cerezo, 2022)

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Priority clustering

Original Method

- Cluster with the following adjustments:
  - Very important clusters cannot be merged
  - Merging clusters with the same importance: centroid = average of clusters
  - Merging clusters with the different importance: centroid = centroid of more important cluster

1 2 3 4 5

$$\begin{pmatrix}1\\1\end{pmatrix}\begin{pmatrix}0.7\\0.5\end{pmatrix}\begin{pmatrix}1\\1.1\end{pmatrix}\begin{pmatrix}0\\0\end{pmatrix}\begin{pmatrix}0.3\\0.4\end{pmatrix}$$

both 4 and 5 are very important

4 and 5 have same importance

1 2 3 4

$$\begin{pmatrix}1\\1\end{pmatrix}\begin{pmatrix}0.7\\0.5\end{pmatrix}\begin{pmatrix}1\\1.1\end{pmatrix}\left[\quad\begin{pmatrix}0.3\\0.4\end{pmatrix}\quad\right]$$

(García-Cerezo, 2022)

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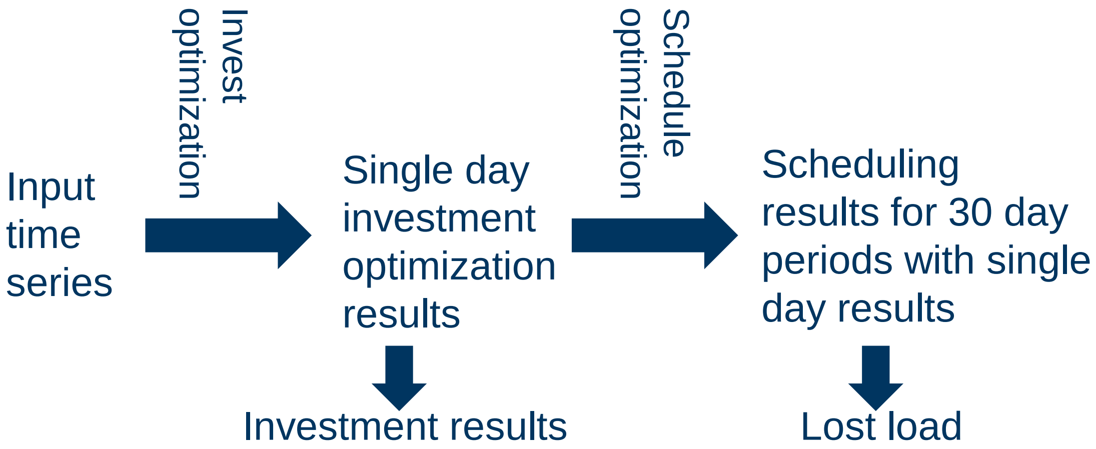
Priority clustering

Lost load as priority indicator

- Robust system: avoid lost load
- Lost load: no result from single day investment optimization
- Perform a schedule run with the single day results on a 30-day sample



(García-Cerezo, 2022)

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Combination

Priority clustering based on opimization results

- Divide timeseries in day-long timeslices
- Optimize timesclices individually

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38

25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48

39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72

49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72

Optimize

(García-Cerezo, 2022)

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Combination

Priority clustering based on opimization results

- Divide timeseries in day-long timeslices
- Optimize timesclices individually
- Run scheduling optimization with single day results

$$\begin{matrix} \text{wind} \\ \text{solar} \\ \text{battery} \\ H_2 \end{matrix} \begin{pmatrix} 10 \\ 20 \\ 10 \\ 0 \end{pmatrix} \begin{pmatrix} 30 \\ 5 \\ 0 \\ 5 \end{pmatrix} \begin{pmatrix} 120 \\ 13 \\ 12 \\ 3 \end{pmatrix}$$

↓

30 day sample from complete time series

↓ Scheduling optimization

Lost load

(García-Cerezo, 2022)

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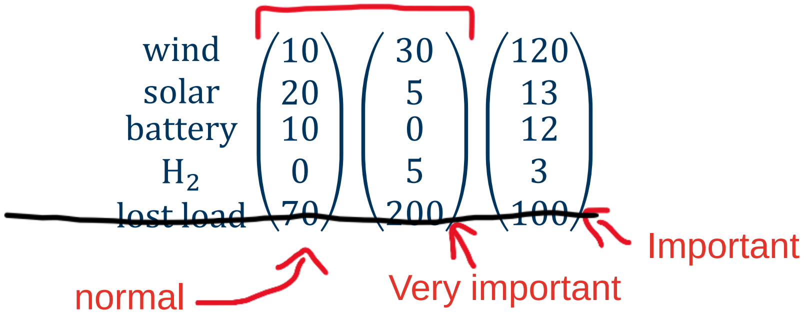
Combination

Priority clustering based on opimization results

- Divide timeseries in day-long timeslices
- Optimize timesclices individually
- Run scheduling optimization with single day results
- Use lost load to divide timesclices into 3 priority groups
- Cluster timesclices based on investment decisions and priority groups



(García-Cerezo, 2022)

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