Building Control and Automation

Introduction to Energy Hubs

Friday 20 April 2018

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Outline

Motivation
– Decentralized energy systems
– Complexity

Energy hub modelling
– What is an energy hub (model)?
– Brief exercise
– Elements of an energy hub model

Computational optimization
– Optimization methods
– Mixed-integer linear programming
– Solution methods

Implementation
– Software tools
– Yalmip Toolbox
– Ehub Modelling Tool

Exercise: Monday 23 April
– Create an energy hub model in Yalmip

Friday 27 April
Energy hubs part 2: Advanced topics
– Minimum part load / activations / run times
– Ramping constraints
– Stepwise linearisation
– Network layout optimisation
– Power flow constraints
– Hierarchies of multi-energy hubs
– Decreasing computational burden
– Bi-level optimisation
– Iterative optimisation
– Multi-objective optimisation
Motivation
Problem

For a given urban area/district/community…

How should a decentralized energy system for the site be optimally designed and operated?

More specifically, e.g.:

- Which energy production/storage technologies should be installed (e.g. PV, heat pumps, gas boilers)?
- What should be the capacities of the installed technologies?
- How should these technologies be operated throughout the year?
- …
Energy performance of buildings
Energy performance of buildings – the energy hierarchy

- **Renewables**
  - Convert: Utilise more wind, solar, geothermal, etc.

- **Increase Energy Efficiency**
  - Control: efficient/intelligent appliances and integrated systems

- **Reduce Energy Demand**
  - Conserve: Building materials and components

Conserve: Building materials and components
Beyond individual buildings – interactions within districts
Example – Brooklyn Microgrid

• Community electric microgrid in Brooklyn, NY, USA
• Residents to buy and sell the energy they produce from rooftop solar power installations, using the existing energy infrastructure.
• Peer-to-peer energy transactions (blockchain for tracking transactions)
• More info: http://brooklynmicrogrid.com
Beyond individual districts – multi-scale problem

How can the interactions between these scales be coordinated to improve overall energy performance?

- Where should energy be produced/stored and in what quantities?
- How should transactions be coordinated?

Source: Marquant, 2014
Implications – improving the energy performance of buildings

1. This is a **multi-scale problem**, so we can’t just look at buildings in isolation
2. Urban areas give rise to the potential for **system integration**
3. Not just energy systems – also **building orientation, density, and (urban) form** impact the ability to utilise local renewable energy sources
4. Adoption of decentralised renewable energy sources may require the **re-engineering of the energy infrastructure** (e.g. technologies, wires, pipes)
   - How much will this cost? Under what conditions does it make sense? Who pays?

**Paradigm shift:**
Centralized generation + Transmission + Distribution $\rightarrow$ Decentralized generation
Why optimization?

For a given urban area/district/community…

How should a distributed energy system for the site be optimally designed and operated…

In order to minimize costs and/or emissions, maximize autonomy, etc…

Given complexities such as:
- Time-varying resource availability
- Multi-energy demand patterns
- Technical & economic constraints
- Regulatory/policy environment
- Uncertainties regarding fuel prices, energy demand, policy, etc.
- Possibilities for electricity market participation
Complexity of integration

- Temporal and spatial variation in electricity, heating, and cooling demands

- Intermittency of certain types of renewable technologies (e.g. PV and wind turbines)
Complexity of integration

- Variable fuel pricing

- Temporal variability in carbon intensity of the grid electricity

 Different technologies with different fuels and different efficiencies operating at different times.

Carbon intensity of Swiss electricity grid?
• Summer vs. winter?
• Day vs. night?
Why optimization?

Optimization can address many of these complexities and can be used to determine:

1. **Optimal system design:** the choice of generation/storage technologies within the energy system and their sizes.

2. **Optimal unit dispatch:** the operational schedule that best matches energy supply with demand at every timestep (e.g. every hour).

3. **Optimal network structure:** the location of the generation/storage units and the structure of the distribution network.
Exercise (1)

Each person has a card representing a type of entity in a district energy system.

4 types of cards:

1. **Energy inputs**: You represent an external energy input to a district energy system

2. **Energy demands**: You represent an energy demand internal to a district energy system

3. **Energy conversion technologies**: You are a distributed energy conversion technology. You convert one form of energy into another.

4. **Energy storage technologies**: You are an energy storage technology. You store a specific type of energy.

Look at your card. What type of card do you have? What are your inputs and outputs?
Exercise (2)

Instructions:

5 minutes: Look for partners who can supply your inputs and use your outputs. Try to make a complete chain (district energy system) from inputs to demands.
Exercise (3)

Questions:
1. How many technologies are in your system?
2. How sustainable (carbon intensive) is your system?
3. How energy autonomous is your system?
Energy hub modelling
What is an energy hub?

**Inputs**
- e.g. Grid electricity, solar radiation, natural gas, etc.

**Energy Hub**

**Outputs**
- e.g. Electricity, Heat, Domestic Hot Water, etc.

What happens in the black box?
What is an energy hub?

A system to convert between and store **multiple energy streams**

In transforming inputs into outputs, certain variables can be controlled, and others cannot.

How many degrees of freedom are there in this system?

Three, maybe four
What is an energy hub model?

A mathematical representation of an energy hub that enables optimization

What do we want to optimize?

The set of processes (energy pathways) by which we transform energy inputs into outputs.
What is an energy hub model?

A mathematical representation of an energy hub that enables optimization

**Variables:** Elements for which you want to identify an optimal value

**Constants:** Elements for which you already know the value

**INPUTS**
- Grid
- PV
- Gas

**OUTPUTS**
- Electricity
- Heat

**Diagram:**
- Inverter
- Heat pump
- Boiler
- Hot water tank
- Q_{heat}(t)
- P_{elec}(t)
- P_{HP}(t)
- P_{boiler}(t)
- I_{grid}(t)
- I_{PV}(t)
- I_{gas}(t)
An exercise

What are the cost minimizing grid and gas purchases of this system (for one hour) if:

HP capacity = 10 kW\textsubscript{th}
Boiler capacity = 30 kW
HP efficiency (COP) = 4
Boiler efficiency = 0.9
Gas price = 0.1 CHF/kWh
Electricity price = 0.3 CHF/kWh

PV generation = 5 kWh
Inverter efficiency = ~100%
Heat load = 12 kWh
Electricity load = 4 kWh
Thermal storage is empty

1st step: set up equations for each node in the system
An exercise

1. Set up your equations for each node in the system

\[ I_{grid} + I_{PV} = P_{HP} + P_{elec} \]
\[ P_{elec} = L_{elec} \]
\[ I_{gas} = P_{boiler} \]
\[ P_{boiler} \times n_{boiler} + P_{HP} \times n_{hp} + Q_{heat,out} - Q_{heat,in} = L_{heat} \]

Objective function: \( Z = I_{grid} \times C_{grid} + I_{gas} \times C_{gas} \)

2. Simplify your equations

\[ I_{grid} + I_{PV} = P_{HP} + L_{elec} \]
\[ I_{gas} \times n_{boiler} + P_{HP} \times n_{hp} = L_{heat} \]

Objective function: \( Z = I_{grid} \times C_{grid} + I_{gas} \times C_{gas} \)

3. Plug in the values you know

\[ I_{grid} + 5 = P_{HP} + 4 \]
\[ I_{gas} \times 0.9 + P_{HP} \times 4 = 12 \]

Objective function: \( Z = I_{grid} \times 0.3 + I_{gas} \times 0.1 \)
An exercise

4. Rearrange and solve

\[ Z = 1.03 - 0.14 \times P_{HP} \]

How do we minimize \( Z \)?
Maximize \( P_{HP} \)
But, max possible value of \( P_{HP} \) is \( \frac{10}{4} = 2.5 \) kWh

\[
\begin{align*}
I_{\text{grid}} + 5 &= P_{\text{HP}} + 4 \\
I_{\text{gas}} \times 0.9 + P_{HP} \times 4 &= 12
\end{align*}
\]

\[
\begin{align*}
I_{\text{grid}} &= 1.5 \text{ kWh} \\
I_{\text{gas}} &= 2.22 \text{ kWh}
\end{align*}
\]

That’s the systematic way. The easy way:

- A quick calculation will show you that it’s cheaper to produce heat with the heat pump than the gas boiler.
- So: Just set the heat pump output to its maximum capacity and solve.
NEST demonstrator, Empa
“Vertical urban district” being constructed at Empa, Dübendorf

Networks:
- Thermal networks
- Gas grid
- Microgrid
NEST energy hub, Empa

Grid

PV

Supercaps

Chilled water

Gas

Hot water

Boiler

Chiller

Cold

Ice

Ground

Warm water

Electricity

PV

Solar heat

Batteries

High temp heat pump

Low temp heat pump

Mobility

Electrolyser

H₂

Fuel Cell

NaOH

H₂

High temp heat pump

Warm

Ground

Hot water

Hot
Objective function:
Cost, carbon emissions, ...

\[
\min f = \sum G_j \times I_j(t)
\]

Charging / discharging

\[
L_k(t) = \Theta_{k,m} \times P_m(t) + A_n^{\text{dis}} Q_n^{\text{dis}}(t) - Q_n^{\text{ch}}(t)
\]

Conversion

\[
E_n(t+1) = A_n^* E_n(t) + A_n^{\text{ch}} Q_n^{\text{ch}}(t) - Q_n^{\text{dis}}(t)
\]

Continuity

Conversion

Input capacity

\[
I_j(t) \leq I_j^{\max}(t)
0 \leq P_m(t) \leq P_m^{\max}
\]

Storage

capacity

\[
E_n(t) \leq E_n^{\max}
\]

Conversion

Storage

Energy hub model – typical constraints

Objective function
\[ \min f = \sum G_j \times I_j(t) \]

Load balance constraint
\[ L_k(t) = \Theta_{k,m} \times P_m(t) + A_n^{dis} Q_n^{dis}(t) - Q_n^{ch}(t) \]
Sum of energy outputs from technologies must be sufficient to provide for demand at the given timestep

Storage continuity constraint
\[ E_n(t+1) = A_n^s E_n(t) + A_n^{ch} Q_n^{ch}(t) - Q_n^{dis}(t) \]
Storage inputs and outputs determine the state of charge at the next timestep.

Capacity constraints
\[ I_j(t) \leq I_j^{max}(t), \quad 0 \leq P_m(t) \leq P_m^{max}, \quad E_n(t) \leq E_n^{max} \]
Conversion technologies cannot produce more than their capacities. Storages must not be filled more than their capacities.

Storage charge/discharge constraints
\[ Q_n^{ch}(t) \leq M d_n(t), \quad Q_n^{dis}(t) \leq M (1-d_n(t)) \]
Storages can only be charged/discharged at a maximum rate.

Part-load constraints
\[ P_m^{min} b_m(t) \leq P_m(t) \leq P_m(t) \leq M b_m(t) \]
Conversion technologies cannot produce below a given power level.
Variables and constants

**Variable**

\[ L_k(t) = \Theta_{k,m} \times P_m(t) + A_{n}^{dis} Q_{n}^{dis}(t) - Q_{n}^{ch}(t) \]

\[ E_n(t + 1) = A_{n}^{*} E_n(t) + A_{n}^{ch} Q_{n}^{ch}(t) - Q_{n}^{dis}(t) \]

**Constant**

Power output of conversion technologies at time \( t \)

Input energy to storage at time \( t \)

\[ I_j(t) \leq I_{j}^{max}(t), \quad 0 \leq P_m(t) \leq P_{m}^{max}, \quad E_n(t) \leq E_{n}^{max} \]

Conversion & storage technology capacities
Variable capacities

\[ L_k(t) = \Theta_{k,m} \times P_m(t) + A_n^{dis} Q_n^{dis}(t) - Q_n^{ch}(t) \]

\[ E_n(t+1) = A_n^{*} E_n(t) + A_n^{ch} Q_n^{ch}(t) - Q_n^{dis}(t) \]

Power output of conversion technologies at time \( t \)
Input energy to storage at time \( t \)

\[ I_j(t) \leq I_j^{\text{max}}(t), \ 0 \leq P_m(t) \leq P_m^{\text{max}}, \ E_n(t) \leq E_n^{\text{max}} \]

Conversion & storage technology capacities
Energy hub model – full formulation

MINIMISE

Investment and Operation Cost =
Fuel purchase costs
+ Electricity purchase costs
+ Operational and maintenance costs
+ Technology capital and installation costs
+ Technology retirement costs
+ Distribution network costs
– Electricity sell back revenue
– Energy subsidy revenue

SUBJECT TO

Technology Availability
Technologies can only be used if they are in the set of purchased technologies

Operational Constraints
All technologies must operate within their installed capacity limits

Energy balance
Electricity purchased plus energy generated must equal energy demand in each time period

Energy Distribution
Energy distribution from generation sites is bounded by the total amount of energy generated by all technologies at that site

Distribution Network Structure
Energy distribution is to buildings that are connected by the distribution network

Stakeholder Preferences
Specific technologies can be precluded or permitted for the optimal energy system depending on stakeholder preferences

Environmental Targets
Annual CO₂ emissions must be less than or equal target values

\[
\begin{align*}
\text{min} & \quad C_{fuel} + C_{elec} + C_{om} + C_{capital} + C_{network} - C_{sell} - C_{subs} \\
C_{fuel} &= \sum_{p} \sum_{r} \sum_{h} \sum_{n} \sum_{i} \sum_{u} N_{h} \cdot N_{r} \cdot \frac{Price_{r} \cdot G_{p,h,n,i,u}}{n_{i}} \\
C_{elec} &= \sum_{n} \sum_{h} \sum_{s} \sum_{p} N_{h} \cdot N_{s} \cdot EPrice_{p,h} \cdot EP_{p,s,n} \\
C_{om} &= \frac{\left( O_{f} \cdot \text{Max}_{i} \cdot U_{n,i,h} + \sum_{s} \sum_{p} N_{h} \cdot N_{s} \cdot O_{f}^{i} \cdot G_{p,s,n,i,u} \right)}{Ann_{i}} \\
C_{capital} &= \sum_{n} \sum_{i} \sum_{h} N_{h} \cdot \text{Max}_{i} \cdot U_{n,i,h} \cdot CapC_{i} \cdot Ann_{i} \\
C_{network} &= \sum_{n} \sum_{s} \sum_{p} \sum_{h} N_{h} \cdot \text{Dist}_{n,s} \cdot L_{n,s} \cdot PCost_{a} \cdot AnP_{a} \\
C_{sell} &= \sum_{n} \sum_{s} \sum_{p} \sum_{h} N_{h} \cdot N_{s} \cdot ESell_{s} \cdot ES_{p,s,n,h} \\
C_{subs} &= \sum_{p} \sum_{s} \sum_{h} \sum_{n} \sum_{i} \sum_{u} N_{h} \cdot N_{s} \cdot Subsidy_{i,u} \cdot G_{p,s,n,i,u}
\end{align*}
\]
Energy hub model implementation

Ax = b
Cx ≤ d
lb ≤ x ≤ ub

Explore network structures & technology options

Energy demands of buildings
Technology options and performance characteristics
Energy availability from renewables
Optimal operation schedules & technology capacities
Energy use & carbon emissions
Example results

Comparison of different optimal system design options

cost vs. sustainability performance
So what can we model with this approach?

**Optimize operational variables**
- Conversions between different forms of energy
- Storage dispatching (short-term and seasonal)
- Grid interaction (peak shaving, grid services)

**Optimize technology selection and technology capacities**
- Storage and conversion selection and sizing (size of zero = not selected)
- Initial and capacity-based costs
- Energy prices & carbon factors

**Represent single system bridging demand and supply**
- Local generation (considering renewables availability)
- Time-varying loads & supply

**Represent and optimize networks**
- Links between hubs = extra continuity equations
- Optimise the network configuration: presence of network link is a binary variable
Computational optimization
Simulation versus Optimization

**Simulation**

*Descriptive* and aim to emulate actual energy system performance, and aid understanding.

Can be developed in software programs like TRNSYS, EnergyPlus, etc. – used to simulate various types of energy systems in conjunction with energy demand modelling.

**Optimization**

*Prescriptive* and aim to provide outputs that indicate how to maximize system performance, thereby aiding decision making.

Can reveal relationships, solutions, and pathways that were not obvious or initially considered.
Optimization Methods

- Integer Programming (IP)
- Mixed Integer Linear Programming (MILP)
- Mixed Integer Non-Linear Programming (MINLP)
- Linear Programming (LP)
- Non-Linear Programming (NLP)

Tractability, scalability, and speed of optimization

LP
MILP
MINLP

Fidelity of system models
Why do we need discrete variables in an energy hub model?

To denote the installation/operation of technologies
To denote the presence/absence of network links

So MILP instead of LP
## Optimization algorithms

<table>
<thead>
<tr>
<th>Optimisation Method</th>
<th>Strengths</th>
<th>Limitations</th>
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<tr>
<td>LP (Simplex)</td>
<td>Scalability</td>
<td>No discrete variables</td>
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<td></td>
<td>Global optima</td>
<td>Linearisation</td>
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<td>Deterministic</td>
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<td>MILP (Branch and Cut)</td>
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<td>Linearisation</td>
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<td>Discrete variables</td>
<td>Deterministic</td>
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<td></td>
<td>Scalability (to a degree)</td>
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<tr>
<td>MINLP (Direct Search)</td>
<td>Discrete variables</td>
<td>Local optima</td>
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<td>MINLP (Heuristics)</td>
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<td>Optima not guaranteed</td>
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<td>Probabilistic</td>
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LP and MILP solution algorithms

- Simplex Algorithm

- Branch and Bound = Simplex + Branching and Bounding

- Branch and Cut = Branch and Bound + Cutting Planes
Solving LPs – Simplex method

Optimal solution must be at a vertex (extreme point)

Therefore:
- Iterate through all the vertices
- Identify the one corresponding to the optimal value
Solving MILPs – Discrete variables

Inequality Constraint Boundary

Extreme Point

Feasible Integer Solution
Solving MILPs – Branch and bound algorithm

1. Bound the solution space with a LP relaxation of the problem -> simplex method
2. Branch into 2 sub-problems, with each sub-problem taking a different integer value
1. The LP relaxation is solved at the root of the search tree using the simplex method to create a lower bound for the MILP solution.

2. The problem is then partitioned into two sub-problems, with each sub-problem taking a different consecutive integer value for the branched decision variable.

3. The branched problem is analysed again using the simplex method. There are a number of possible outcomes for each sub-problem that is analysed:
   - If a sub-problem has no solution, it is discarded, i.e. fathomed.
   - If a sub-problem has an integer solution that is worse than the current incumbent solution, i.e. best solution, it is also fathomed.
   - If sub-problem has an integer solution that is better than the incumbent, the solution becomes the new incumbent.
   - If no integer solution is found, the sub-problem is branched again and these new sub-problems are added to the list of candidate sub-problems that must be processed.

4. The algorithm continues selecting and processing sub-problems until the list of candidate sub-problems is empty.

5. At the end of this analysis the current incumbent is the optimal solution, and if there is no incumbent then there is no solution.
Solving MILPs – Branch and cut

Branch and bound algorithm with **cutting planes** to tighten the LP relaxations. Cutting planes are **implied constraints** = logical outcome of other constraints.
The limitations of energy hub modelling with MILP

- Mixed-integer linear programming (MILP) approach requires maintaining linearity of constraints
  - **Linear technology models**

- MILP model size and solving time **scales exponentially** with the number of discrete variables

- Critical to develop models that limit the number of discrete variables by minimising
  - Time intervals
  - Distinct consumption/generation nodes

Models that effectively balance **accuracy** of representation with **simplicity** of formulation
Time discretization

• What time period are we interested in optimizing?
• Into how many discrete time periods do we divide the overall time period?
• Every minute, hour, day, week?
• Every day in the year, or just “representative” days?
• How do we choose days which are sufficiently representative?

- Balancing accuracy & solvability
- Different answers for different problems
Spatial aggregation/clustering

Instead of representing each building individually, we aggregate buildings into clusters.

How to define clusters?
- Distance based
- K-means or K-medoids method
- Distance and demand based
- Locate an anchor load (i.e. Hospital)
- Set a large analysis radius, one limited by heat loss and physical boundary limitations
- Analyse the diurnal energy demands of the buildings within that radius
Implementation
Optimization software

- IBM ILOG
- Aimms
- Yalmip (Matlab)
- Pyomo (Python)
- GAMS
- ...
% Define variables
x = sdpvar(2,1);
% Define constraints and objective
Constraints = [sum(x) <= 1, x(1)==0, x(2) >= 0.5];
Objective = x'*x + norm(x);
% Set some options for YALMIP and solver
options = sdpsettings('verbose',1,'solver','cplex','cplex.qpmethod',1);
% Solve the problem
sol = optimize(Constraints,Objective,options);
% Extract and display value
solution = value(x)

Yalmip Toolbox in MATLAB
A modelling language for advanced modelling and solution of convex and nonconvex optimization problems, available as a free toolbox for MATLAB.
% Capacity parameter
hp_cap = 10;

% Input and output variables
hp_in = sdpvar(1,Horizon);
hp_out = sdpvar(1,Horizon);

% Energy conversion constraints
hp_con = [hp_out == hp_in*hp_eff, hp_in >= 0, hp_out >= 0, hp_out <= hp_cap];

%% Balance equations
heat_con = hp_out + boiler_out == heat_load(1:Horizon);
elec_con = grid_elec - hp_in == elec_load(1:Horizon);

%% Collect all constraints
constraints = [hp_con, pv_con, storage_con, heat_con, elec_con];

%% Objective function: 20 years of energy costs
objective = 20*sum(gas_price*gas + elec_price*elec);

%% Start the optimization
% define MATLAB LP solver
ops=sdpsettings('solver','linprog');
% optimize the design
optimize(constraints,objective,ops);
What is it?

Tool for preliminary design optimization of multi-energy systems for districts and communities.

How is it novel?

1. Significantly reduces the effort and time required for implementing advanced analyses.

2. Enables integration of energy hub modeling innovations (e.g. uncertainty analysis, network optimization, etc.) into a common framework.

Freely accessible at:
https://github.com/hues-platform/python-ehub/tree/NextGen
Easy to use:
• Suitable for both “quick and dirty” modeling or more in-depth analyses
• Fast model setup through spreadsheet interface
• Intuitive and flexible navigation of results

Flexible:
• Energy systems can be defined to capture a wide range of scales and scopes (e.g., building level, neighborhoods, cities, cantons, etc.)
• A wide range of energy conversion, distribution and storage technologies can be defined by users

Easy to develop:
• Python-based, open-source code
• Transparent documentation and code
1. **Input data spreadsheet:** Defines the properties of the system you’d like to optimize, the range of technology options you’d like to consider, and the objective of your optimization

2. **Model generator:** Automatically generates the mathematical formulation of an energy hub model from the input data

3. **Optimization solver:** Identifies an optimal solution to the optimization problem defined in your energy hub model

4. **Visualization module:** Automatically generates visualizations of the results
Ehub Tool – Getting started

Download the latest version of the E-Hub Tool from GitHub: https://github.com/hues-platform/python-ehub/tree/NextGen

- Getting Started guide
- Optimization problem formulation documentation
- Input/output file templates
- Demonstration cases

Requirements:
- Python 3.6+
- Python libraries: pandas, numpy, Pyomo
- Solver (e.g., gurobi, glpk)
- Spreadsheet editor (e.g., Microsoft Excel, OpenOffice)
Conclusions

- Improving energy performance is a multi-scale problem and we cannot focus on buildings alone – also need to analyze at the neighborhood and city scale.
- Urban areas give rise to significant opportunities for system integration.
- Energy hub models are a powerful tool for assessing different system integration possibilities.
- Energy hub models are optimization models, and are often implemented as mixed-integer linear programmes (MILPs), solved using a branch-and-cut algorithm.
- MILPs require linearized technology representations and scale exponentially with the number of discrete/integer variables.
- This creates a necessity for smart approaches to balance accuracy and simplicity of system representation.