An Adjustable Robust Optimization Approach to Scheduling of Continuous Industrial Processes Providing Interruptible Load

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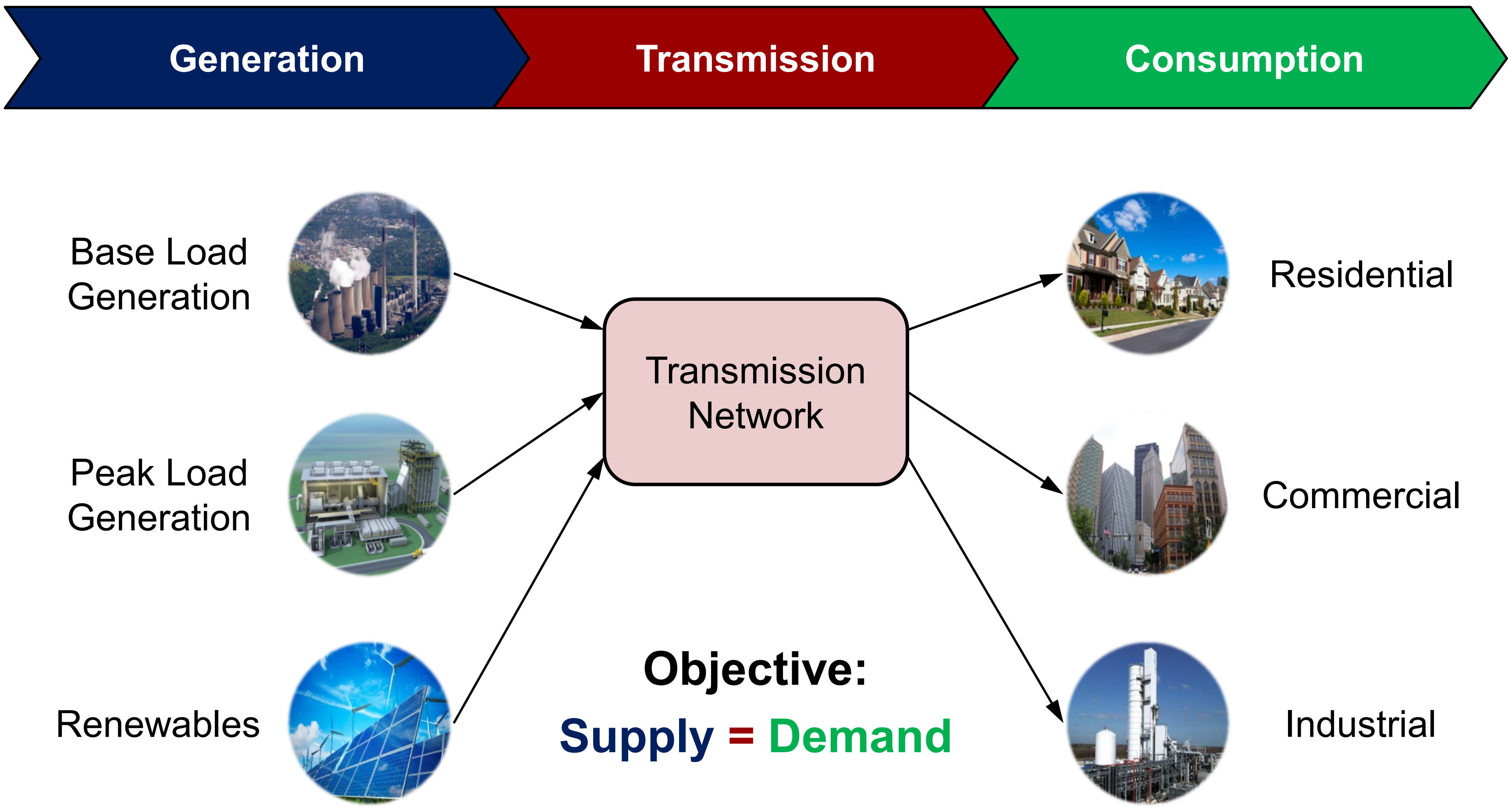
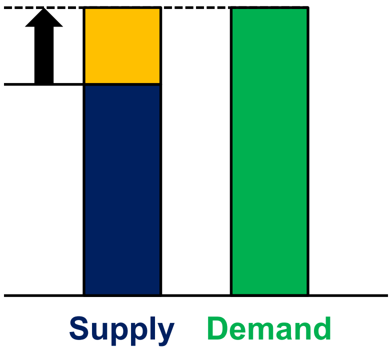
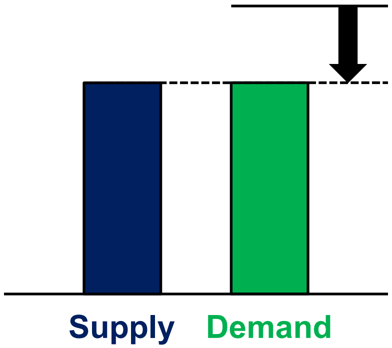
A power grid matches electricity supply and demand



Operating reserves ensure the reliability of the grid



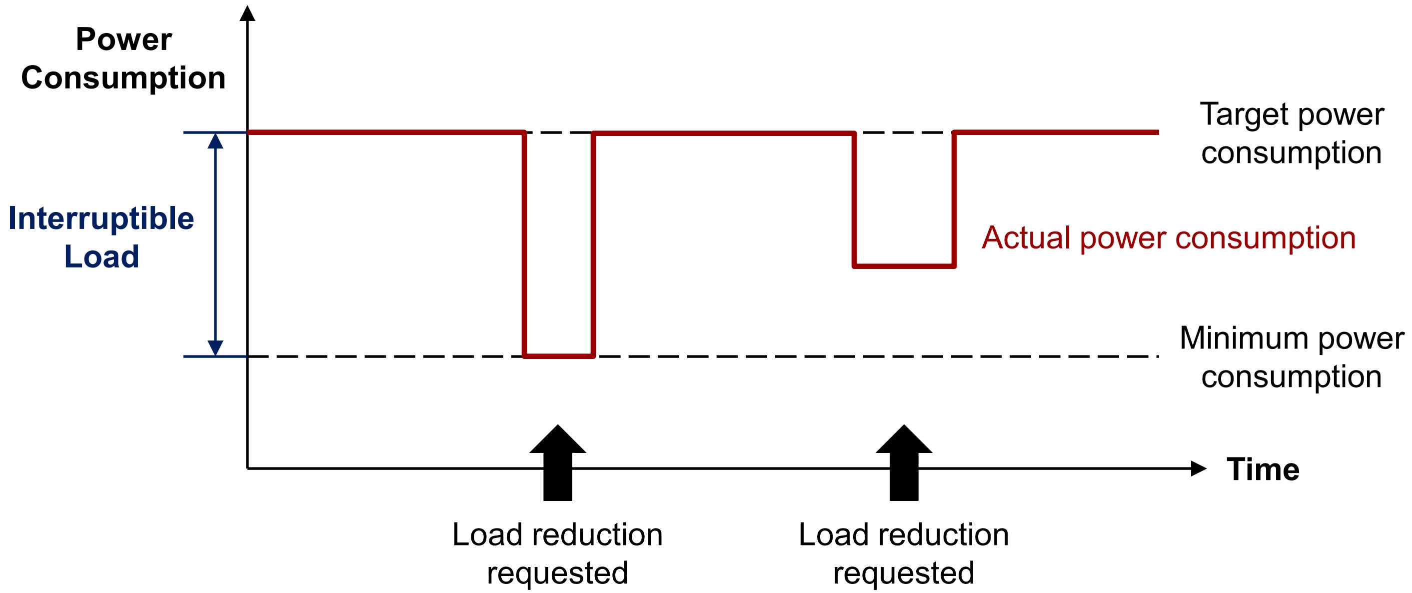
- Shortage of supply compensated by generators with short ramp-up times
- Referred to as **operating reserve** (spinning and non-spinning)
- To provide spinning reserve, generators have to be already running
- Expensive, requires underutilization of generation facilities



- Supply-demand mismatch eliminated by reducing electricity consumption
- Also referred to as **interruptible load**
- Can be regarded as spinning reserve
- Increases flexibility in the grid, reduces the need for building new power plants

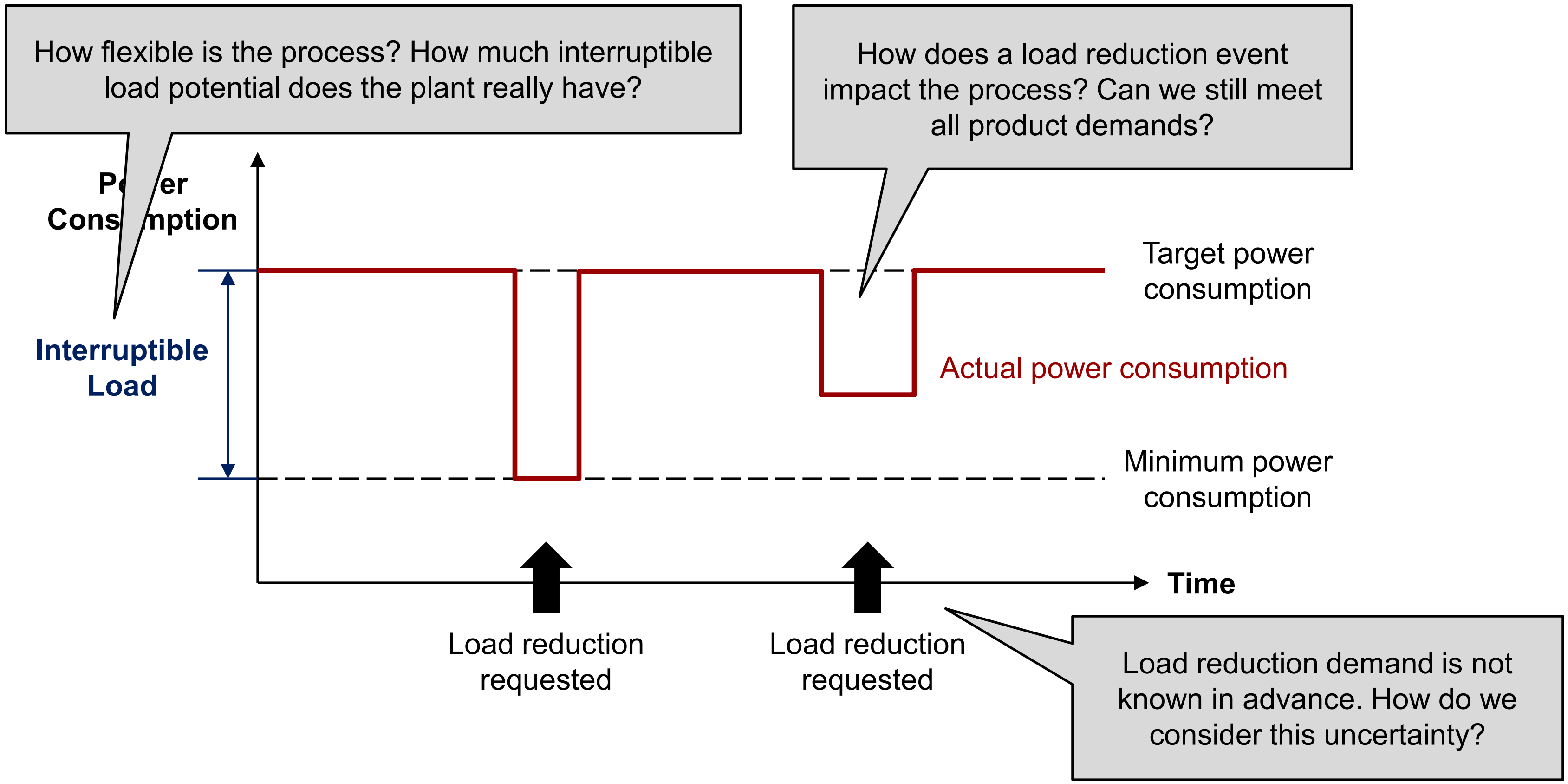
Interruptible load provides new opportunities for power-intensive industries

- Interruptible load is specified as the **maximum possible reduction in electricity consumption** that can be requested by the grid operator



- Provision of interruptible load is encouraged by attractive financial incentives
→ **great potential benefits for large industrial electricity consumers**

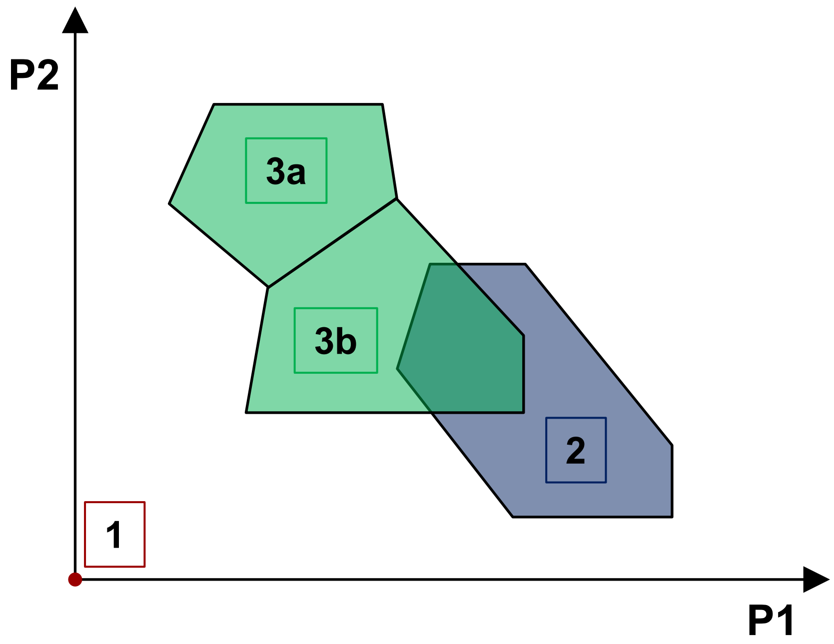
Challenge lies in the proper modeling of process flexibility and uncertainty



Need detailed scheduling model that incorporates uncertainty.

Plant is represented by different operating modes

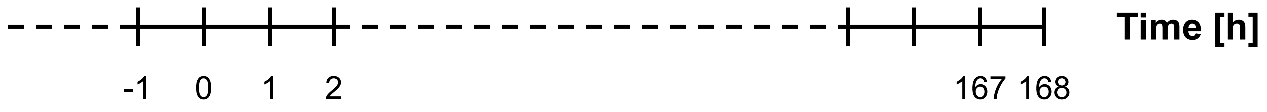
- Assume that plant can operate in different operating modes
- For each operating mode, we need to know the range of possible **production rates** and the corresponding **electricity consumption**
- Approximate the feasible operating region by a set of **polyhedral regions** in the product space
- In each subregion, the electricity consumption is approximated by a **linear function** of the production rates
- Surrogate model is created by using data from the real process or a detailed mathematical model[1]



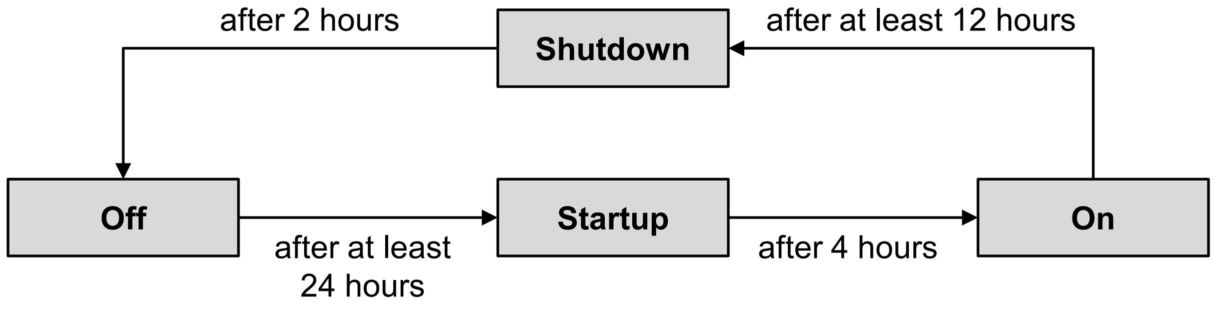
1. Zhang et al. (2015). *Optimization and Engineering.*

Use surrogate model in a scheduling framework that considers transitions between operating modes

- Time horizon is discretized into time intervals of equal length
- Length of time interval depends on process characteristics and electricity price



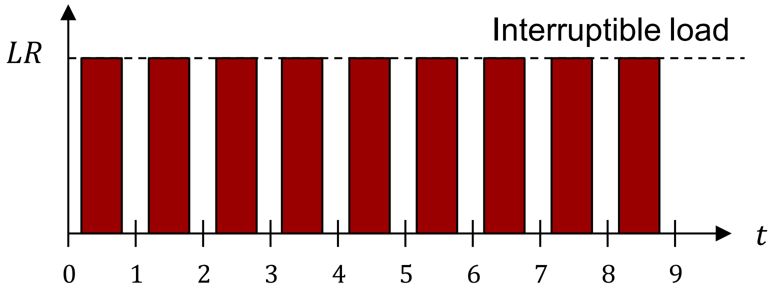
- For every time interval, **operating mode** and **production rates** are determined
- Constraints on **mode transitions** can be imposed[1]



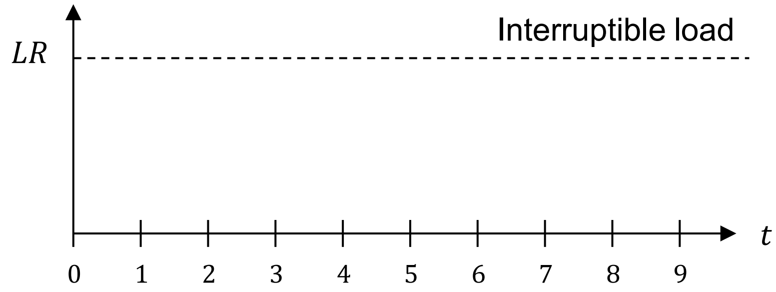
1. Mitra et al. (2012). *Computers and Chemical Engineering.*

Providing interruptible load is associated with high uncertainty

- Load reduction is requested in case of contingency
  → **Not known in advance: When? How much? For how long?**
- To provide interruptible load, load reduction upon request has to be guaranteed
- **Still financially attractive** because payment is made regardless how much load reduction has actually been requested



Worst case: maximum load reduction



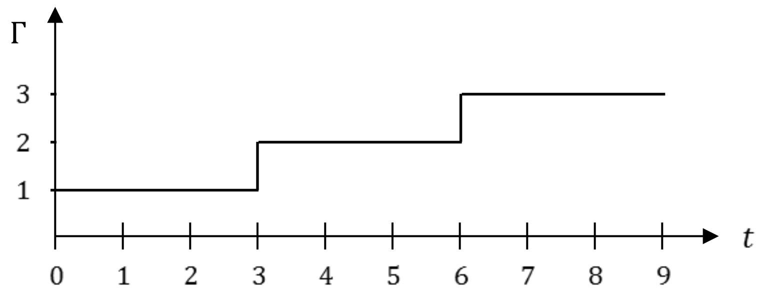
Best case: no load reduction

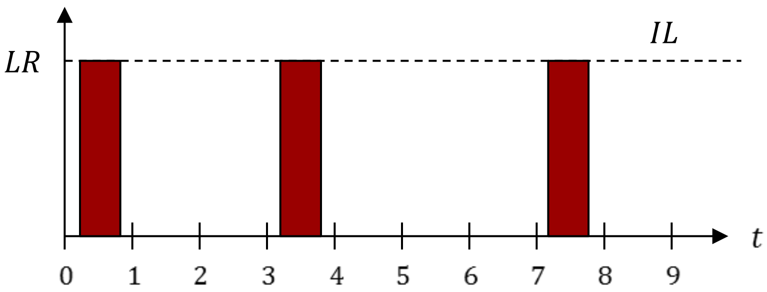
Assuming worst case is too conservative. Need a more realistic approach.

Define uncertainty set of appropriate size

- Apply robust optimization approach to guarantee feasibility
- **In practice, load reduction is only requested a few times in months**[1]
- Apply the following "budget" uncertainty set[2] (limits the number of time periods in which maximum load reduction can be requested):

$$W(IL) = \left\{ w : \left(LR_t = IL_t\, w_t,\ 0 \leq w_k \leq 1\ \forall\, 1 \leq k \leq t,\ \sum_{k=1}^{t} w_k \leq \Gamma_t \right) \forall\, t \in \overline{T} \right\}$$





1. EnerNOC (www.enernoc.com/our-resources/brochures-faq)
2. Zhang et al. (2015). *AIChE Journal.*

Apply adjustable robust optimization approach to incorporate recourse decisions

- **Decisions have to depend on the realization of the uncertainty**
- "Traditional" robust optimization: No recourse, only "here-and-now" decisions
- Adjustable robust optimization[1]: Recourse decision variables are specified as **functions of the uncertain parameters**
- For tractability reasons, restrict to affine functions:

decision coefficient

uncertain load reduction

$$P_t = p_t + \sum_{k=t-\zeta}^{t} q_{tk} w_k$$

actual production

planned production

multistage linear decision rule

- p_t and q_{tk} are decision variables
- ζ defines the extent of recourse

1. Ben-Tal et al. (2004). *Mathematical Programming.*

Proposed model is applied to a real-world industrial case study provided by Praxair

- **MILP Model:**

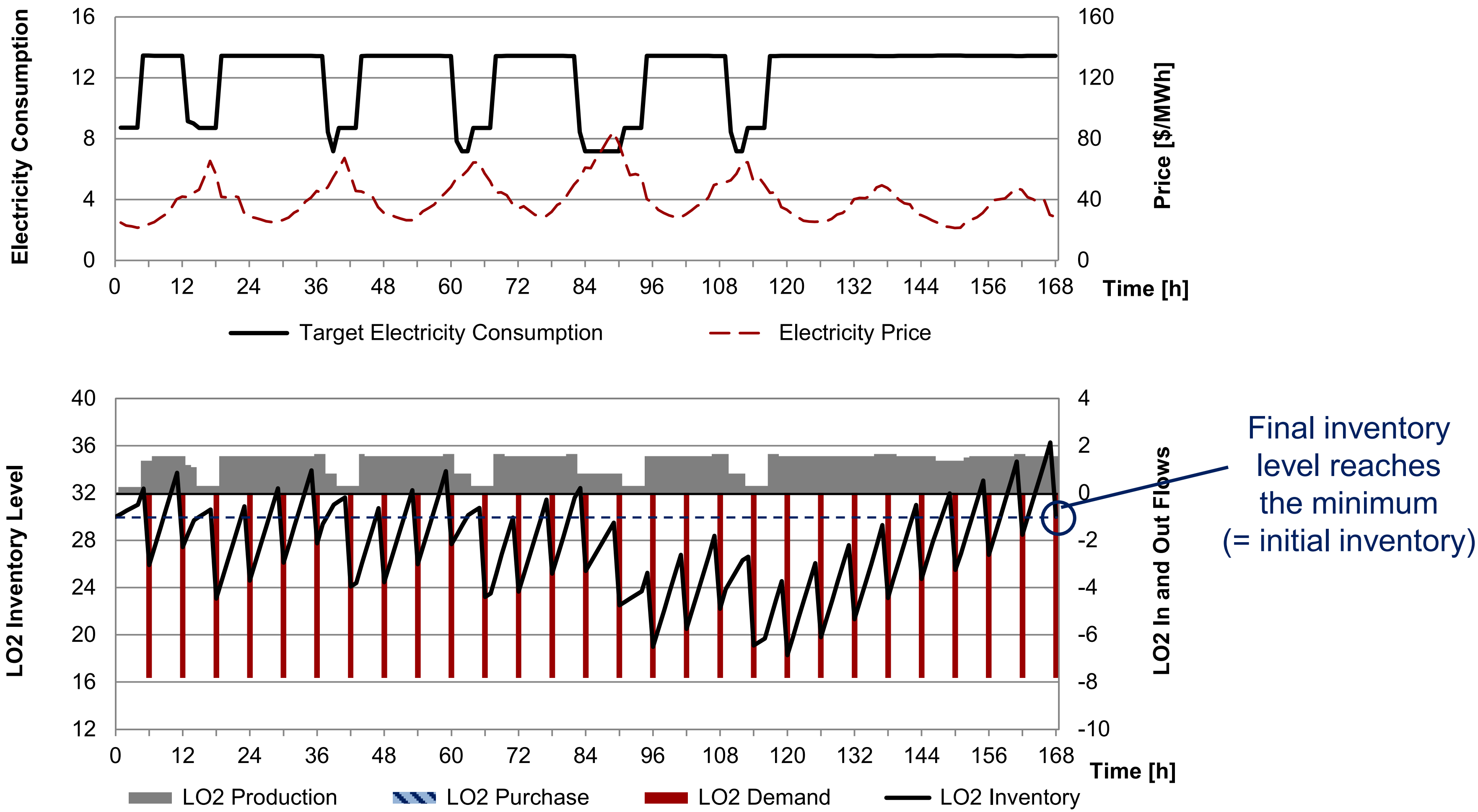
minimize **max(**electricity cost + product purchase cost - interruptible load sales**)**

subject to
- surrogate process model
- mass balances
- energy balances
- mode transition constraints
- initial conditions
- terminal constraints

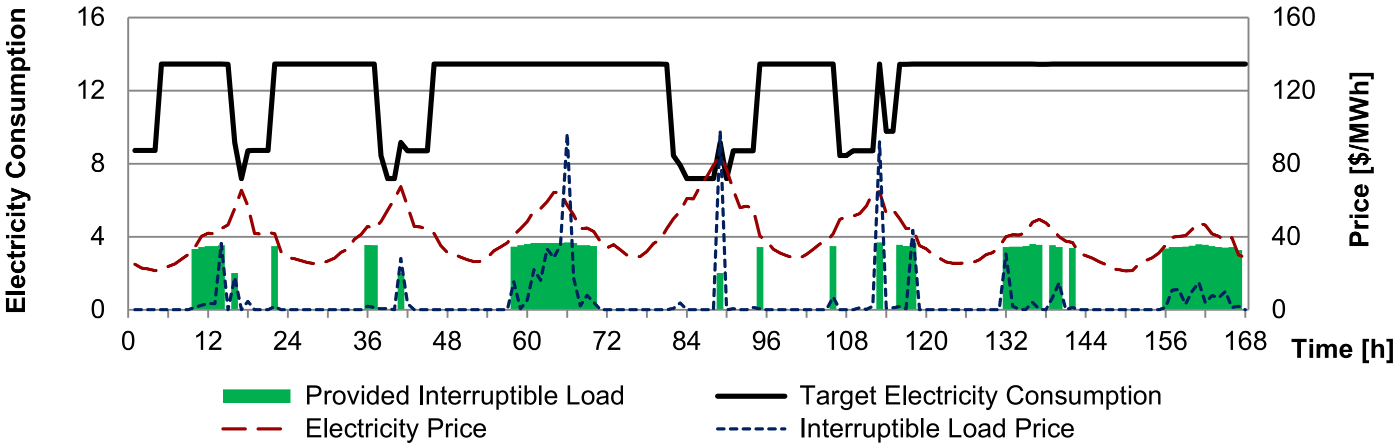
for all possible realizations of the uncertainty, i.e. $\forall\, w \in W(IL)$

- **Benchmark Case:**
  - Cryogenic air separation plant
  - Products: liquid oxygen (LO2), liquid nitrogen (LN2)
  - 90% plant utilization

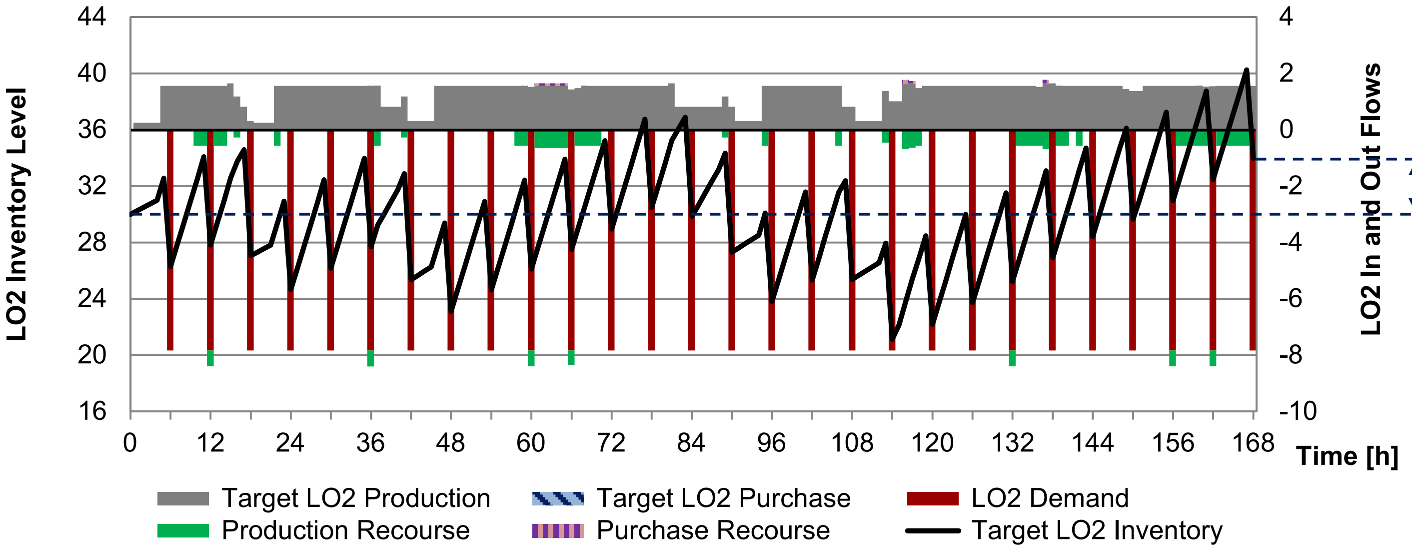
If no interruptible load is provided, the solution suggests operating the plant such that high-price periods are avoided



Providing interruptible load reduces the total operating cost, even with minimum extent of recourse ($\zeta = 0$)

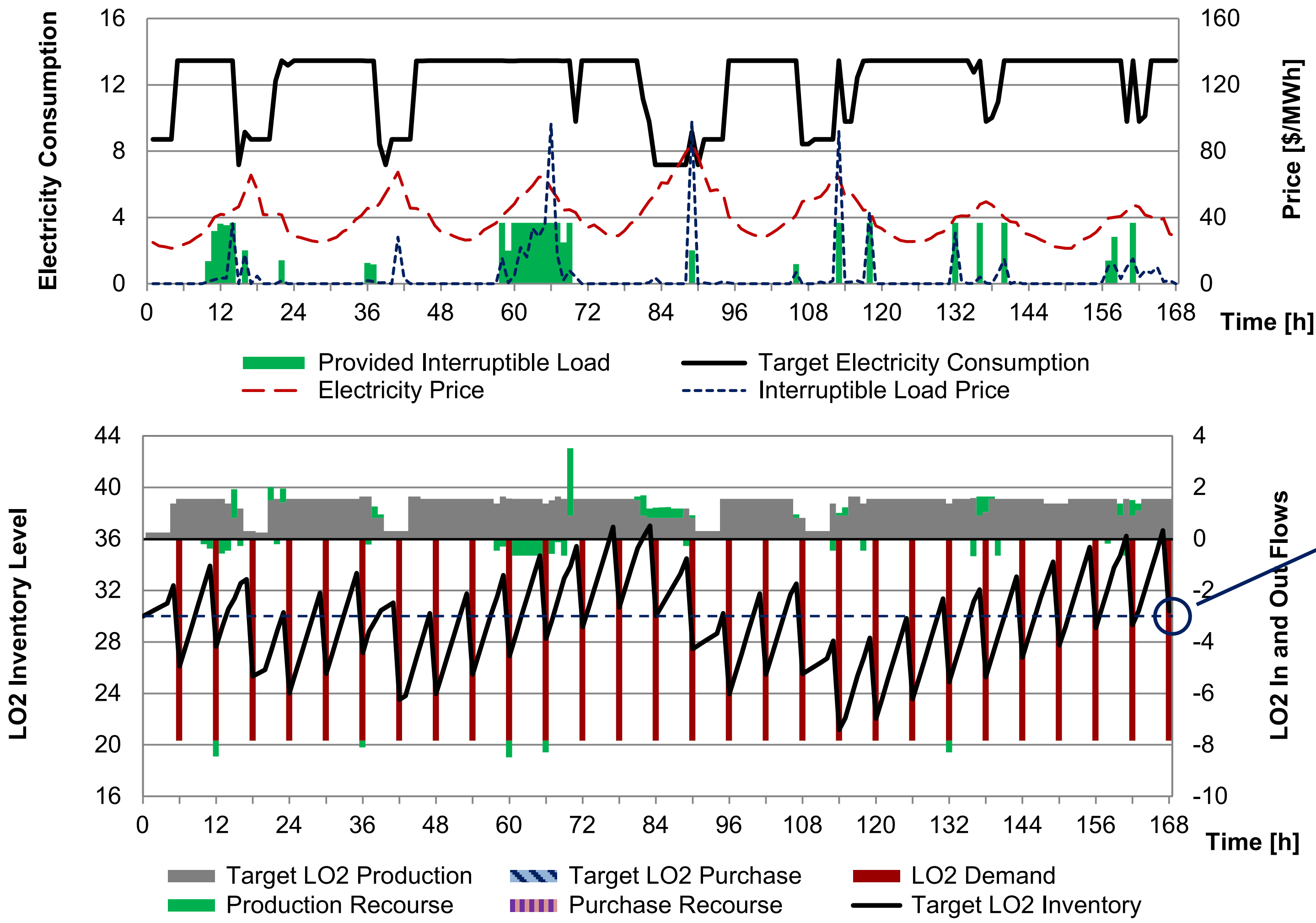


1.2%
cost savings



Inventory buffer built to ensure feasibility

Cost savings increase by 50% if greater extent of recourse is considered ($\zeta = 23$)



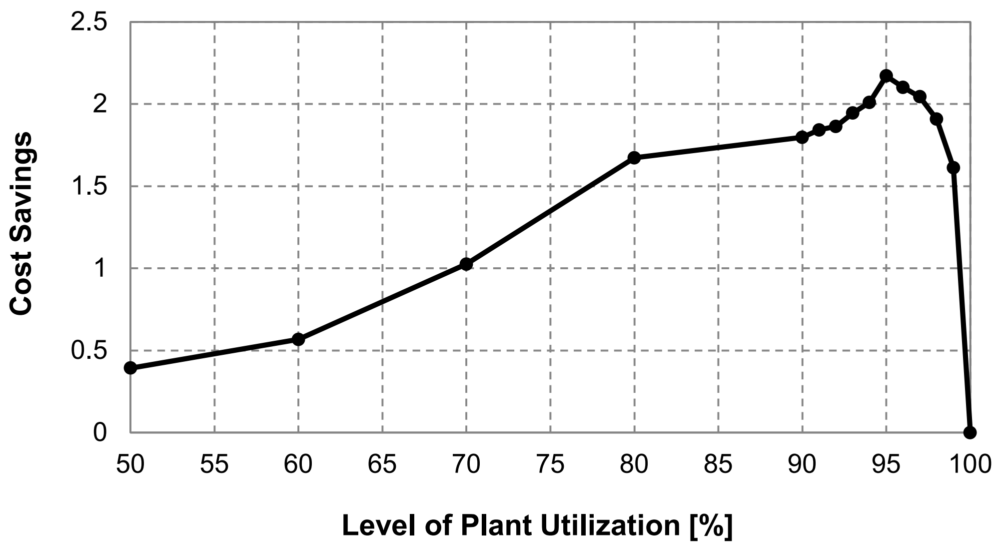
1.8%
cost savings

50% increase

No inventory buffer required

Cost savings depend on the level of plant utilization

- Lower plant utilization implies higher process flexibility, which allows more effective load shifting
- Higher plant utilization implies higher target production levels, which allow more interruptible load to be provided



Highest cost savings are achieved at a plant utilization of 95%.

Conclusions

- Developed robust MILP scheduling model for continuous power-intensive plants that can provide interruptible load
- Proposed adjustable robust optimization approach accounts for uncertainty in load reduction demand and considers recourse actions in the form of linear decision rules

- Proposed model has been applied to an industrial case study provided by Praxair
- Results show the financial benefit of providing interruptible load, and demonstrate the effect of the considered extent of recourse
- Further insight: Largest cost savings are achieved at a high, yet not maximum level of plant utilization