Finding what is real: Capturing worst-case scenarios in Tulipa

Evaluating Real-Period Selection for Energy System Optimization

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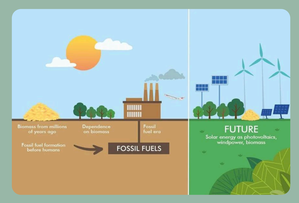
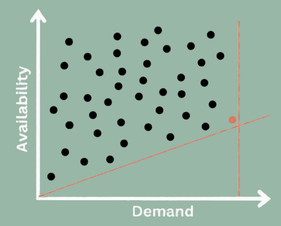
1. Background

- **Context:** To move away from fossil fuels, decision-makers rely on energy modelling to identify which renewable energy technologies to invest in. Investment decisions shape energy infrastructure for decades
- **Tulipa:** TNO is developing software called Tulipa which is an energy model for investment planning in electricity, heat, and gas across Europe.
- **Problem:** Tulipa tries to find the cheapest plan that still meets future energy demand, but full-scale models become hard to solve when many years of weather and demand data are included. Full-resolution models are computationally intractable



- **Solution:** Cluster energy time series to reduce model complexity while preserving worst-case conditions with the Tulipa energy model, but still capturing worst-case days (high demand, low energy supply)
- **Literature:** Previous work by Kremer showed that artificial worst-case representative periods improve feasibility and reduce regret in reduced models. These artificial extremes ensure solutions remain practical even with a few representative periods [1]. Artificial extremes guarantee feasibility but may never have occurred in reality

- **Artificial worst-case period creation [2]:**
  1. Find the highest demand
  2. Take the lowest availability-to-demand ratio for each generator
  3. Multiply to get availability when demand is high, but availability is low



- **Goal:** This project explores whether non-artificial representative periods can be selected to capture real worst-case behavior, making reduced models more useful for decision-making.

2. Research question

Can **real worst-case** observed periods replace an **artificial worst-case construction** in representative period selection and does this **improve solution quality** and **system reliability**?

3. Experimental evaluation

Input data

- 3 climate scenarios (1995, 2008, 2009)

Profiles types

Solar Onshore Offshore Hydro Demand

Clustering

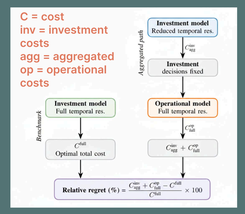
- **Benchmark clustering algorithms:** k-medoids, artificial worst-case unit weight
- **Real-worst case clustering:** Net-load scoring, real-Elgersma scoring and ENS-guided clustering

Run energy model

Evaluation

Regret

C = cost
inv = investment costs
agg = aggregated
op = operational costs

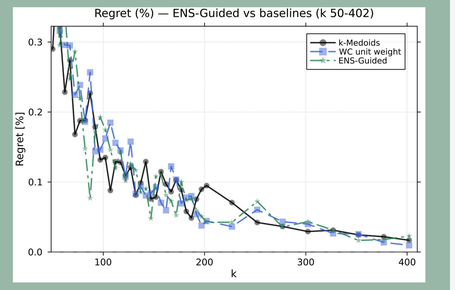


Loss of load

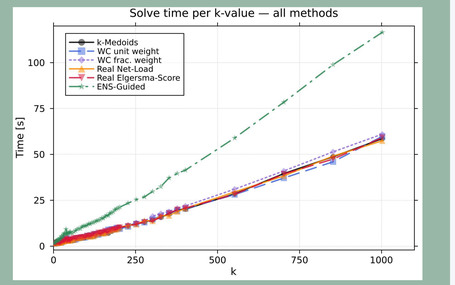
When the demand of energy is **higher** than the supply
→
Energy does not get served

4. Results

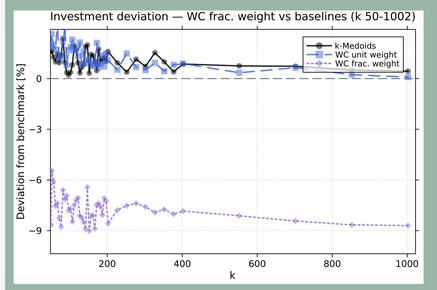
No method outperform baseline
All 3 contributed clustering methods do not outperform either k-medoids or the unit weight artificial clustering. In the plot the one from ENS is shown, but the other real worst case cluster methods also have roughly the same regret pattern (similar to k-medoids)

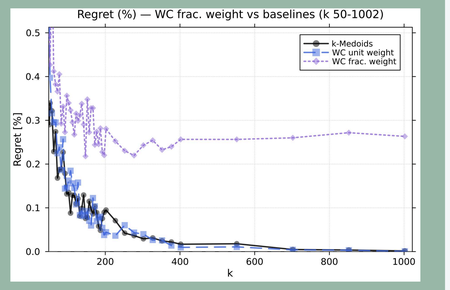


Double the solve time
Plotted is the time for clustering and solving the model against the amount of clusters. And you can see ENS-guided real worst case clustering which solves the energy model twice, but does not provide a 2x improvement on regret, so it is not worth the roughly 2x time investment



Other finding in fractional weighting
Using the artificial scaled clustering method a bias which makes it with regret plateau at roughly 0.25%, regardless of the amount of representative periods. The scaling scales the operational cost, so the model underinvests in the energy infrastructure.





5. Final remarks

Conclusions
- Real worst-case periods match artificial construction in solution quality
- Fractional weighting: structural flaw, which creates a bias
- ENS-Guided: 2× cost, no 2× benefit on tested dataset

Limitations
- Single dataset with low ENS penalty, reliability results inconclusive
- Small system generalisation to full-scale European models unknown

Future work
- Re-run with realistic ENS penalty (calibrated to ~4 h/yr LOLE target)
- Test on larger, real-world European planning dataset

[1] Kremer, L.A.A., de Weerdt, M.M., Neustroev, G., Morales-España, G. (2025). Stochastic programming for energy models: A blended cross-scenario representative periods approach. Master Thesis, TU Delft - Electrical Engineering, Mathematics and Computer Science. <https://resolver.tudelft.nl/uuid:0e87f306-1c92-4eec-805f-72377ed57fb2>

[2] Maaike Elgersma, Luca Santosuosso, Sonja Wogrin, Germán Morales-España, Mathijs de Weerdt, Greg Neustroev, and Lotte Kremer. Obtaining upper bounds for GEP with storage fast: Performance guarantees for TSA based on the worst case. Working draft, 2026.