PUBLIC

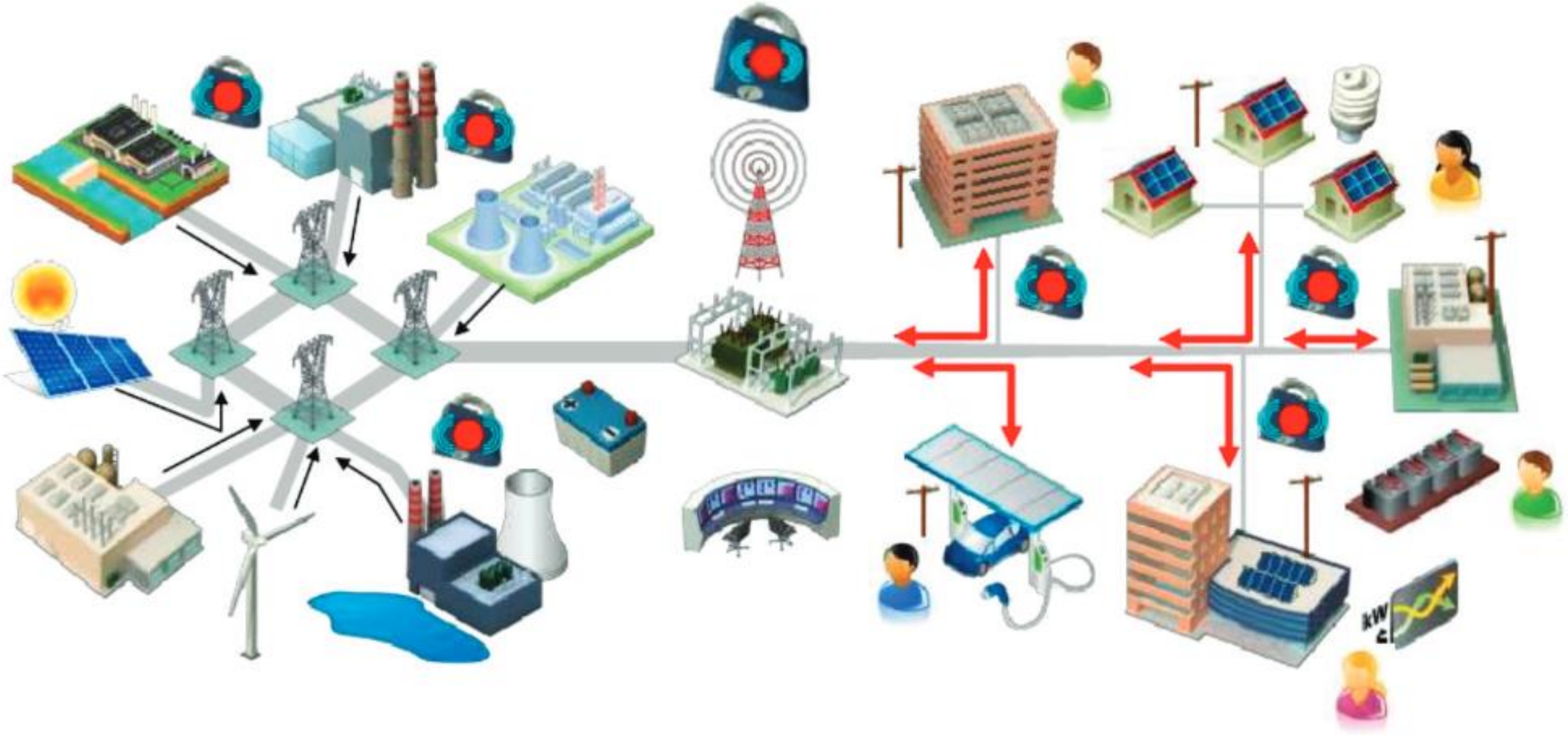
Scheduling and Energy

Industrial Challenges and Opportunities

Scheduling Seminar - 2022-04-27, Iiro Harjunkoski

Hitachi Energy

The Future of Electric Power is Bi-Directional and Smart(er)



Source: National Academies of Sciences, Engineering, and Medicine 2021. The Future of Electric Power in the United States. Washington, DC: The National Academies Press. https://doi.org/10.17226/25968.

Energy system 2050: towards a carbon-neutral vision

Hitachi Energy

“Electricity will be the backbone of the entire energy system

01
Accelerated shift from fossil-based to renewable power generation

02
Growing electrification of Transportation, Industry and Buildings sectors

03
Sustainable energy carriers, complementary to direct electrification

Fast facts

“ Global electrification will be more than 50% of total energy demand

“ Electrification improves energy efficiency

“ All market sectors converting towards electrification

“ Energy sector-coupling beneficial

So what?

Digital and energy platforms are needed…

…to manage the enormous power system energy transition challenges:

increased complexity
additional capacity

for reduction of CO_2 emissions

Accelerating the transition to a carbon-neutral energy system requires adapting and adopting policies and regulations to enable technology and new business models to support Scalable, Flexible and Secure energy systems

Goal of This Talk…

Hitachi Inspire the Next

- Highlight the importance of energy / electricity
- Give insights to solving industrial-scale scheduling problems (demand-side management)
- Present some strategies to speed up large-scale optimization problems
- Share some personal experiences from working with MILP problems
  - Melt-shop (steel) scheduling
  - Unit Commitment

MILP is an important (although not only) component in solving industrial scheduling problems

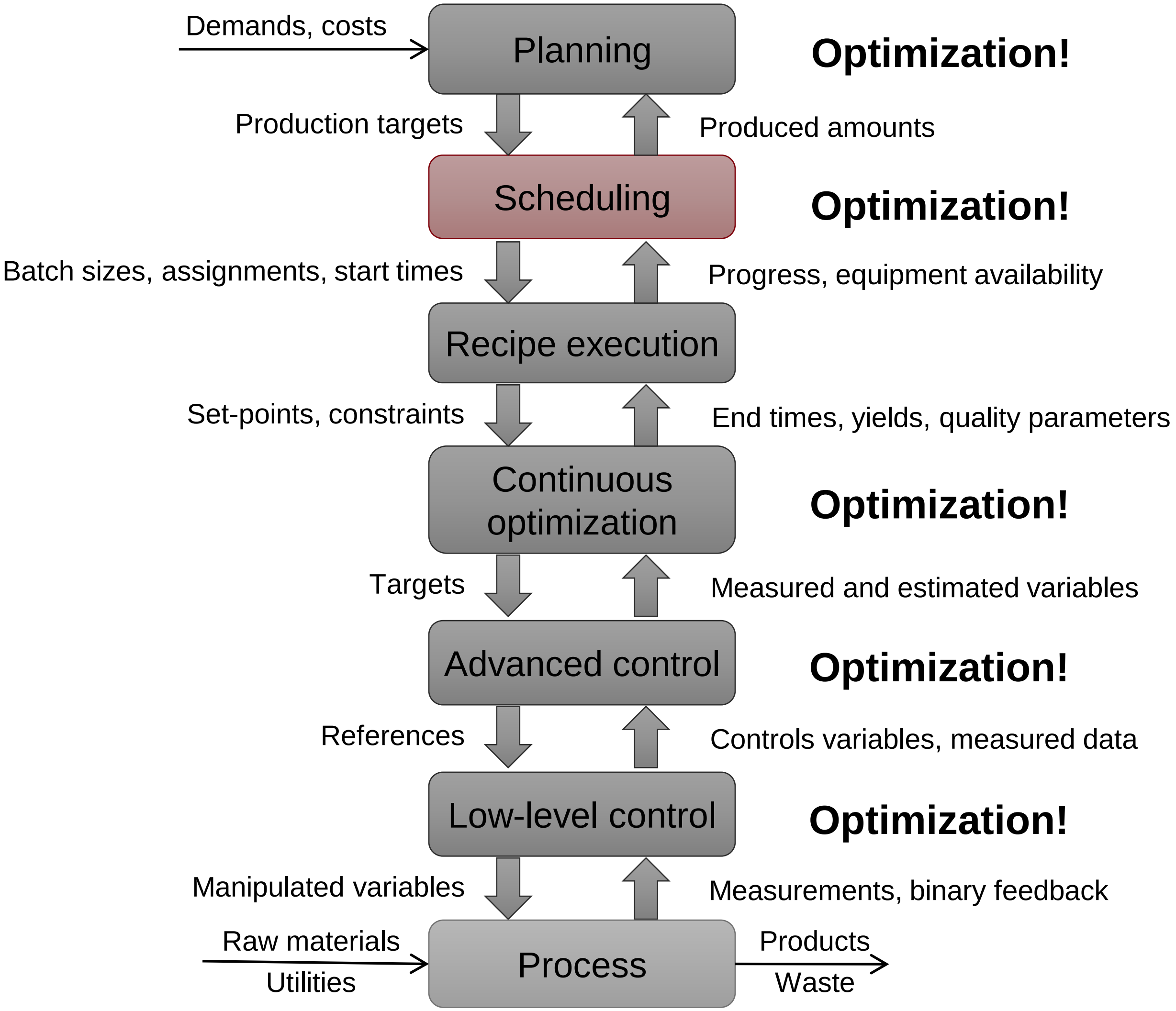
Hitachi Energy

Outline of the Talk

1. Why MILP?
2. Demand-side Management – Short Introduction
3. Steel Production Scheduling (continuous-time)
4. Unit Commitment Problem (discrete-time)
5. Conclusions

Why MILP?

Several Optimization Layers – Potential of Conflicting Actions

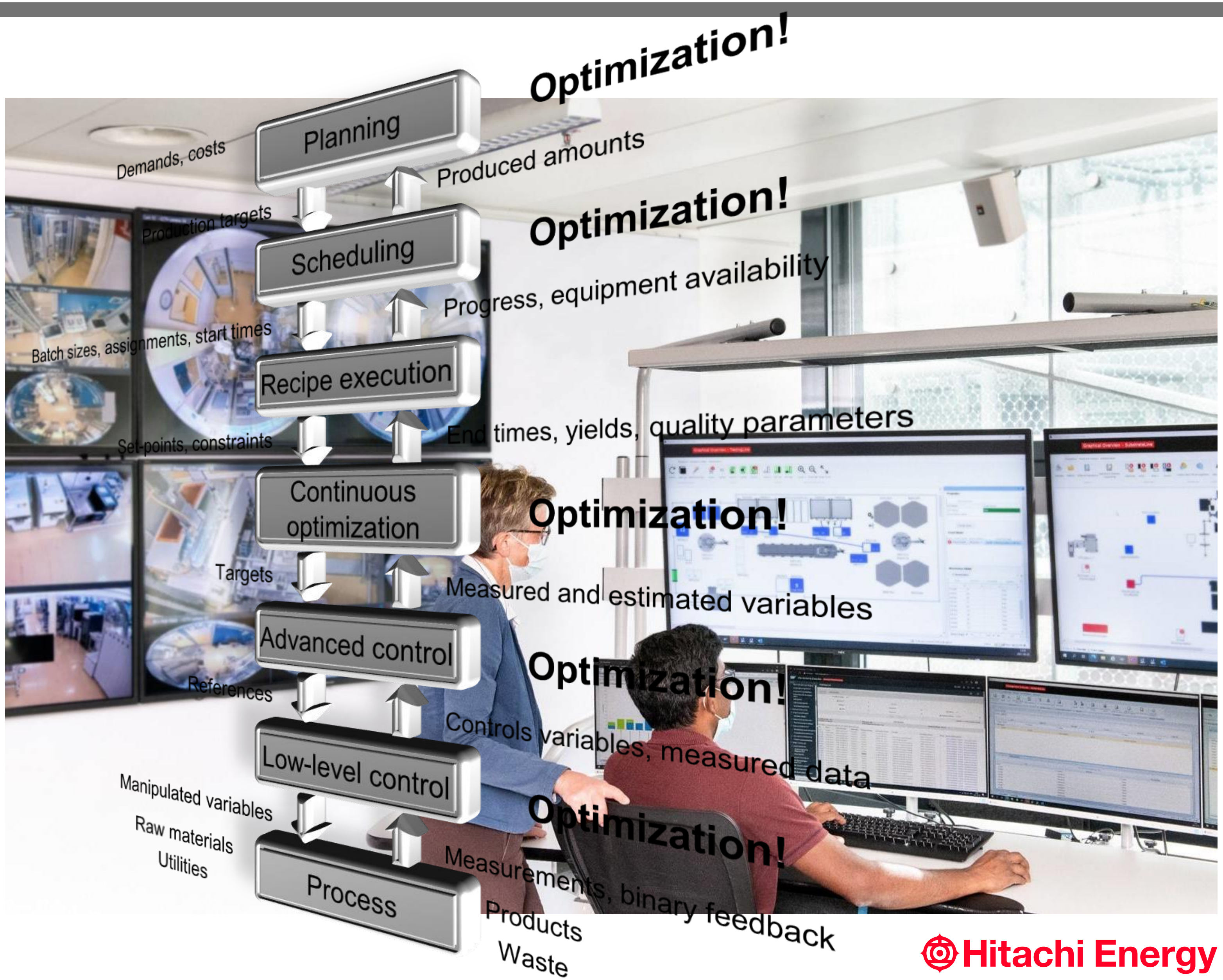


Why MILP?

HITACHI
Inspire the Next

MILP models are flexible and "elastic"

- Consider physical and business constraints
- No adaptation to old model needed when adding new constraints
- Commercial solvers – benefit from top OR achievements
- Separate modeling experts and software developers
- Scheduling only one part of automation systems



Public

Hitachi Energy

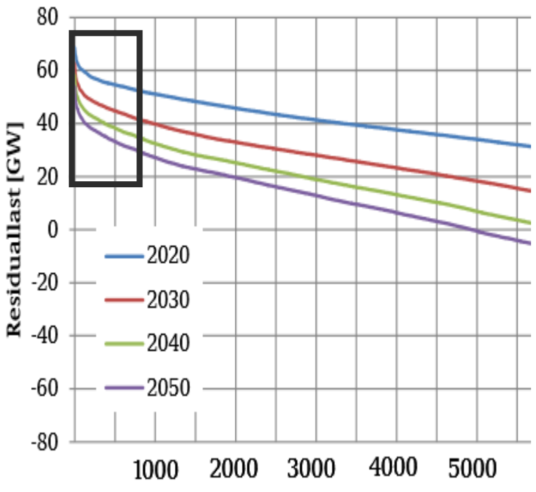
Demand-side Management

Short Introduction

Changing Energy Markets: Challenges and Opportunities

Volatile energy prices

Renewable generation



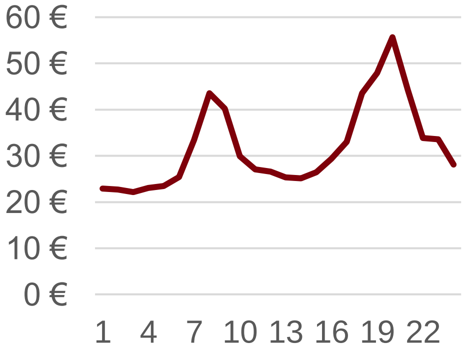
source: dena – Integration EE

Consumption & generation

Covering consumption peaks

Market liberalization

Grid availability and stability



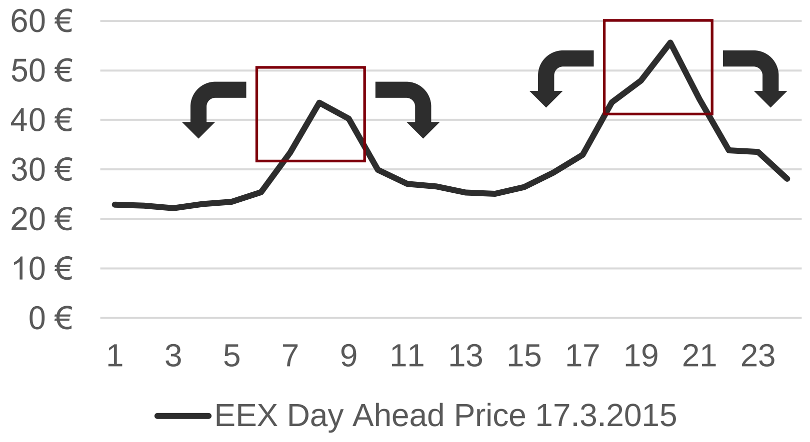
Demand side management offers benefits in new market environment

Public

Hitachi Energy

Using process flexibility for iDSM

Shifting loads of energy intensive process steps to low-cost times

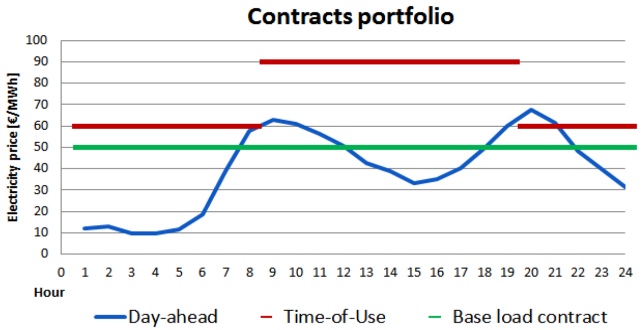


Reduce critical load of power grids

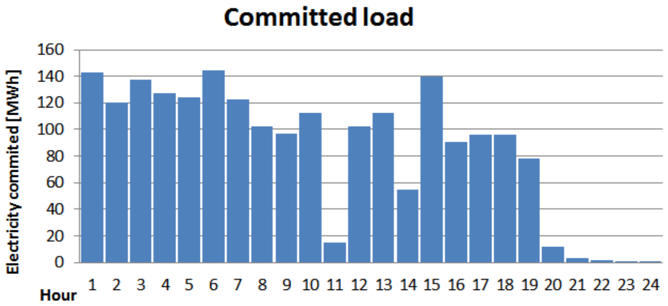
iDSM allows important cost savings

Scheduling of Energy-Intensive Processes

HITACHI
Inspire the Next

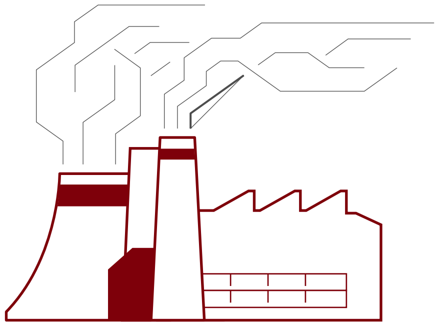


Multiple contracts – time dependent price levels

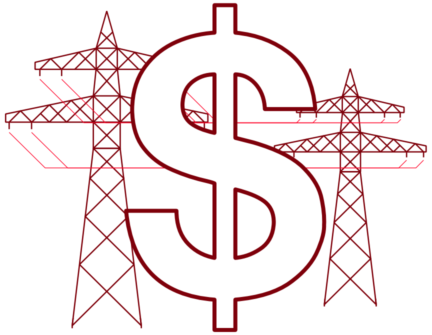


Pre-agreed load curve – penalties for deviation

Demand from production process



On-site generation – with special constraints



Selling back to grid

Hitachi Energy

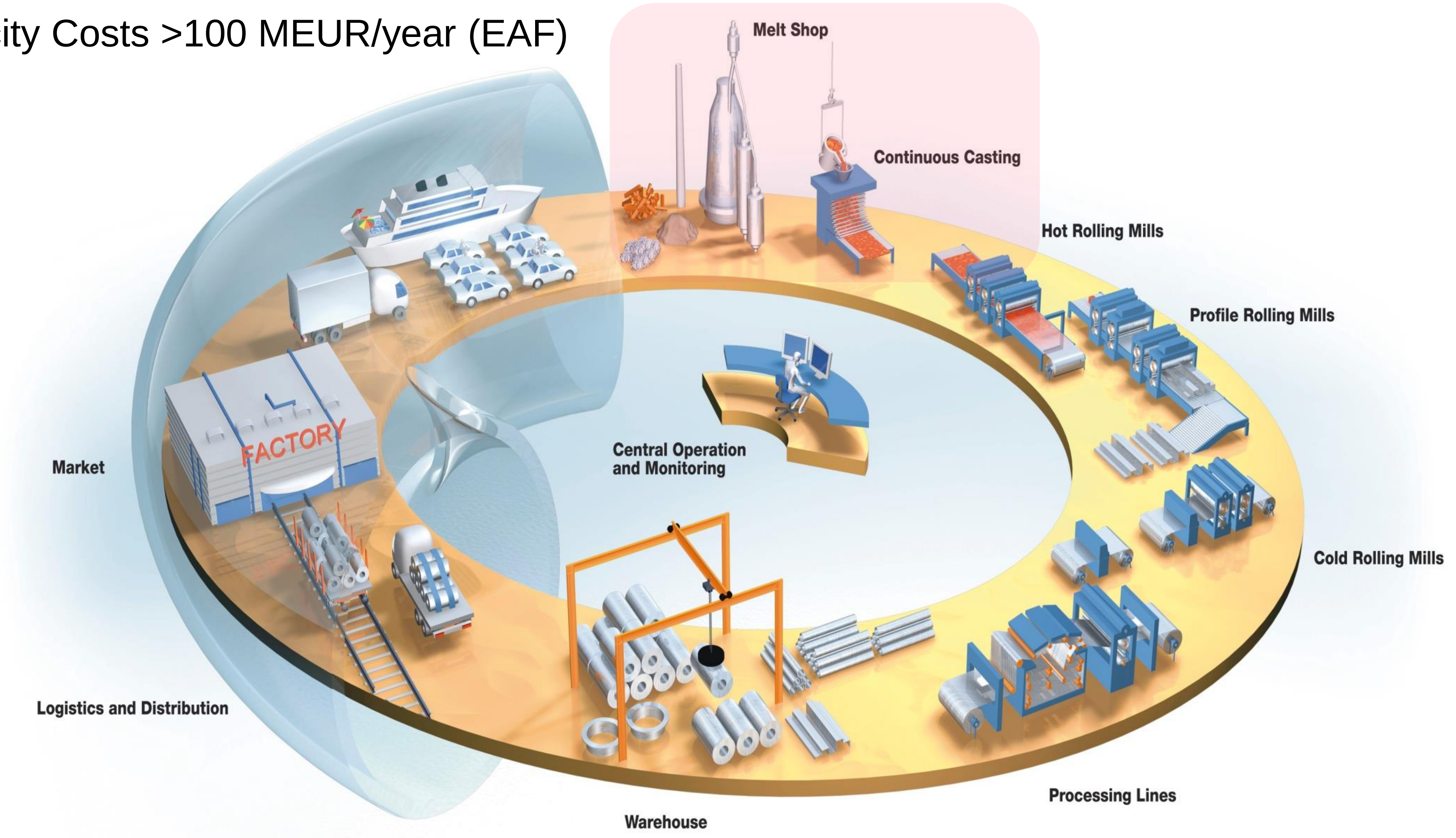
Steel Production Scheduling

Continuous Time

Melt Shop in the Steel Production Supply Chain

HITACHI
Inspire the Next

Typical Electricity Costs >100 MEUR/year (EAF)



Source: ABB

Hitachi Energy

iDSM in Steel Production: Melt Shop Process

HITACHI
Inspire the Next

From scrap to steel

Step 1: Electric Arc Furnace (EAF)

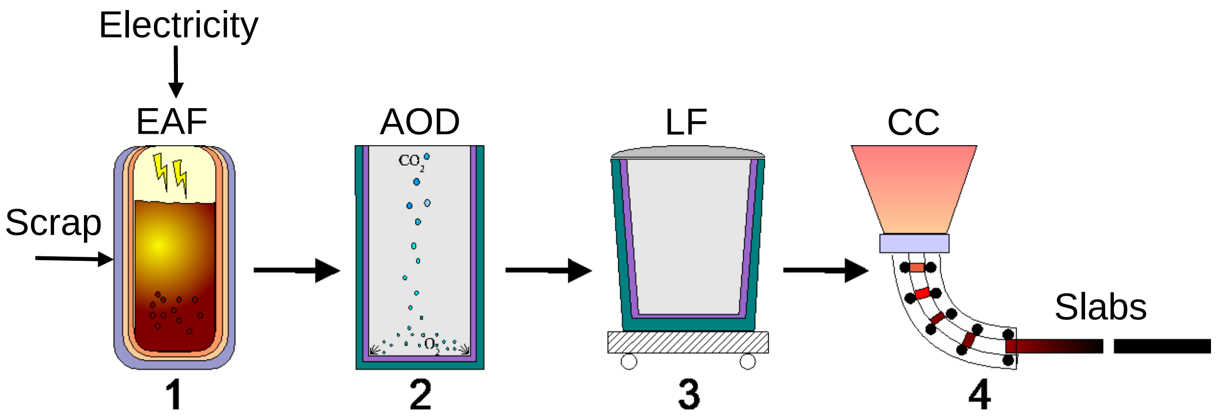
- The largest electricity consumer
- Done in batches (called heats)

Steps 2-3: Adapt the chemical properties

- Argon-oxygen decarburization (AOD)
- Ladle Furnace (LF)

Step 4: Continuous Casting (CC)

- Cast multiple heats without interruption



Electricity-intensive process with many constraints

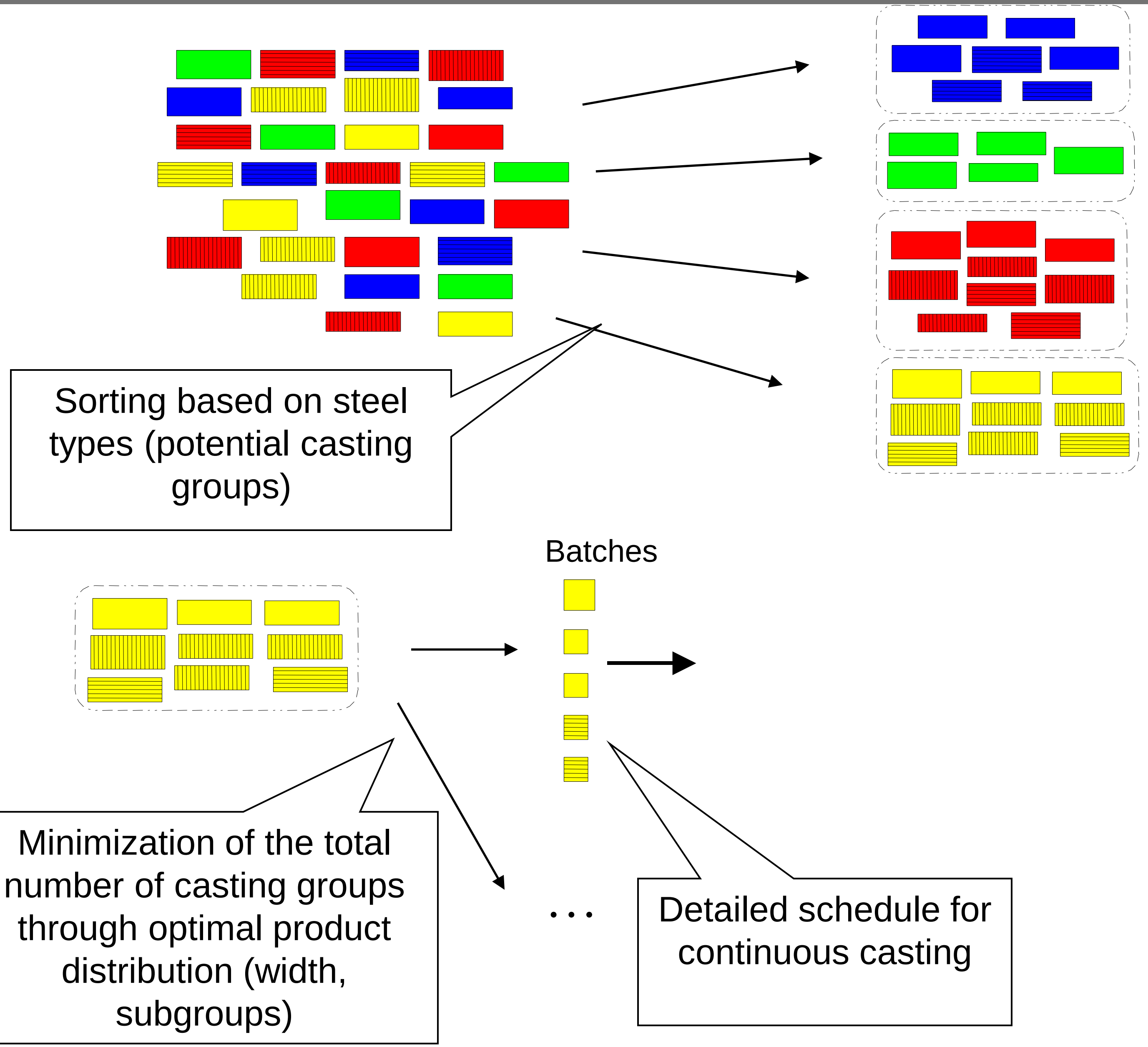
- Avoid intermediate cooling (quality problems)
- Sequence-dependent changeovers
- Grade incompatibilities
- Transfer times between equipment
- Coordination of production steps

Harjunkoski and Grossmann, 2001, Castro et al., 2009; Hadera and Harjunkoski, 2013

Hitachi Energy

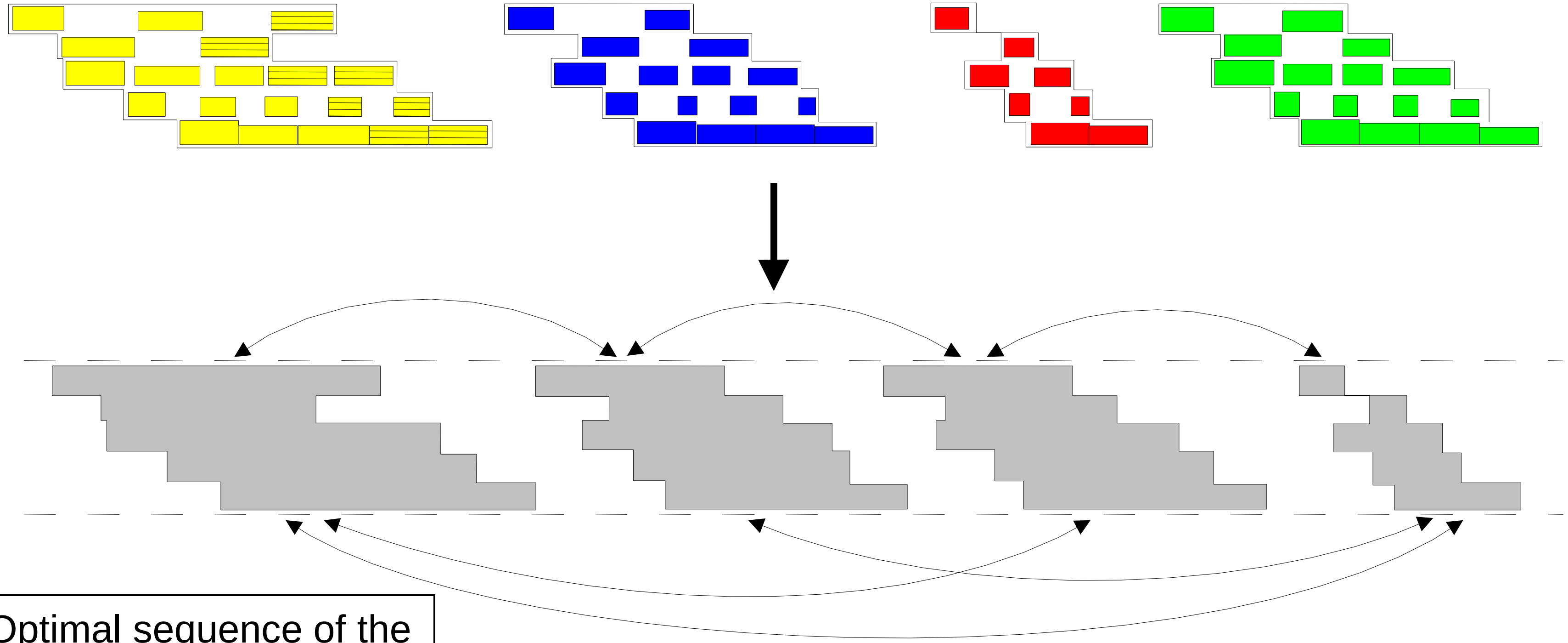
Optimization step I – Grouping and Scheduling

HITACHI
Inspire the Next

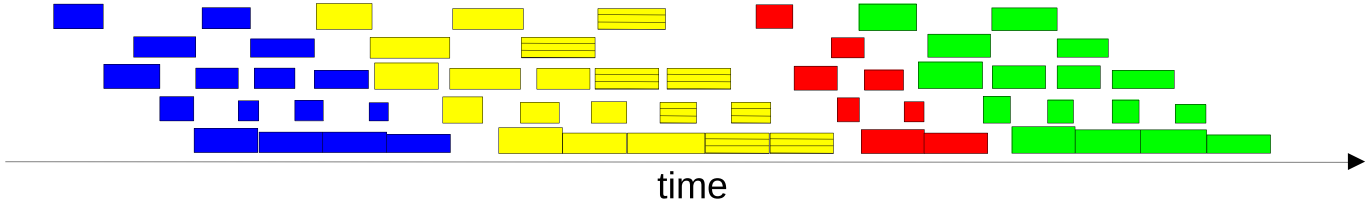


Hitachi Energy

Optimization step II – Aggregation and Finalization



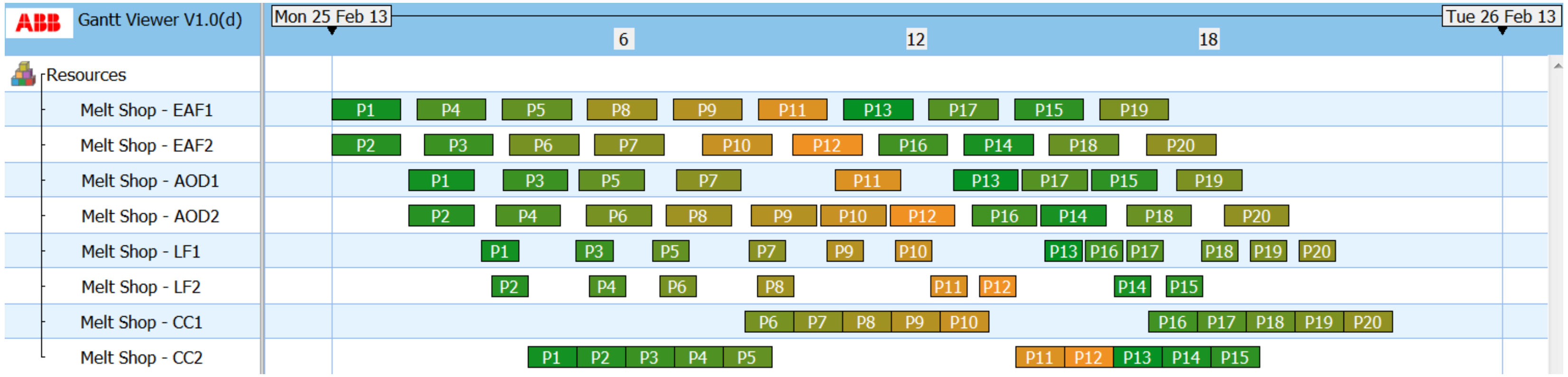
Optimal sequence of the casting groups (maximum throughput / minimum setup-times)

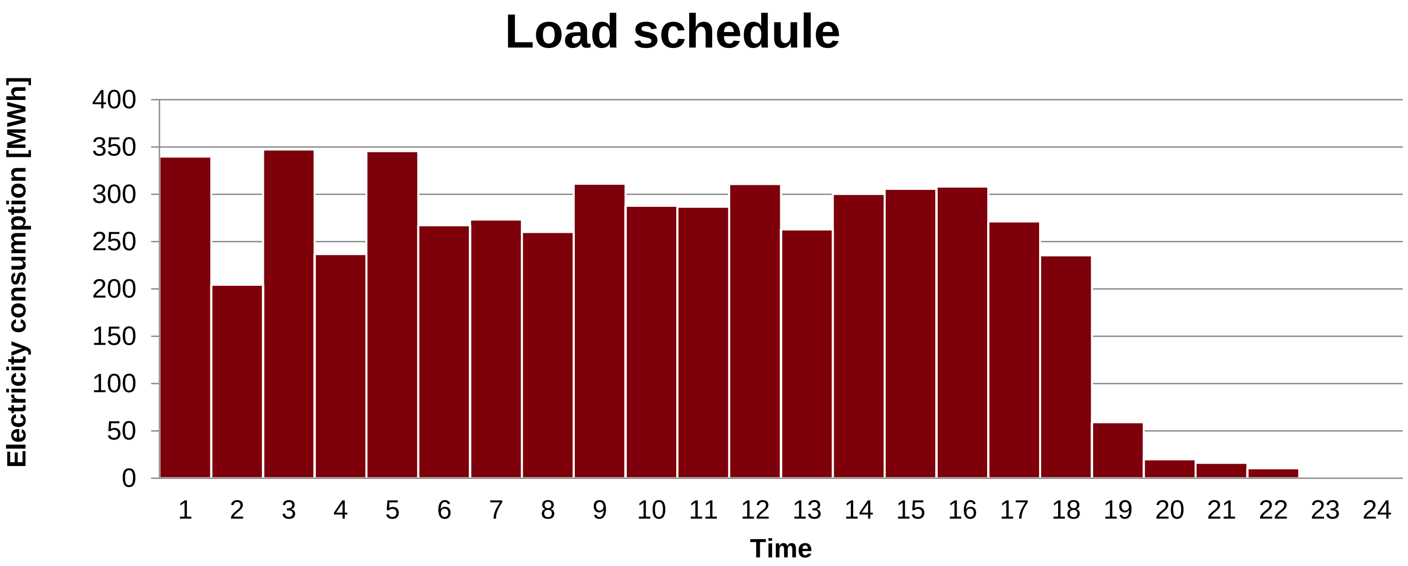


Source: Harjunkoski, I., & Grossmann, I. E. (2001). A decomposition approach for the scheduling of a steel plant production. Computers and Chemical Engineering, 25(11-12), 1647-1660

Production Management

Volatile Prices as Opportunity





Hitachi Energy

Production Scheduling under Volatile Energy Prices

HITACHI
Inspire the Next

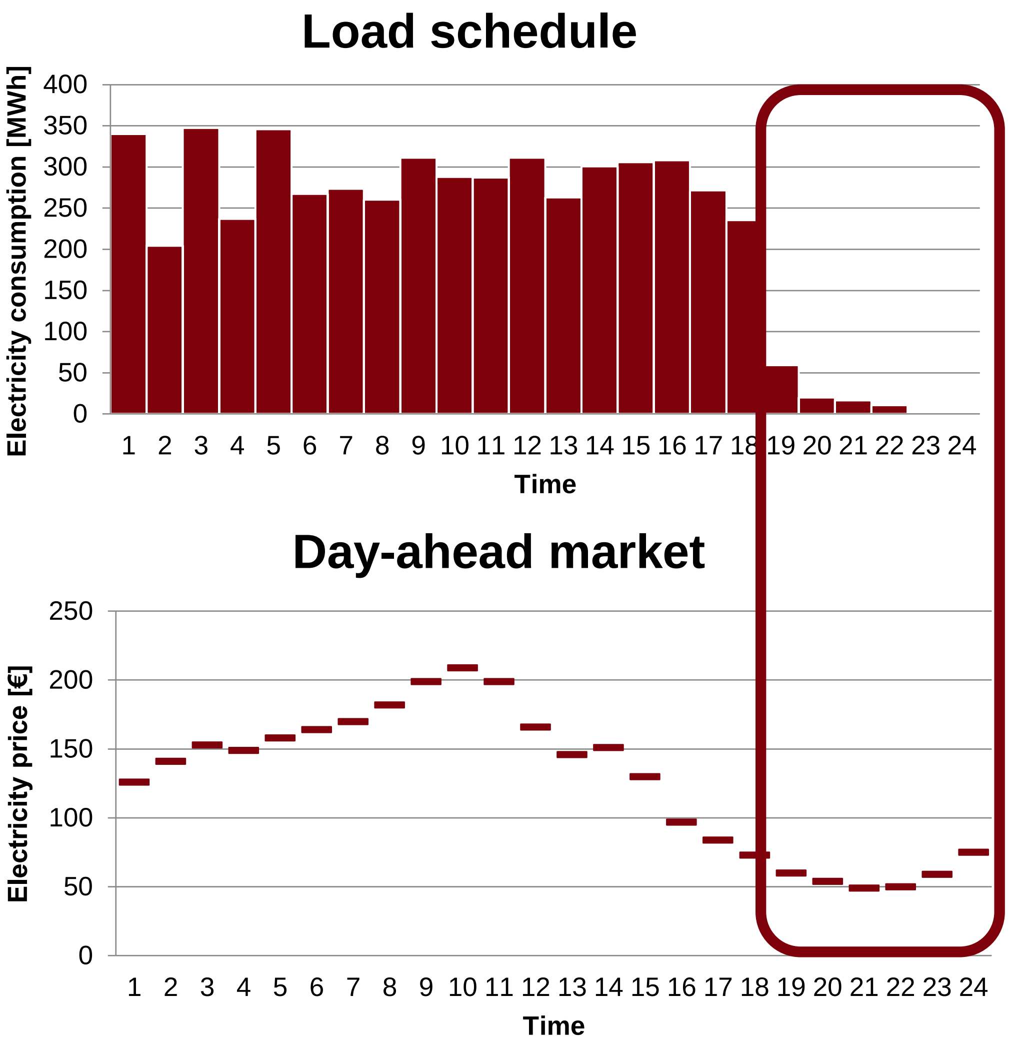
Volatile Prices as Opportunity

Enable energy-intensive industry to

- Participate in future energy markets (virtual power plant)
- Actively support grid stability and reliability

Use process flexibility to intelligently schedule the production in order to

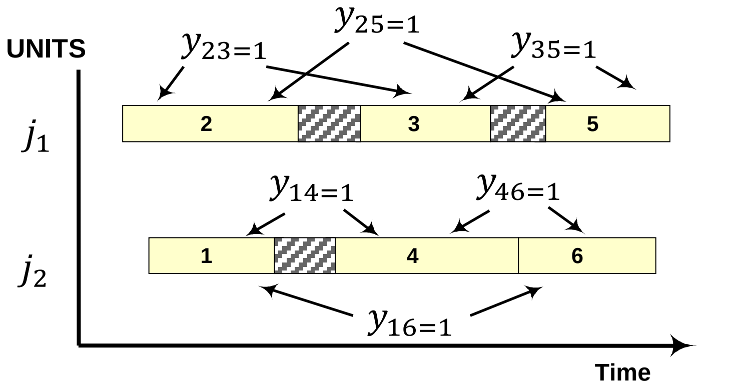
- Lower energy cost
- Efficiently manage resources



Hitachi Energy

HITACHI
Inspire the Next

MAJOR MODEL VARIABLES



6 BATCHES, 2 UNITS
(6*5)/2= 15 SEQUENCING VARIABLES

BINARY VARIABLES

$y_{ii'}, x_{ijs}$

job/batch unit stage

Note: The same unit may be used in multiple stages!

$y_{ii'} = 1$ if batch i' is processed after batch i, else zero (global precedence)

$x_{ijs} = 1$ if batch i is processed in unit j on stage s (stage-based assignment)

CONTINUOUS VARIABLES

t_{is}^{s} = start time of batch i on stage s

t_{is}^{f} = end time of batch i on stage s

Can be easily generalized to multistage processes and to several resources

Source: Méndez, C. A., & Cerdá, J. (2003). Dynamic scheduling in multiproduct batch plants. Computers and Chemical Engineering, 27(8-9), 1247-1259

Hitachi Energy

Global General Precedence

(Méndez and Cerdá, 2003)

$$\sum_{j \in J_{is}} x_{ijs} = 1 \quad \forall i \in I, s \in S_i$$

ALLOCATION CONSTRAINT

Sets

S_i = stages needed for job i

J_{is} = units that can execute stage s for job i

$J_{is,i's'} \in J_{is} \cap J_{i's'}$

$$t_{is}^{f} = t_{is}^{s} + \sum_{j \in J_{is}} T_{ijs}\, x_{ijs} \quad \forall i \in I, s \in S_i$$

PROCESSING TIME

End time = start time + duration (depends on equipment choice)

$$t_{i's'}^{s} \geq t_{is}^{f} + T_{is,i's'}^{clean} + T_{i's'}^{setup}$$

$$\forall i, i' \in I, i < i', s \in S_i, s' \in S_{i'}, j \in J_{is,i's'}$$

Sequencing only makes sense for jobs on the same machine

SEQUENCING CONSTRAINTS

$$t_{is}^{s} \geq t_{i's'}^{f} + T_{i's',is}^{clean} + T_{is}^{setup}$$

$$\forall i, i' \in I | i < i', s \in S_i, s' \in S_{i'}, j \in J_{is,i's'}$$

Indices and variables

i = job

j = unit or machine

s = production stage

x = assignment variable

y = sequencing variable

$$t_{is}^{s} \geq t_{i,s-1}^{f} + T_{i,s-1,s}^{tr} \quad \forall i \in I, s \in S_i, s > 1$$

STAGE PRECEDENCE

Source: Méndez, C. A., & Cerdá, J. (2003). Dynamic scheduling in multiproduct batch plants. Computers and Chemical Engineering, 27(8-9), 1247-1259

Energy Awareness – Altenative Formulation

HITACHI
Inspire the Next

Continuous-time scheduling model

Accounting for Electricity Consumption

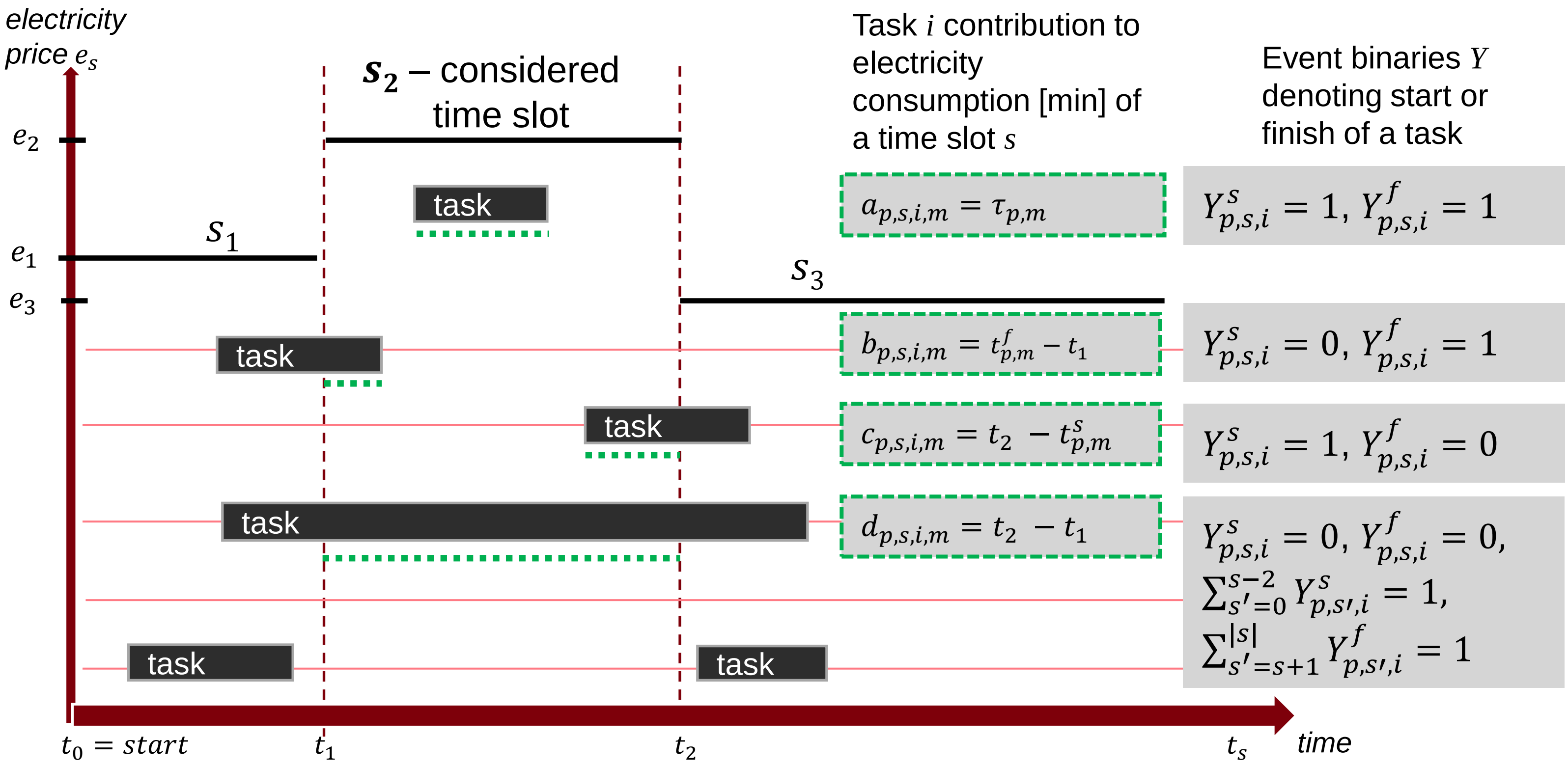
Model the relation between tasks i and time slots s through a discrete time-grid (MILP)

Model structure

- Production scheduling
- Energy awareness
- Price response
- Deviation response

Image on right

- Production task
- Time spent within a time slot



Source: Nolde, K., & Morari, M. (2010). Electrical load tracking scheduling of a steel plant. Computers and Chemical Engineering, 34, 1899-1903; Hadera, H. et al. (2015). Optimization of steel production scheduling with complex time-sensitive electricity cost. Computers and Chemical Engineering, 76, 117-136

Hitachi Energy

Link Event Binaries to the Start/End Variables

HITACHI
Inspire the Next

ST: stages in the original scheduling formulation

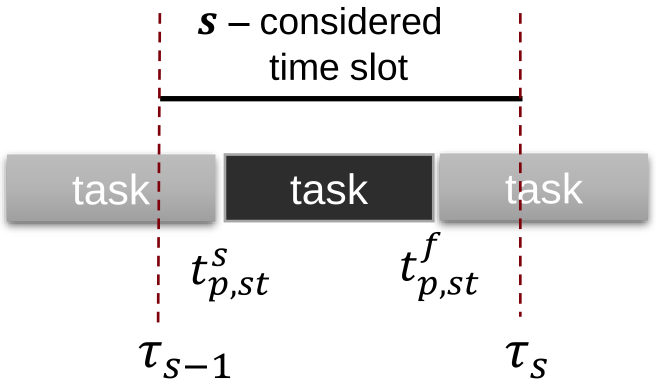
S: time slots for electricity tracking

$$t^{s}_{p,st} \geq \tau_{s-1} \cdot Y^{s}_{p,st,s} \quad \forall p \in P, st \in ST, s \in S$$

$$t^{s}_{p,st} \leq \tau_{s} + (M - \tau_{s}) \cdot (1 - Y^{s}_{p,st,s}) \quad \forall p \in P, st \in ST, s \in S$$

$$t^{f}_{p,st} \geq \tau_{s-1} \cdot Y^{f}_{p,st,s} \quad \forall p \in P, st \in ST, s \in S$$

$$t^{f}_{p,st} \leq \tau_{s} + (M - \tau_{s}) \cdot (1 - Y^{f}_{p,st,s}) \quad \forall p \in P, st \in ST, s \in S$$



For more information on how to link the auxiliary variables a, b, c, d to the scheduling problem, see paper by Hadera et al. (2015)

Source: Hadera, H. et al. (2015). Optimization of steel production scheduling with complex time-sensitive electricity cost. Computers and Chemical Engineering, 76, 117-136

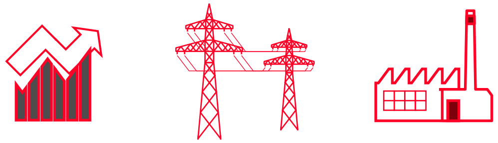
Hitachi Energy

iDSM for Electric Arc Furnace Steelmaking

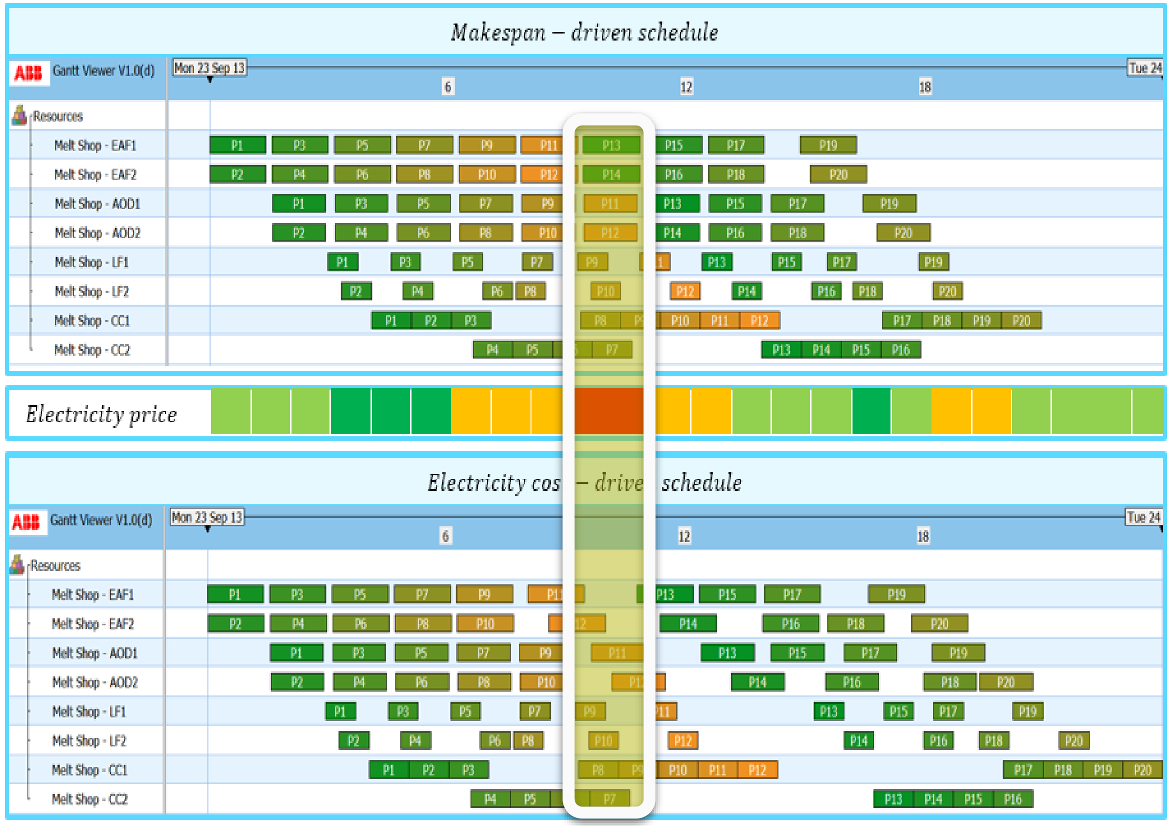
Intelligent Production Planning

Lower energy costs by

- Utilization of variable pricing
- Keeping committed load profiles



Scenario	Bin	Vars	MIP (600 s)	Gap (600 s)	MIP (3600 s)	Gap (3600 s)
1 (20-hi)	4065	29508	247838	29,30%	241136	26,80%
2 (20-lo)	4065	29508	200038	24,90%	180023	16,10%
3 (16-hi)	3229	23428	155226	22,81%	146339	17,93%
4 (16-lo)	3229	23428	204173	22,50%	180965	12,10%



Hadera et al. (2015), Merkert et al. (2015), Castro et al. (2013)

Benefits of Collaboration: 5% Savings at pilot plant

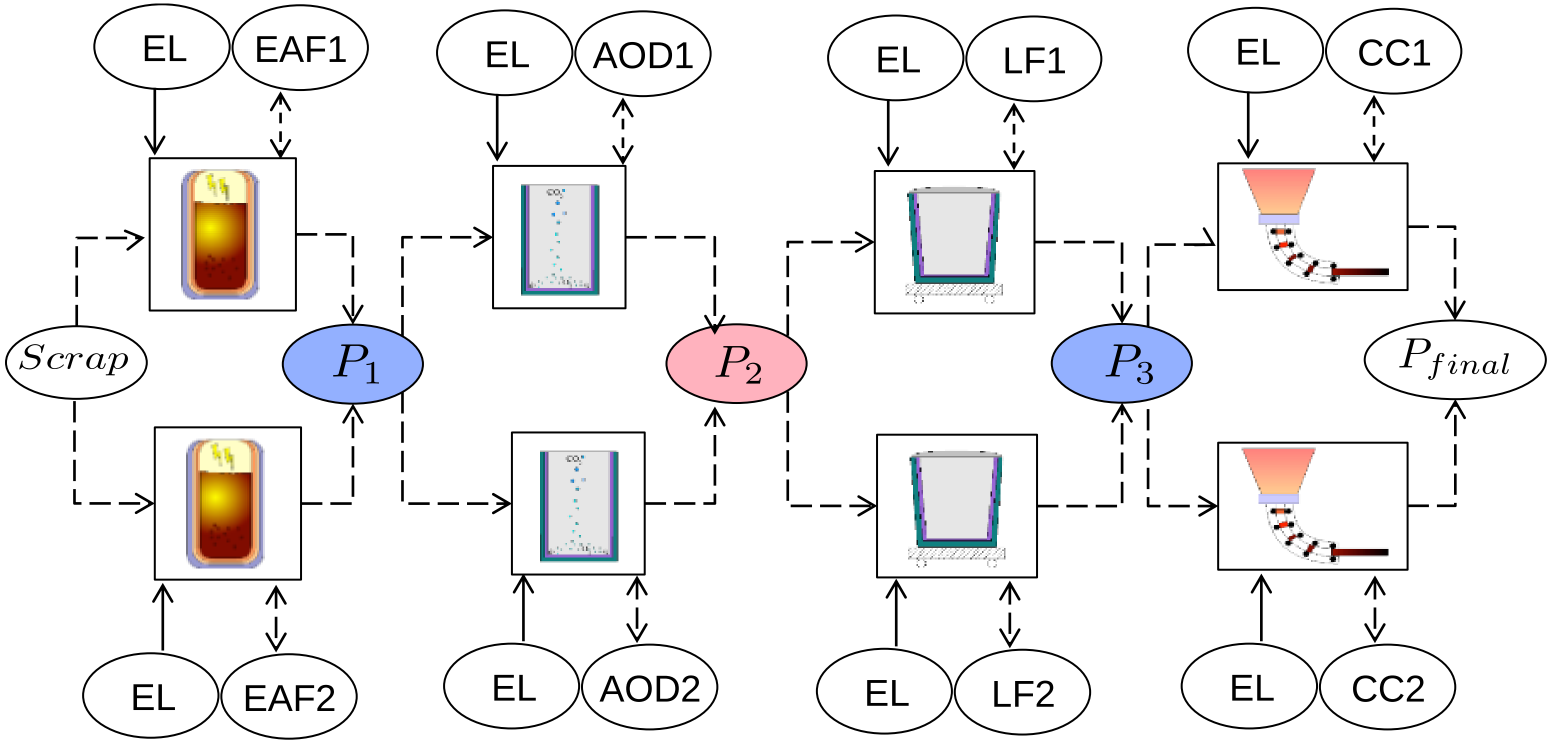
iDSM in Steel Production: Basic RTN Formulation

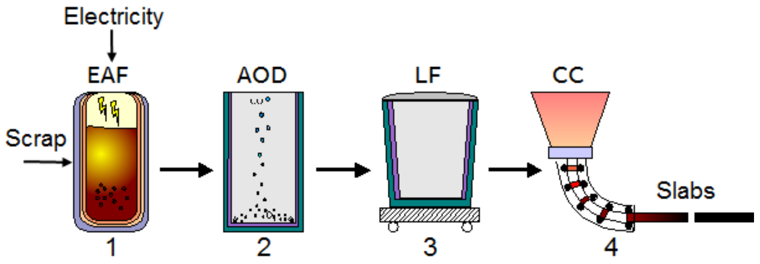
HITACHI
Inspire the Next

Discrete-time scheduling model

Modeling Approach Based on Resource Balances

$$Re_{r,t} = Re_{r,t-1} + \sum_k \sum_i N_{k,i,t} \mu_{r,k,i} + \sum_k \sum_i N_{k,i,t-\theta_{k,i}} \bar{\mu}_{r,k,i} + \sum_k \sum_i \sum_{t'=t-\theta_{k,i}+1}^{h} N_{k,i,t'} \xi_{k,i,r} + \pi_{r,t} \quad \forall r,t$$





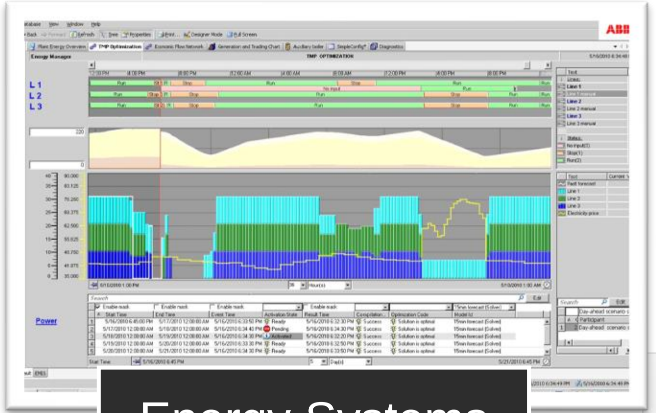
Source: Castro et al., 2009 & 2013

Hitachi Energy

iDSM: End of Isolated Solutions

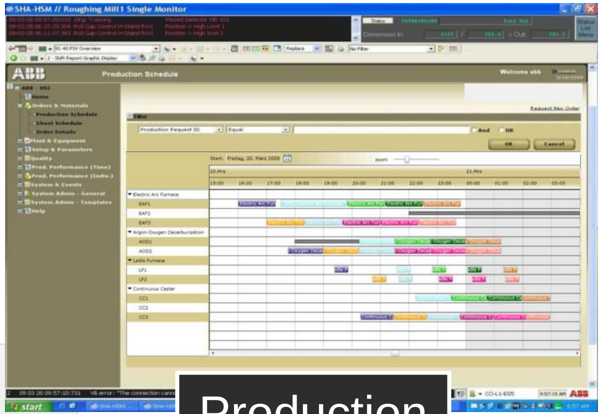
HITACHI
Inspire the Next

Integrated Production Planning & Energy Management



Energy Systems Scheduling

iDSM module



Production Planning

Coordination through
- Monolithic model (PP&EM)
- Model decomposition
- Data exchange

- **Reduce energy cost** using time varying energy prices
- **Increase flexibility** / agility wrt. energy availability
- Connect to **existing environment**
- Steel/TMP mills: **3-20% energy cost savings**

Source: Hadera, H. et al. (2015). Optimization of steel production scheduling with complex time-sensitive electricity cost. Computers and Chemical Engineering, 76, 117-136; Hadera, H. et al. (2019). Integration of production scheduling and energy-cost optimization using mean value cross decomposition. Computers and Chemical Engineering, 129, 106436

Hitachi Energy

Grid vs. Plant Perspectives Brought Together

Power Grids Focus

Different Industrial Processes

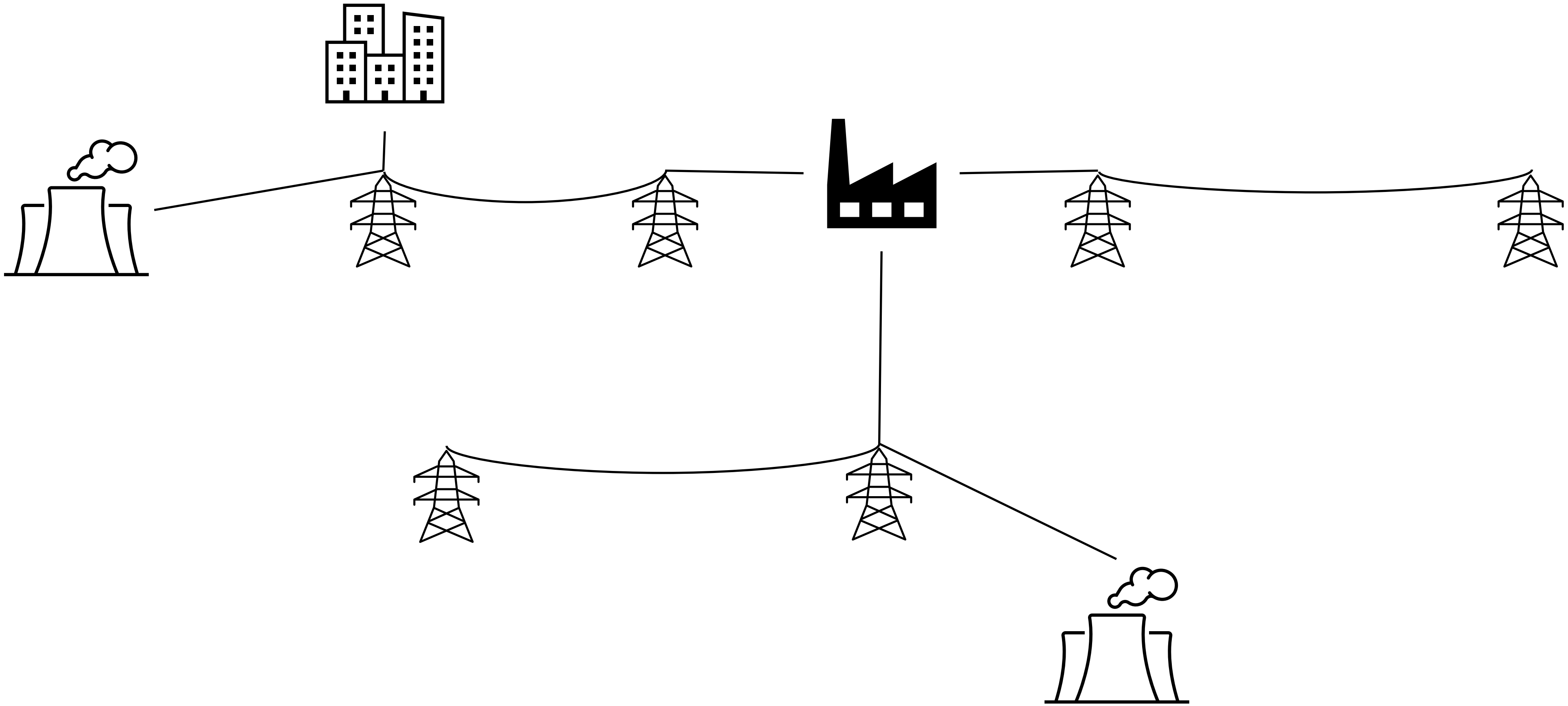
Coordination of Energy Production and Consumption is a Very Large Scheduling Problem

Two Worlds Separated – Cannot See all Details of the Other

Source: https://www.uwphotographyguide.com/over-under-split-photography

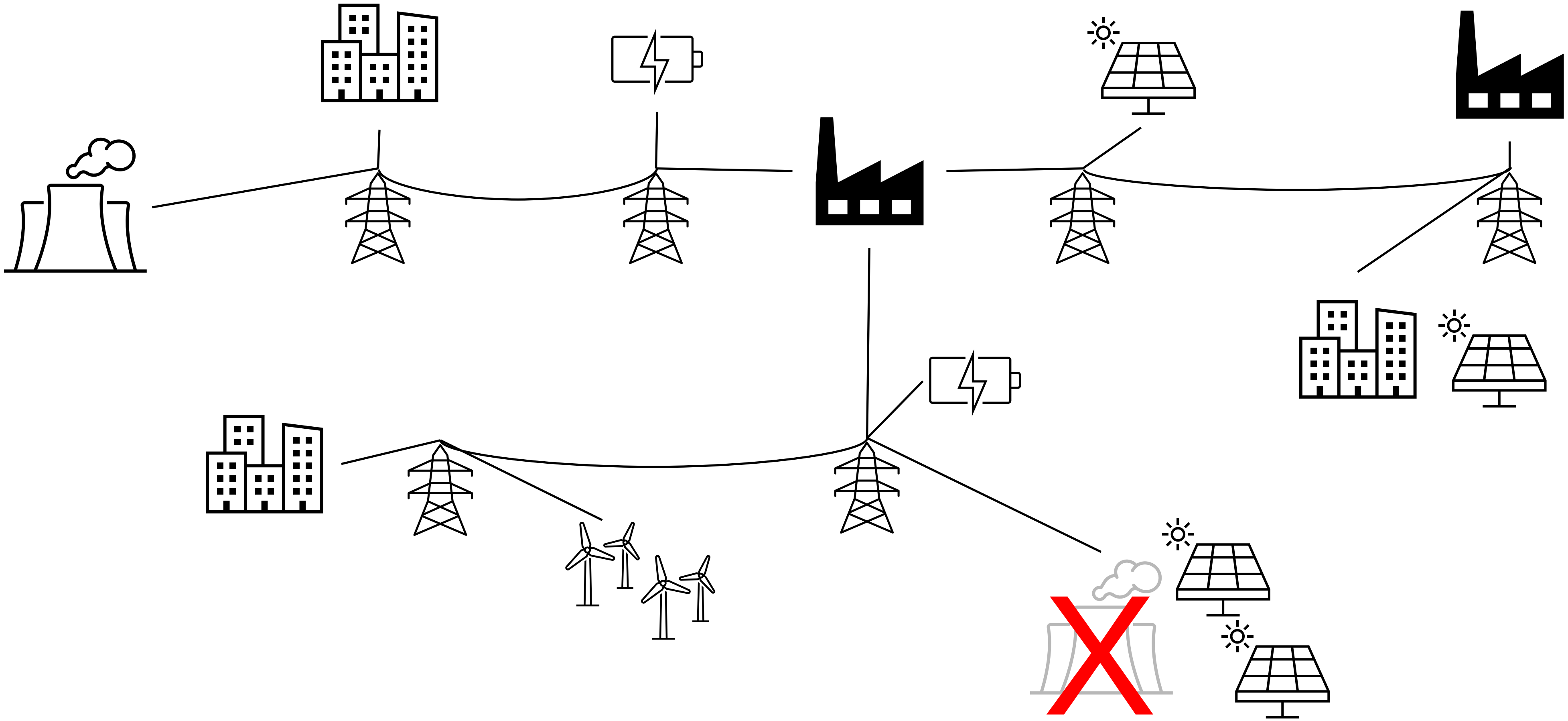
How Are Things Related Together?

Traditional Power System – main concern sufficient electricity availability at each time



How Are Things Related Together?

Modern Power System – main concerns electricity availability at each time as well as network capacity



Unit Commitment Problem

Discrete Time

Unit Commitment Problem

Inspire the Next

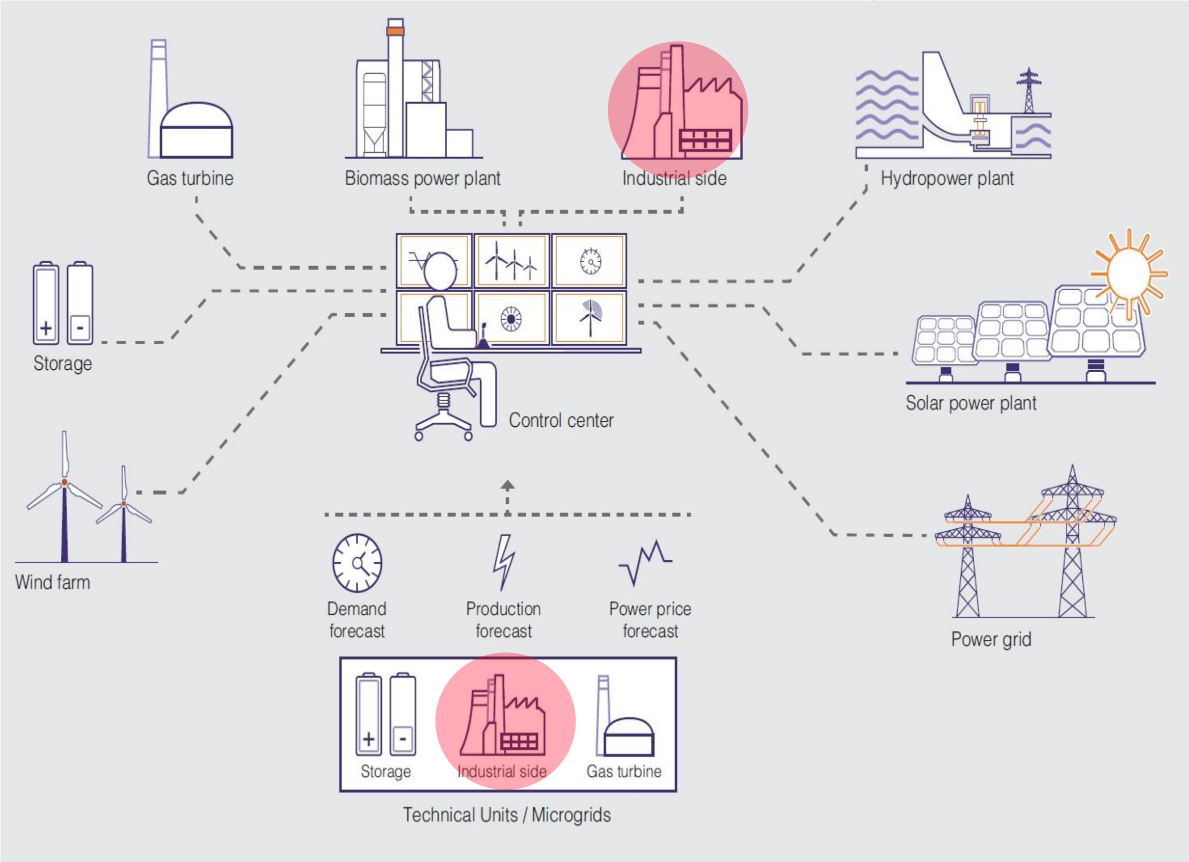
Electricity Production = Consumption

Ensure that the Electricity Production = Consumption

- Schedule and coordinate electrical generation in order to match the energy demand and supply at minimum cost

Optimal (lowest cost) balance between the “players” by solving MILP-based models

- Including: Generators, Renewables, Energy storage, Industrial sites, Power markets (buy & sell)
- Ensuring: Demand being met also with strong renewable participation
  - Most economical operations
  - Healthy ramp-up / ramp-down phases
  - Feasible w.r.t. power grid limitations



Hitachi Energy

Unit Commitment Problem

HITACHI
Inspire the Next

Mathematical Formulation (5 units, 5 time points)

Indices

i generation unit (I)

t time slot (T)

Parameters

P_t^{dem} electricity demand at time t (MW)

C_i^{var} variable generation cost (EUR/MW)

Variables

$p_{i,t}$ generation level, e.g. in MW (continuous)

Constraints

$\sum_i p_{i,t} = P_t^{dem} \quad \forall t$

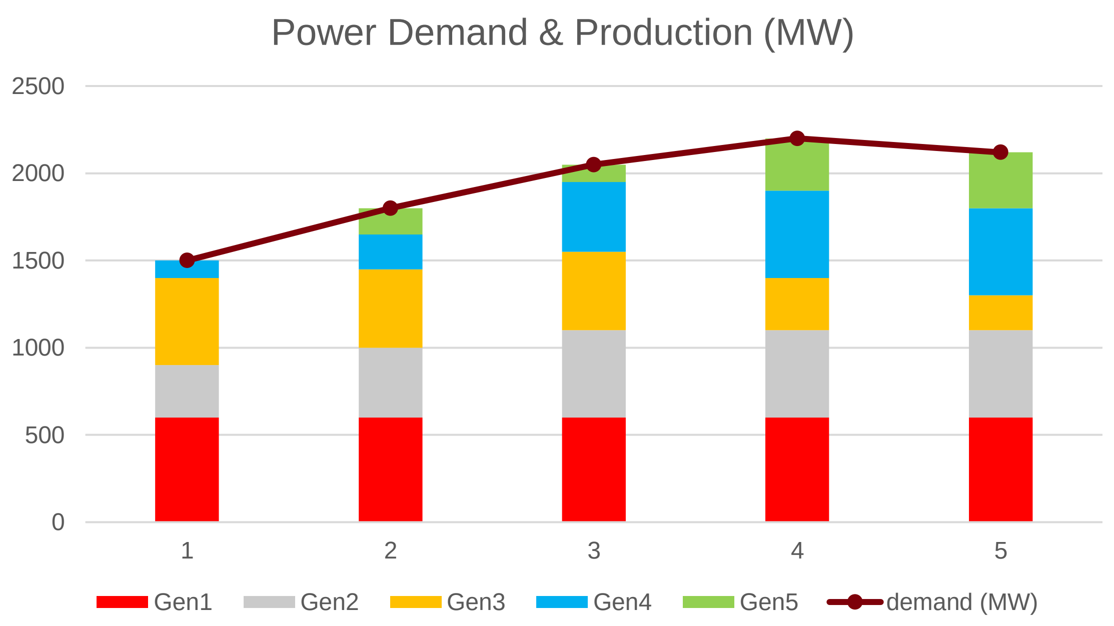
Objective function

$min \sum_t \sum_i C_i^{var} \cdot p_{i,t}$

Unit allocation can be done based on unit-specific costs (still simple)!

- However, a unit may be turned on/off… (we need a binary variable)
- Each unit also has a lower and upper operation limits (MW)

Illustration



Hitachi Energy

Unit Commitment Problem

Individual Generator Limitations

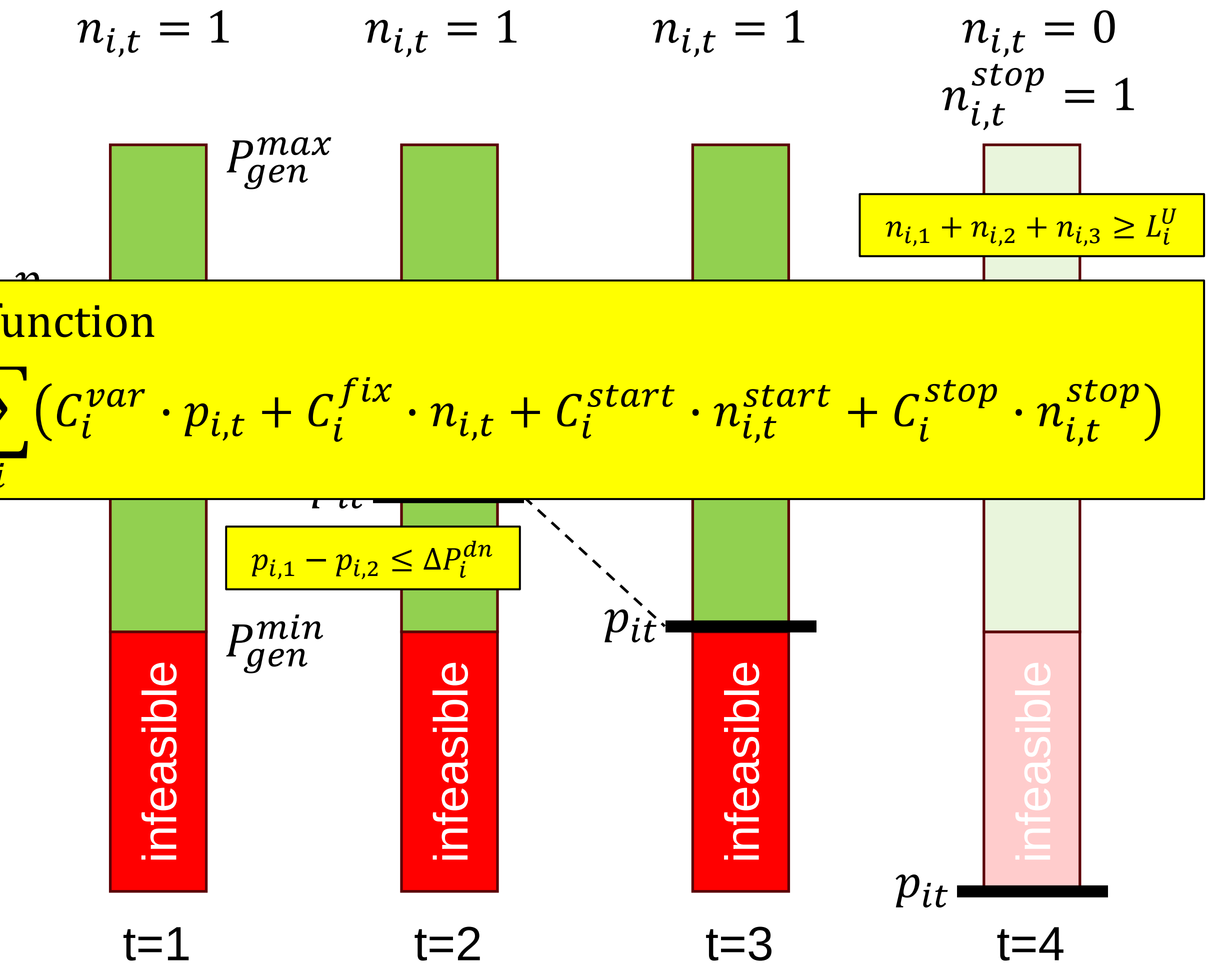
Parameters

C_i^{fix}	fixed generation cost (EUR/time step)
C_i^{start}	start-up cost of generator (EUR)
C_i^{stop}	shut-down cost of generator (EUR)
L_i^U	minimum uptime (time steps)
L_i^D	minimum downtime (time steps)
ΔP_i^{up}	ramp-up limit (MW/time step)
ΔP_i^{dn}	ramp-down limit (MW/time step)
P_i^{min}	minimum feasible (stable) generation (MW)
P_i^{max}	maximum feasible (stable) generation (MW)

Variables

$p_{i,t}$	generation level, e.g. in MW (continuous)
$n_{i,t}$	state of generator i at time t: on/off (binary)
$n_{i,t}^{start}$	start-up indicator of generator i s at time t (binary)
$n_{i,t}^{stop}$	shut-down indicator of generator i at time t (binary)

Illustration



Objective function

$$min \sum_t \sum_i (C_i^{var} \cdot p_{i,t} + C_i^{fix} \cdot n_{i,t} + C_i^{start} \cdot n_{i,t}^{start} + C_i^{stop} \cdot n_{i,t}^{stop})$$

Public

Unit Commitment Problem

HITACHI
Inspire the Next

Additional Constraints for Every Generator

Generation level

$$\boxed{P_i^{min} \cdot n_{i,t} \leq p_{i,t} \leq P_i^{max} \cdot n_{i,t} \quad \forall i,t}$$

Ramp-up/down limits

$$p_{i,t} - p_{i,t-1} \leq \Delta P_i^{up} + P_i^{min} \cdot n_{i,t}^{start} \quad \forall i, t > 1$$

$$p_{i,t-1} - p_{i,t} \leq \Delta P_i^{dn} + P_i^{min} \cdot n_{i,t}^{stop} \quad \forall i, t > 1$$

Start-stop constraints

$$n_{i,t} - n_{i,t-1} = n_{i,t}^{start} - n_{i,t}^{stop} \quad \forall i, t > 1$$

$$n_{i,t}^{start} + n_{i,t}^{stop} \leq 1 \quad \forall i, t > 1$$

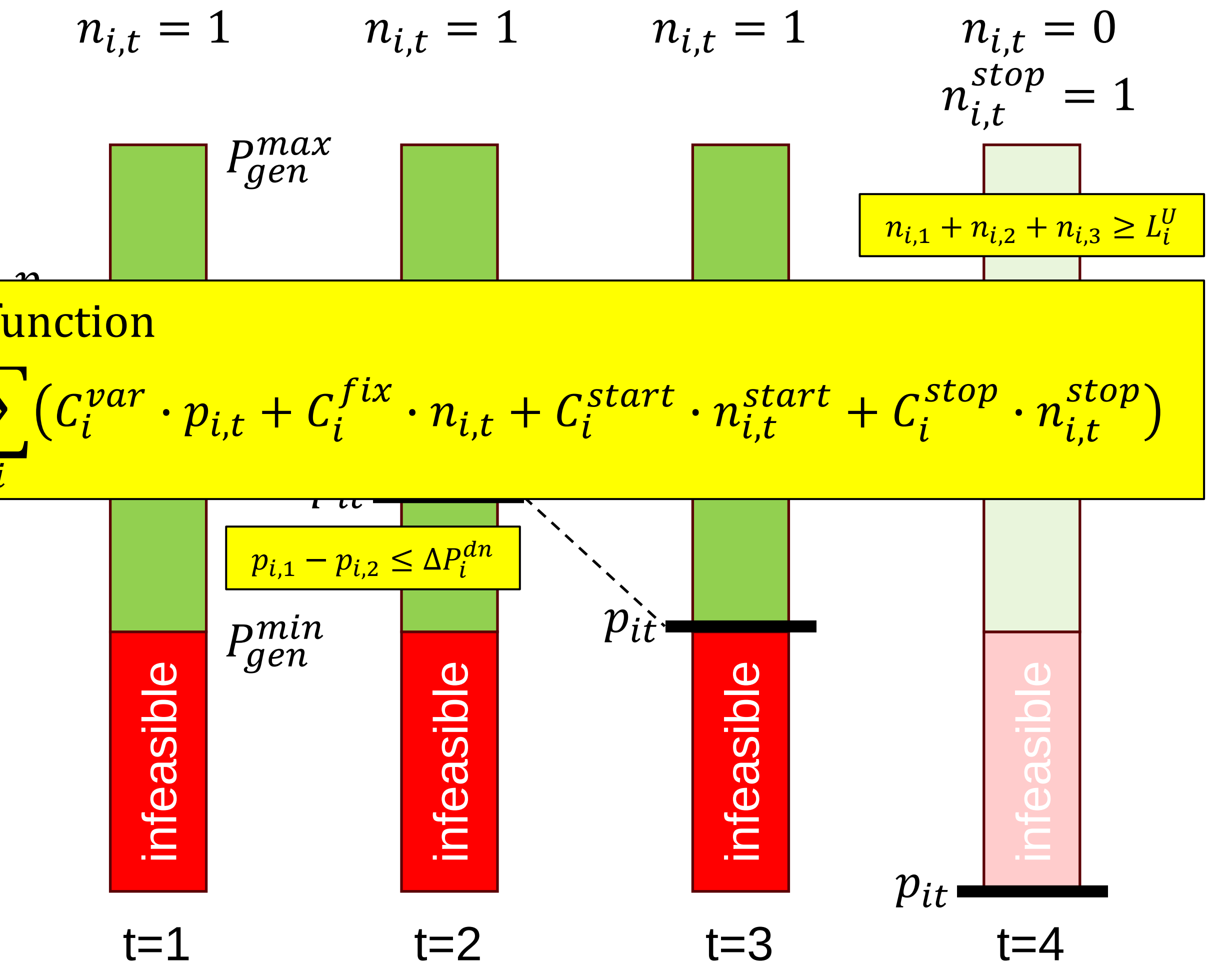
Minimum up/down-times

$$n_{i,\tau} \geq n_{i,t}^{start} \quad \forall i, t, \tau = t+1, \min\{t + L_i^U - 1, T\}$$

$$n_{i,\tau} \leq 1 - n_{i,t}^{stop} \quad \forall i, t, \tau = t+1, \min\{t + L_i^D - 1, T\}$$

\+ Reserve variables & constraints, network constraints (iterative process), …

Illustration



Objective function

$$min \sum_t \sum_i (C_i^{var} \cdot p_{i,t} + C_i^{fix} \cdot n_{i,t} + C_i^{start} \cdot n_{i,t}^{start} + C_i^{stop} \cdot n_{i,t}^{stop})$$

Hitachi Energy

Unit Commitment Problem

HITACHI
Inspire the Next

Problem Size

Number of units significantly increasing (small renewable units, energy storage units, …)

- Yesterday: 50-200 generation units
- Today: >1000 plannable units
- Future: >5000+ units…

Planning horizon: 24 hours, time grid of 1 hour, 30 or 15 min → 24, 48 or 96 time points.

- A problem with at least 24000 binary variables (1000 units) → $5.24 \cdot 10^{7224}$ combinations

Any brute force method will fail …

We need to be able to solve several UC problem runs (iterative procedure) typically within 5-10 minutes!

Optimality

Optimization plays a crucial role as we are often optimizing the power use for an entire country or state

Assume

- a typical consumption of 40 GW…
- Average power price 40 EUR/MWh (4 cents / kWh)

This result in a daily generation cost of 38.4 MEUR (in a year 14 billion EUR)

- Each 1% away from the optimal solution means 384 kEUR loss / day (this is still acceptable) → 140 MEUR / year

Optimization matters!!!

Hitachi Energy

Proposed Approach

Basic target: Speed up the solution of the UC problem without loss off (near) optimality!

LP problem much faster than corresponding MILP

- Rounding e.g. fractional values 0.9 → 1 (binary) does not work well!

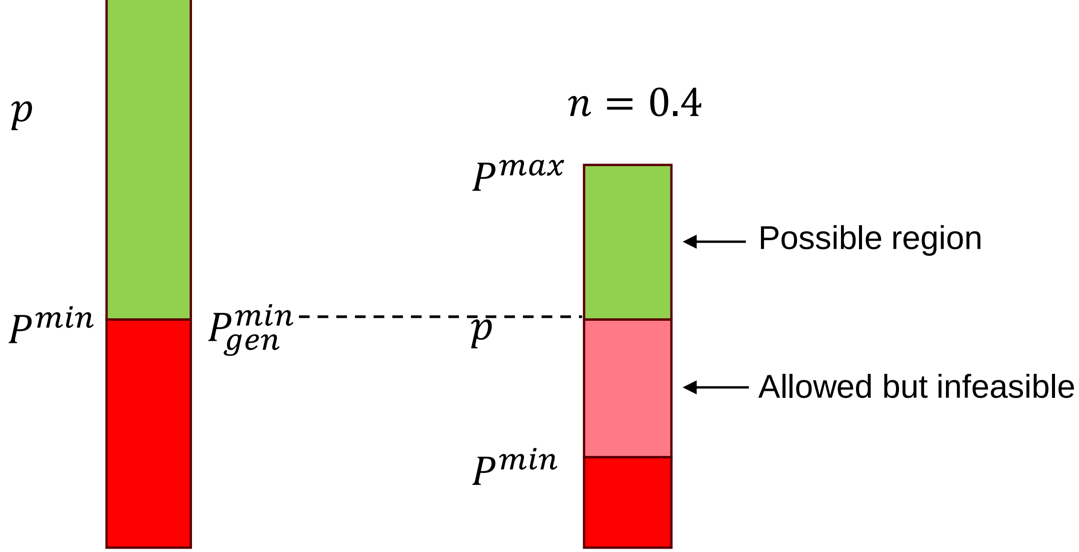
Idea: Analyze LP solution and fix binary variables for generators respecting the physical generation limits $(P_{gen}^{min}, P_{gen}^{max})$ in the relaxed solution by checking the key equation:

$$n_{i,t} \cdot p_{i,t} \geq P_i^{min}$$

If this is satisfied, then the generator operates on a valid region even in the relaxed solution → **assume** also needed in MIP → fix $n_{i\,t} = 1$

$$P_{gen}^{min} \cdot n \leq p \leq P_{gen}^{max} \cdot n$$

$$n \in \{0,1\}$$



MIP solution

Relaxed MIP solution (LP)

Unit Commitment Problem – LP-based Heuristics

Proposed Approach

Basic target: Speed up the solution of the UC problem without loss off (near) optimality!

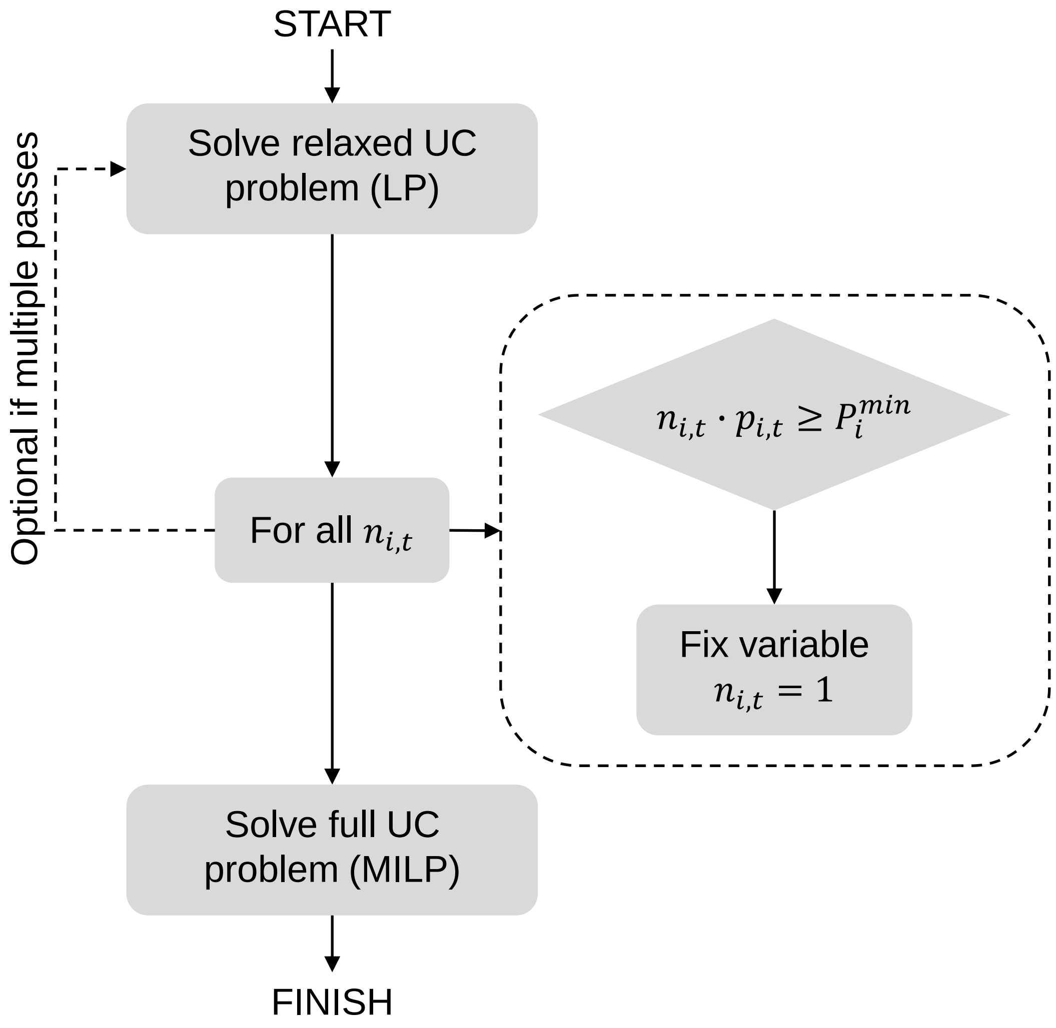
LP problem much faster than corresponding MILP

- Rounding e.g. fractional values 0.9 → 1 (binary) does not work well!

Idea: Analyze LP solution and fix binary variables for generators respecting the physical generation limits $(P_{gen}^{min}, P_{gen}^{max})$ in the relaxed solution by checking the key equation:

$$n_{i,t} \cdot p_{i,t} \geq P_i^{min}$$

If this is satisfied, then the generator operates on a valid region even in the relaxed solution → **assume** also needed in MIP → fix $n_{i\,t} = 1$



Unit Commitment Problem – LP-based Heuristics Results

HITACHI
Inspire the Next

Test Cases with 1200/50 Units

Results: 1200 units (large example)

- Average speed-up: 3.7
- Longest solution time (critical): 132 → 13 seconds!
- Average solution improvement

Results: 50 units (small example)

- Average speed-up: 1.8
- Longest solution time: 226 → 65s
- In average 0.7% worse solutions
  - One outlier case with 41% (caused by inflexible units)

Many runs: Better than MIP

- All runs: mipgap = 1%

First UC example (1200 units, 44 instances)

Solution times (s)	MIP	LPHeur	FixedVars	Speed-Up	ObjDiff
Min	9.24	7.24	8002	0.944	0.992
Max	**131.99**	**12.72**	10494	13.918	1.004
Average	36.63	9.82	10053	**3.731**	0.999
Median	25.37	9.76	10086	2.553	0.999
Total (sum)	1611.78	432,00		N/A	N/A

Second UC example (50 units, 225 instances)

Solution times (s)	MIP	LPHeur	FixedVars	Speed-Up	ObjDiff
Min	0.168	0.208	29	0.130	0.994
Max	**226.825**	**65.418**	355	6.093	1.410
Average	9.797	5.154	137	**1.863**	**1.007**
Median	1.074	0.565	128	1.515	1.001
Total (sum)	1498.903	788.570	N/A	N/A	N/A

Harjunkoski, I. et al. (2021). Matheuristics for speeding up the solution of the unit commitment problem. Paper presented at the Proceedings of 2021 IEEE PES Innovative Smart Grid Technologies Europe: Smart Grids: Toward a Carbon-Free Future, ISGT Europe 2021

Hitachi Energy

Unit Commitment Problem – Conclusions

HITACHI
Inspire the Next

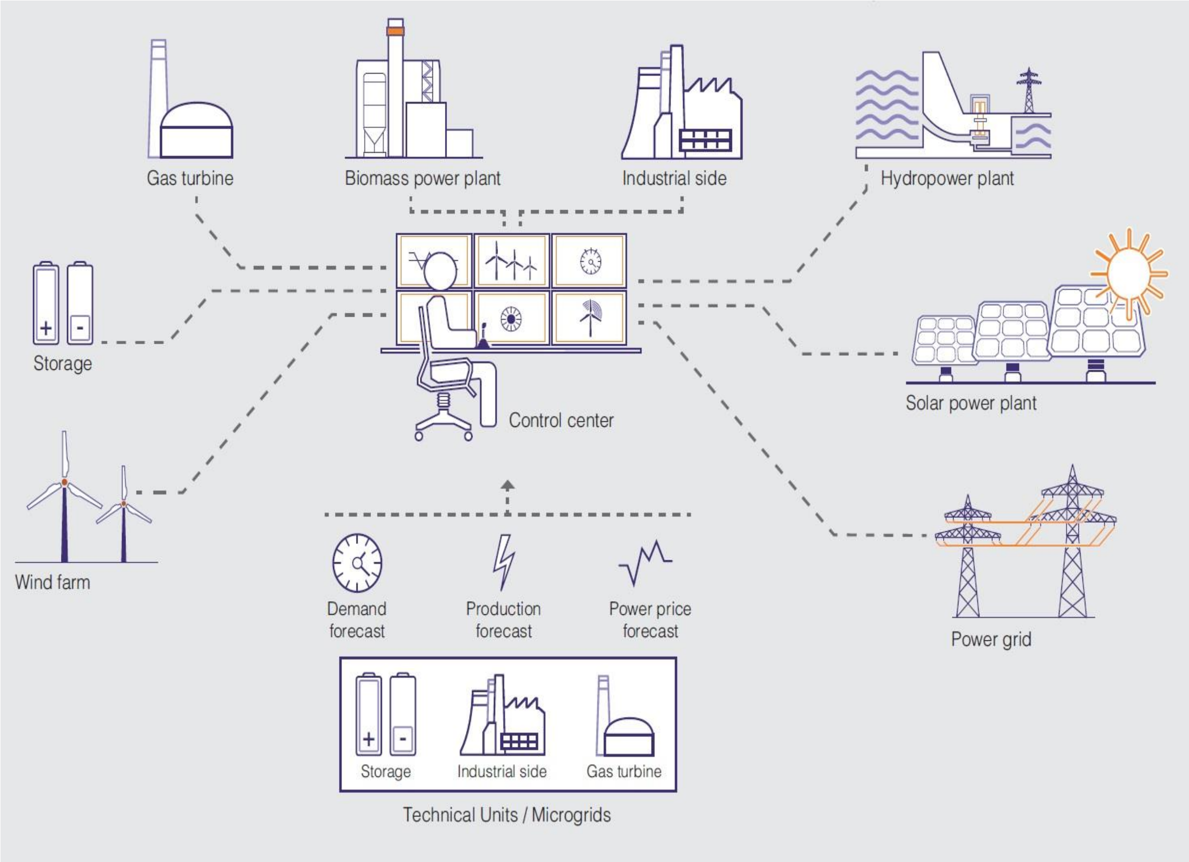
Promising results

A simple approach can make a big difference!

- Increasing the robustness of solving the UC problem
- All instances on the same grid → large variations
- Possible to build up on this, combine it with ML etc.
    - Nevertheless, due to strong optimality need and many cost types optimal cost balancing can be challenging
    - Important: enough problem-specific data for training

Deployment of proposed LP-based heuristic relatively straightforward in an existing product environment

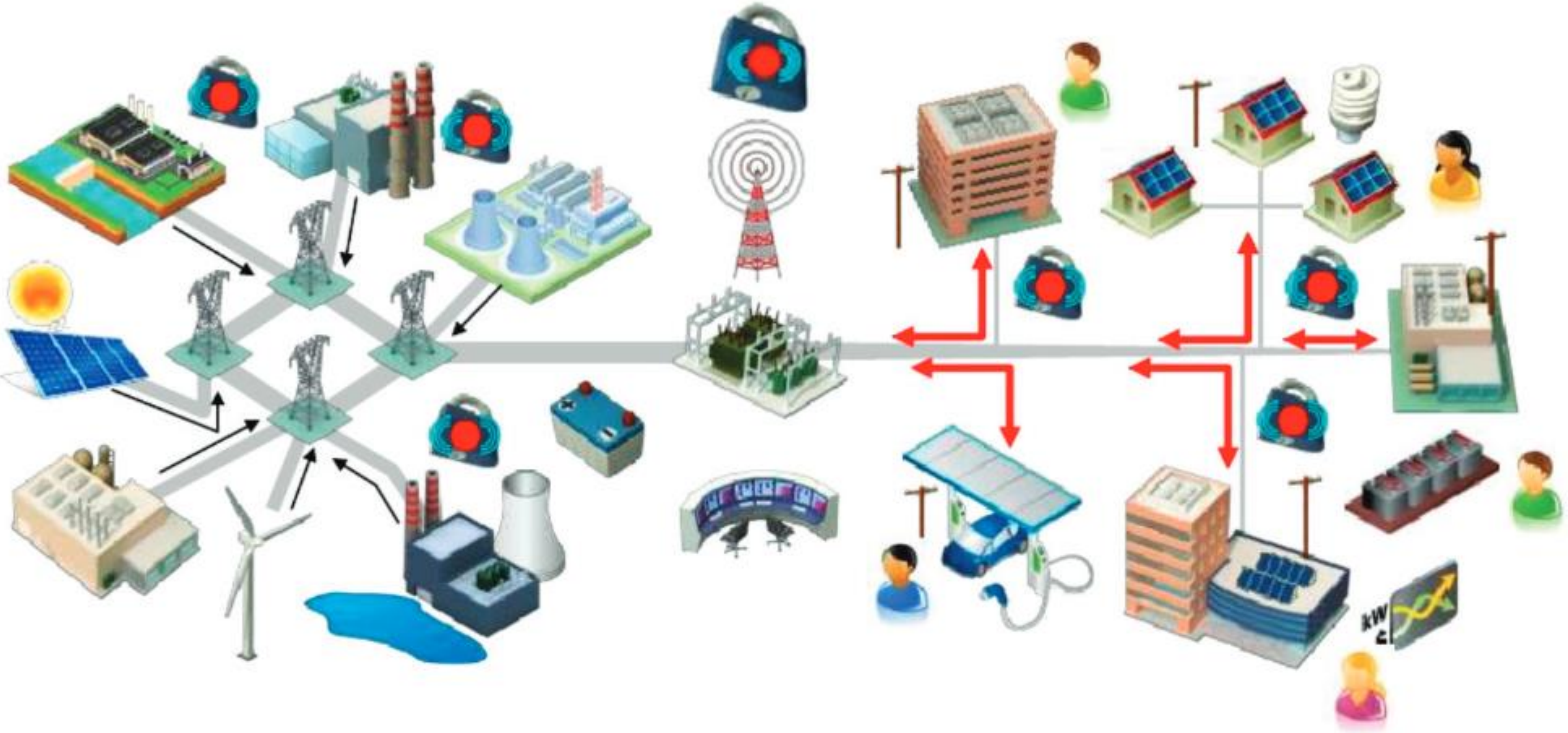
- Sometimes, relaxed LP-solution took > 50% of total time (done twice in LP-based heuristics)



Hitachi Energy

Conclusions

The Future of Electric Power is Bi-Directional and Smart(er)



Public

Goal of This Talk…

- Highlight the importance of energy / electricity
- Give insights to solving industrial-scale scheduling problems (demand-side management)
- Present some strategies to speed up large-scale optimization problems
- Share some personal experiences from working with MILP problems
  - Melt-shop (steel) scheduling
  - Unit Commitment

MILP is an important (although not only) component in solving industrial scheduling problems

Conclusions

Optimization is critical to many industrial problems

- MILP a good tool, especially for modeling complex constraints
- Commercial MILP solvers embed most advanced algorithms

MILP alone not sufficient in solving many real-size problems

- Need supporting heuristics, decomposition schemes, AI/ML, …
- Models must be both very tight and expandable

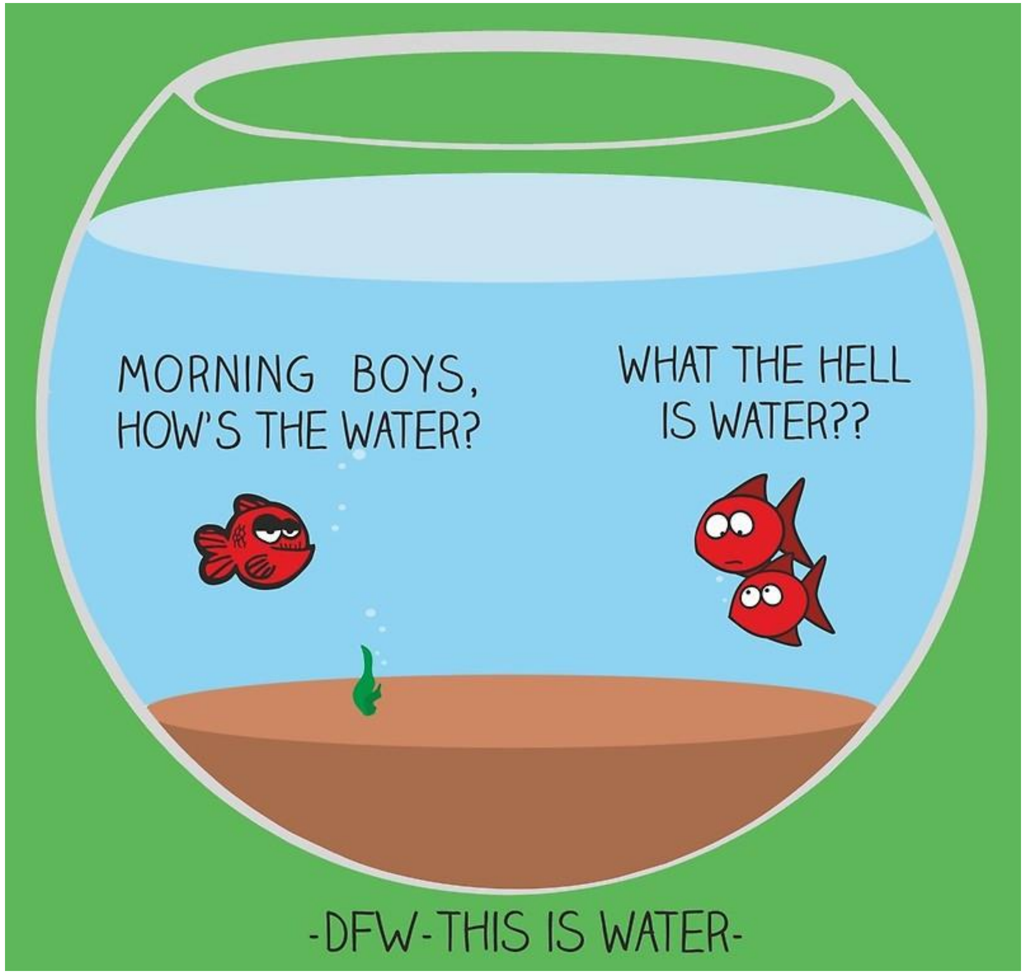
Energy combines different players and becomes more important

- Demand-side management seek to identify process flexibility
- Combination of scheduling processes and energy is hard but necessary: Need more solutions crossing the domain borders!

Important: Research cultures meet and collaborate: Math, CS/OR, Engineers (ChemE, Elec, SW, …) and Natural Scientists

- Not to forget about industrial/academic collaboration…

Still many industrial challenges not even yet been modeled!



References

- Harjunkoski, I., & Grossmann, I. E. (2001). A decomposition approach for the scheduling of a steel plant production. Computers and Chemical Engineering, 25(11-12), 1647-1660
- Castro, P. M., Harjunkoski, I., & Grossmann, I. E. (2009). New continuous-time scheduling formulation for continuous plants under variable electricity cost. Industrial and Engineering Chemistry Research, 48(14), 6701-6714
- Méndez, C. A., & Cerdá, J. (2003). Dynamic scheduling in multiproduct batch plants. Computers and Chemical Engineering, 27(8-9), 1247-1259
- Hadera, H., Harjunkoski, I., Sand, G., Grossmann, I. E., & Engell, S. (2015). Optimization of steel production scheduling with complex time-sensitive electricity cost. Computers and Chemical Engineering, 76, 117-136
- Castro, P. M., Sun, L., & Harjunkoski, I. (2013). Resource-task network formulations for industrial demand side management of a steel plant. Industrial and Engineering Chemistry Research, 52(36), 13046-13058
- Merkert, L., Harjunkoski, I., Isaksson, A., Säynevirta, S., Saarela, A., & Sand, G. (2015). Scheduling and energy - industrial challenges and opportunities. Computers and Chemical Engineering, 72, 183-198
- Nolde, K., & Morari, M. (2010). Electrical load tracking scheduling of a steel plant. Computers and Chemical Engineering, 34(11), 1899-1903
- Dua, V., Pistikopoulos, E., 2000, An Algorithm for the Solution of Multiparametric Mixed Integer Linear Programming Problems, Ann Oper Res, 99, 1-4, 123-139
- Hadera, H. et al. (2019). Integration of production scheduling and energy-cost optimization using mean value cross decomposition. Computers and Chemical Engineering, 129, 106436
- Harjunkoski, I. et al. (2021). Matheuristics for speeding up the solution of the unit commitment problem. Paper presented at the Proceedings of 2021 IEEE PES Innovative Smart Grid Technologies Europe: Smart Grids: Toward a Carbon-Free Future, ISGT Europe 2021

Hitachi Energy

HITACHI
Inspire the Next