# Opportunities and Challenges in Design and Operation of Integrated Energy Systems

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# Introduction


***Johan Åkesson***
Associate Director, Computational Engineering
Carrier


**MSc Computer Science** (Lund university, Sweden)
**PhD Automatic Control** (Lund university, Sweden)

**20 years of global experience** (Lund university, Modelon, Carrier)

**Contributor to standards** (Modelica, FMI)

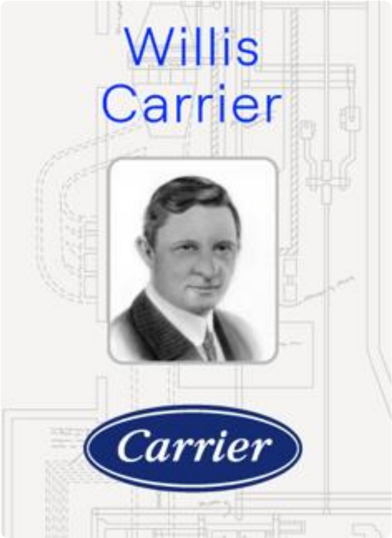
**100+ publications** (Optimization, Controls, Computational Software…)

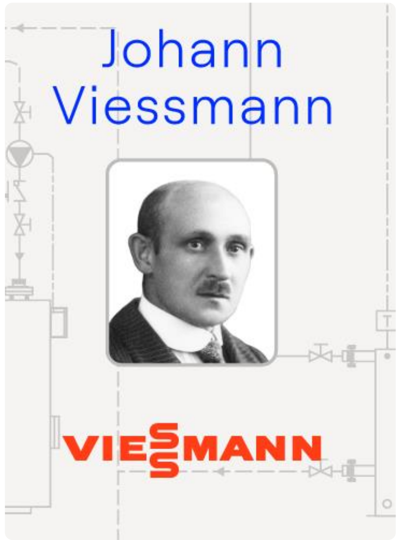
# Outline

- Introduction
- What are Integrated Energy Systems and Why Do They Matter?
- Real-World Examples – District heating system design and data center energy optimization
- Challenges
- Key Takeaways and Outlook

# This is Carrier

## The Inventors Behind Our Success




## 2024 Overview

**$22.5B**
2024 Net sales

**~160**
Countries

**35+**
Brands

**~48,000**
Employees

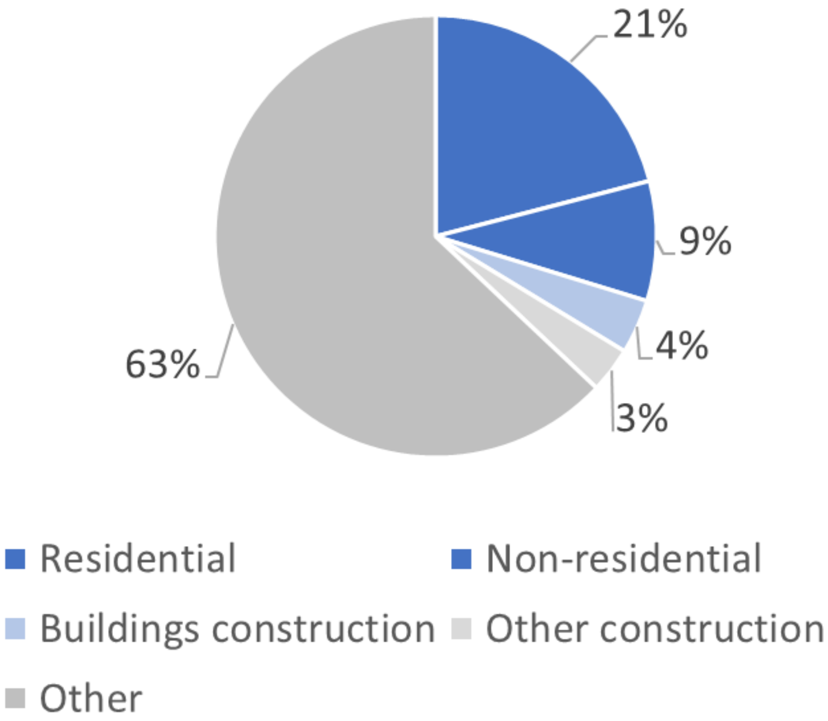
**80+**
New products in 2024

## Our Verticals

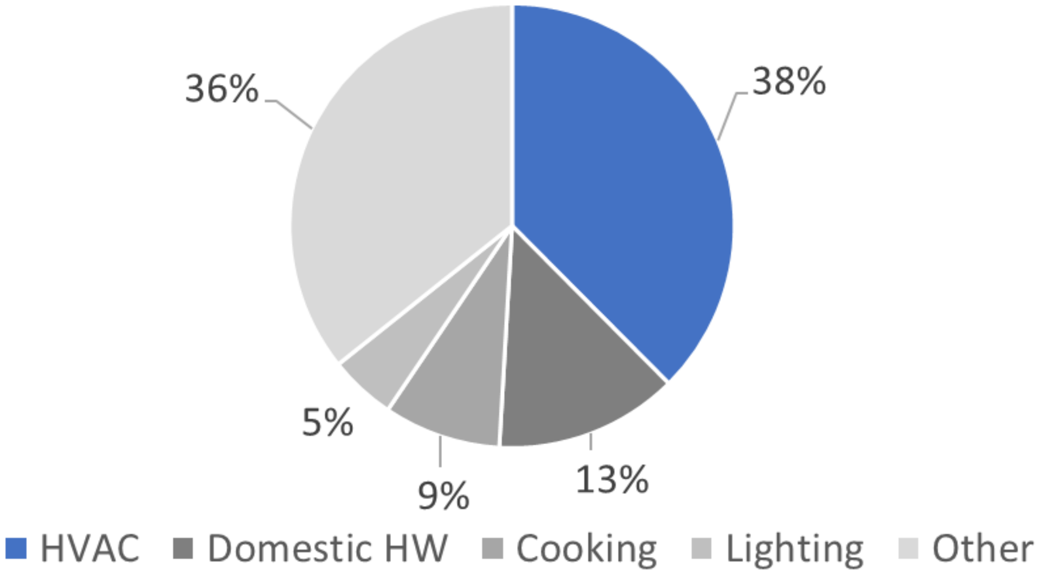
- Hospitality
- Industrial
- Life Sciences
- Residential
- Retail
- Commercial Real Estate
- Data Centers
- Education
- Food & Beverage
- Healthcare

# The Building Energy Challenge

## Buildings Final Global Energy Consumption 2022




## Buildings Energy Global Consumption 2020



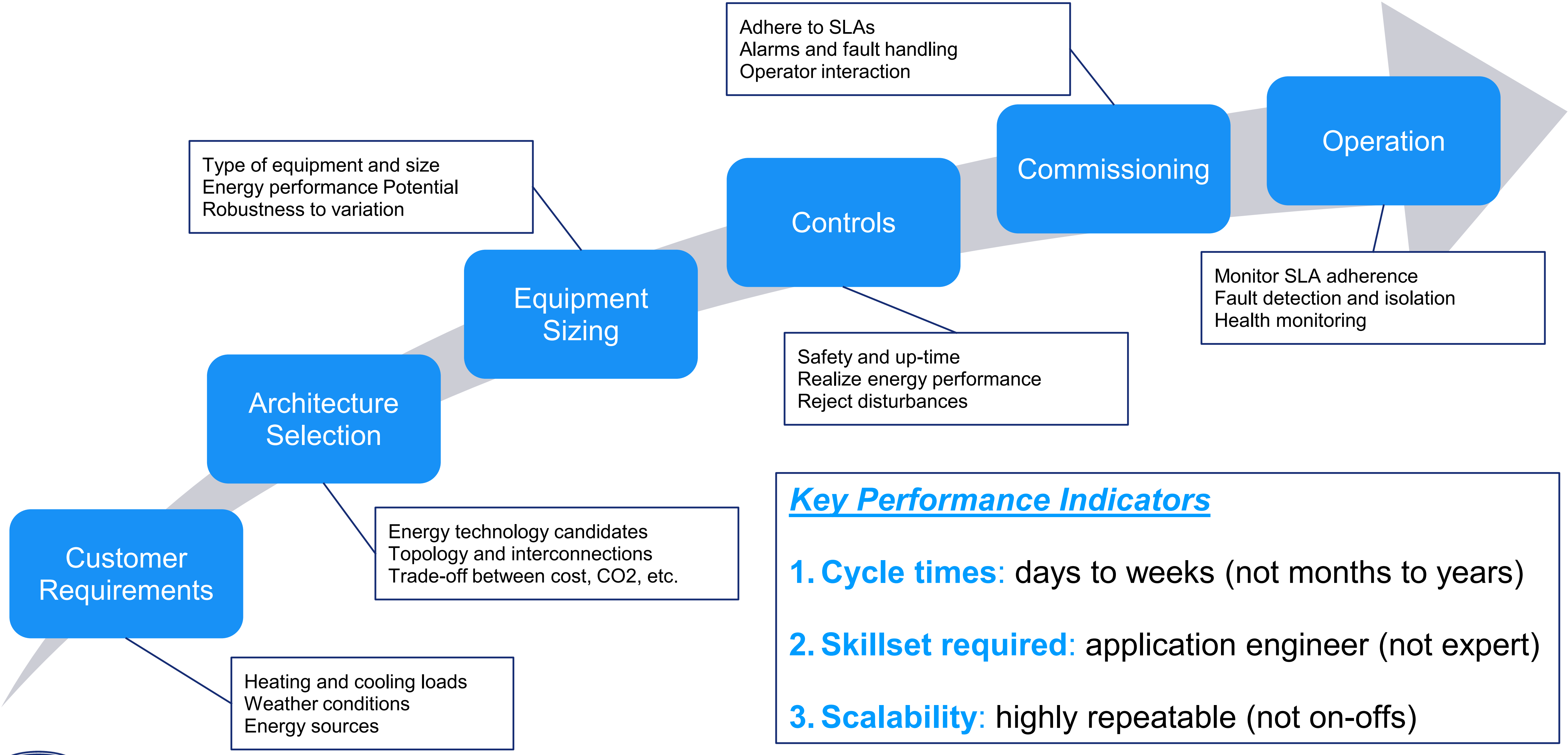

Building operation consume ***30% energy worldwide***

Heating, Ventilation and Air Conditioning consumes ***38% of building operation energy***

https://www.iea.org/energy-system/buildings

https://www.sciencedirect.com/science/article/pii/S235248472101427X

# Vision – Integrated Energy Systems at Scale




***Key Performance Indicators***

1. **Cycle times:** days to weeks (not months to years)
2. **Skillset required:** application engineer (not expert)
3. **Scalability:** highly repeatable (not on-offs)

# Key Points

- ***Modelica and FMI continue to bring significant value to Carrier*** in our product design – and has done so for 25 years!
  - Thank you!
- ***Design, control and operation of Integrated Energy Systems (IES) is fundamentally different*** from equipment (chillers)
  - Heterogeneity, scale, interconnections – and no labs
- ***Efficient IES exists*** – but they are often ***one-offs***, they take ***months to years*** to build even for ***skilled experts***
  - Need speed in creation and operation
- ***Systems engineering and platform-based design*** offers process to formally verify that standardized designs align with requirements
  - Tools and methodology exist but is not widely used in the energy sector
- ***Modeling, simulation and optimization is a (the) key enabler*** – actions required to mitigate challenges for IES – work ahead
  - Heterogeneity of computations, scale to very large systems, uncertainty management

# Integrated Energy Systems

What they are and why they matter

# Integrated Energy Systems – Definition

*Integrated Energy Systems (IES) are the **physical and digital integration** of **energy sources** (e.g., nuclear, fossil, wind, solar, hydropower and geothermal-based), **energy users** (e.g., grid consumers and industrial users), and **energy storage** (e.g., thermal and electrical) to increase the thermodynamic efficiency and use of the system. The goal of IES' is to **create efficient, affordable, and reliable energy generation and delivery technologies**.*

***Themes***

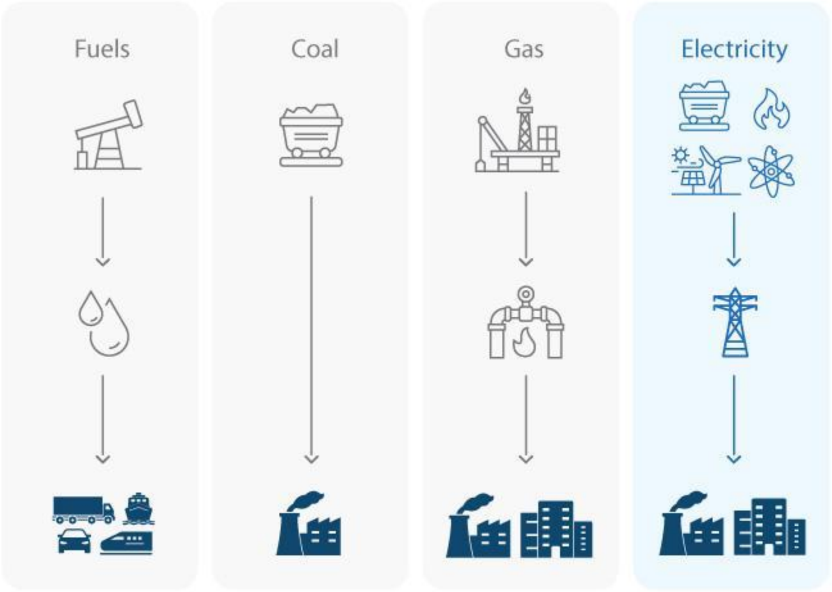
- **Integration** of diverse energy sources and sectors
- **Optimization** of energy flows and thermodynamic efficiency
- **Flexibility** to adapt to variable renewable energy
- Support for decarbonization and **sustainability goals**

***Benefits***

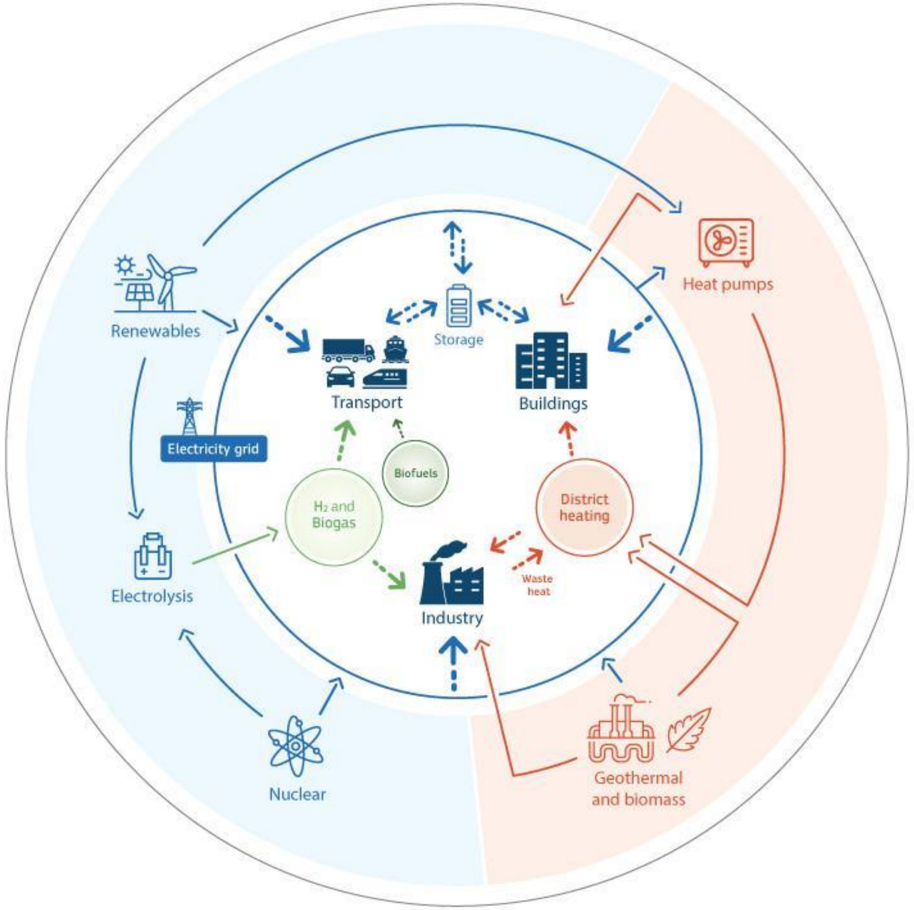
- Environmental: Decarbonization and waste heat recovery
- Technical: System efficiency and flexibility, grid resilience
- Economic: Cost savings and optimization
- Social and Community: Energy access, job creation, innovation

# What are Integrated Energy Systems?

## Siloed



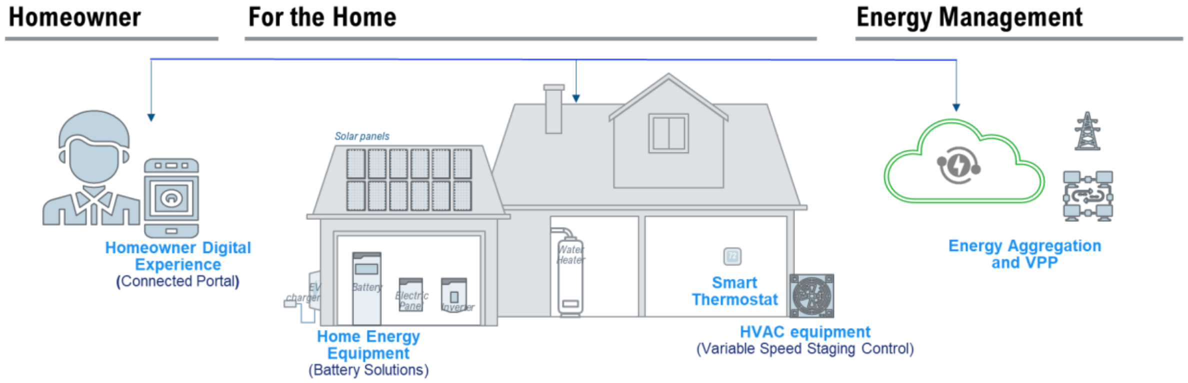

## Interconnected



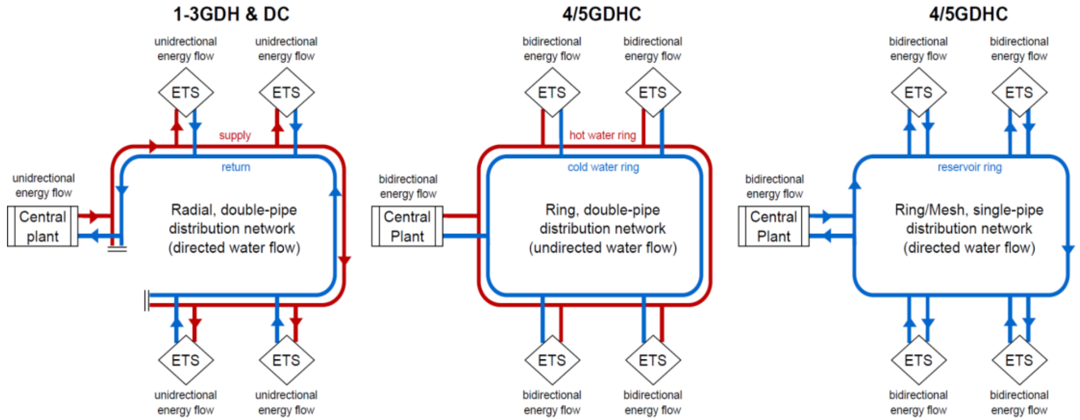

European Commission https://energy.ec.europa.eu/topics/eus-energy-system/energy-system-integration_en

# Integrated Energy Systems Examples

## Home energy management systems



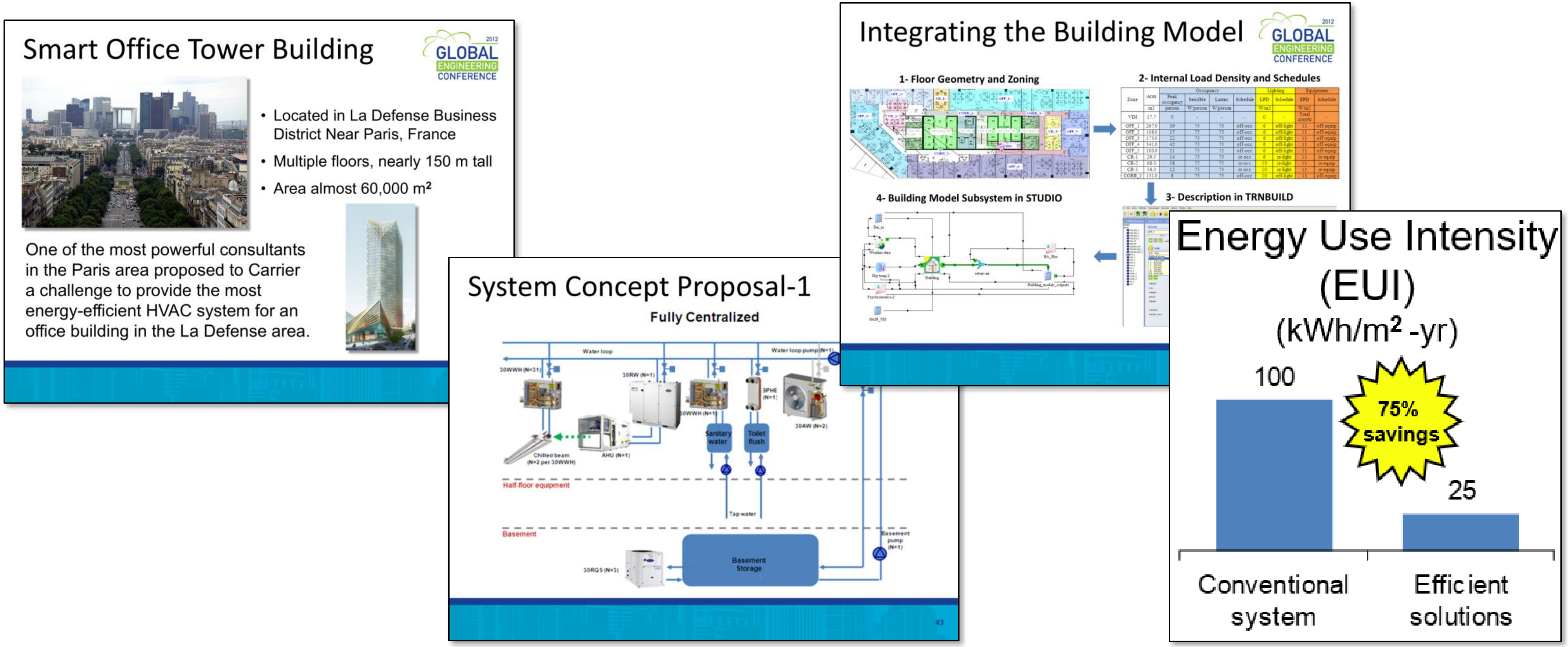

## District heating and cooling systems





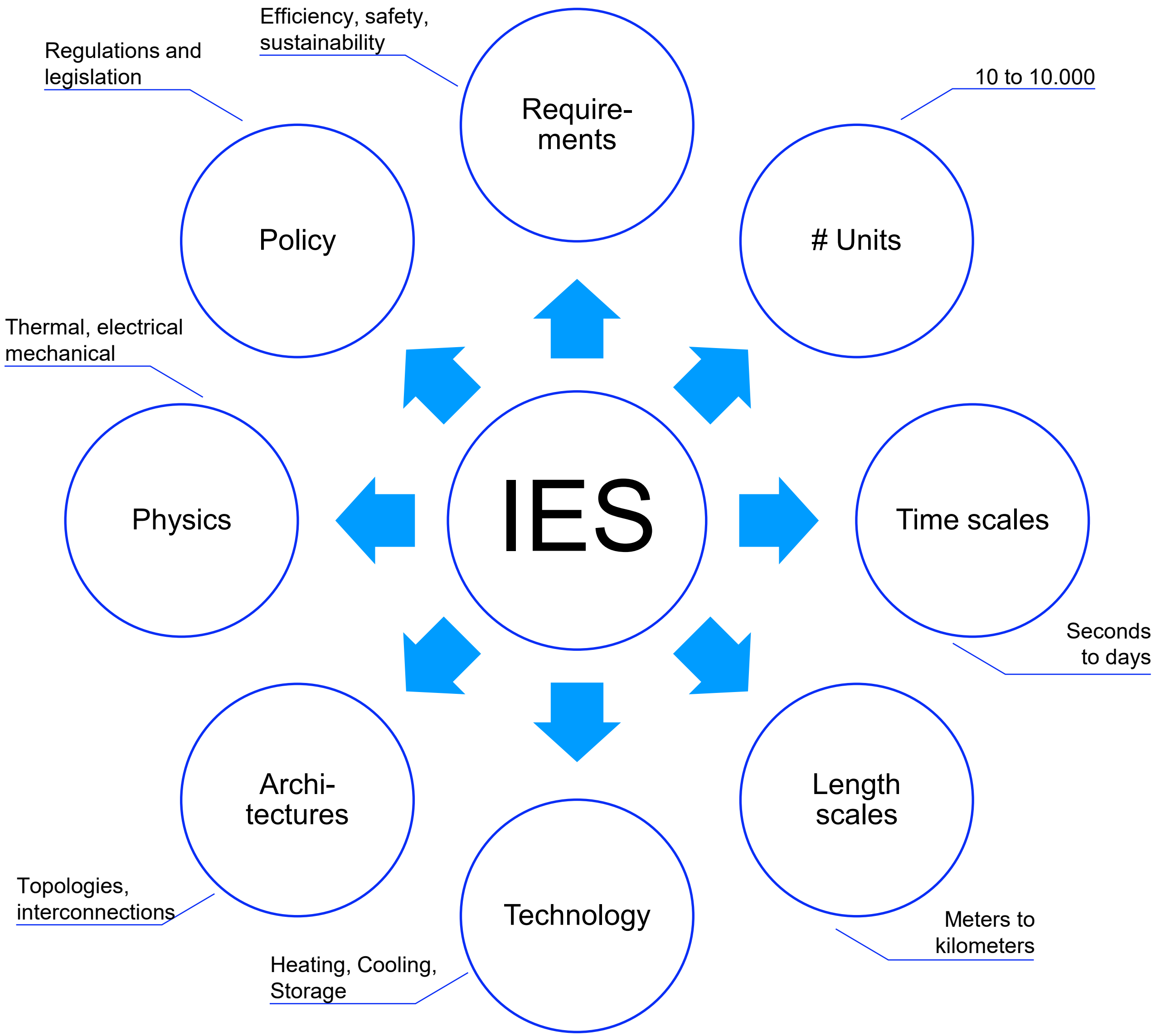

## Data center cooling systems

# Energy Efficient Building Systems Exists

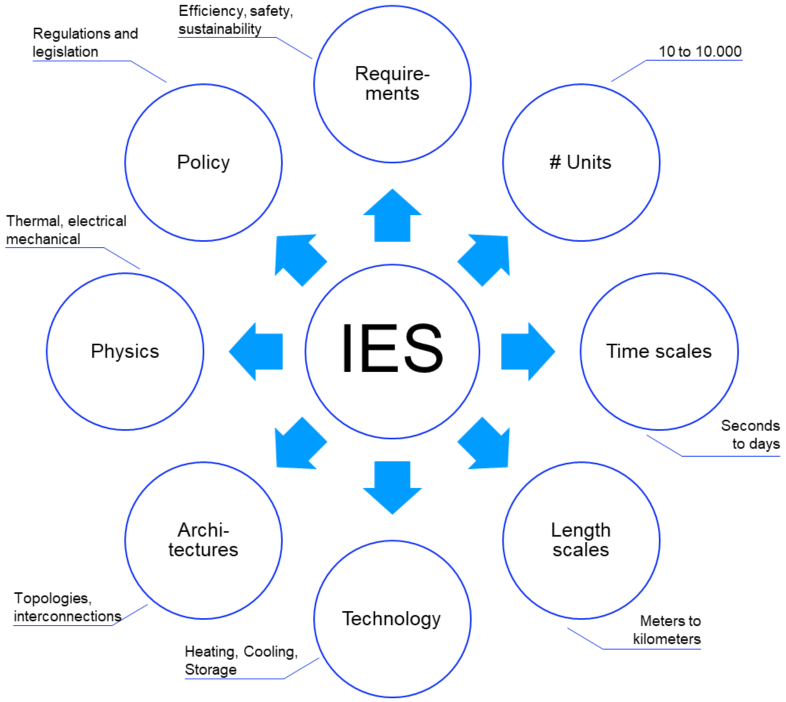



Energy efficient building systems exists – ***cycle times are often quarters to years and require highly skilled experts***

# Why is Design, Control, and Operation of IES Hard?



# What is Needed for Design, Control, and Operation of IES?




***Key Performance Indicators***

1. **Cycle times:** days to weeks (not months to years)
2. **Skillset required:** application engineers (not experts)
3. **Scalability:** highly repeatable (not on-offs)

***Domain knowledge*** – Thermal systems

***Systems Engineering*** – Manage complexity

***Physical Models*** – Predict behavior

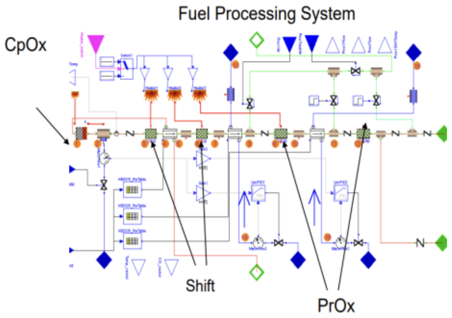
***Optimization*** – Trade-off requirements

# Carrier’s Modelica Journey

Interlude

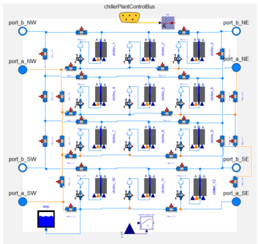
# Carrier's / UTC's Modelica Journey

First Modelica project – fuel cells



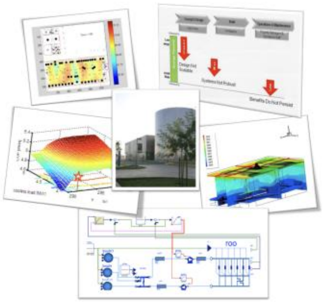

Aerospace – air management systems design

Data-center thermal cooling system safety and energy optimization

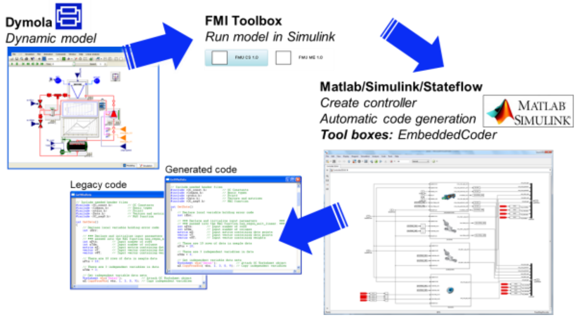


1999-2003 | 2005-2011 | 2010- | 2013-2015 | 2017-2020 | 2023-

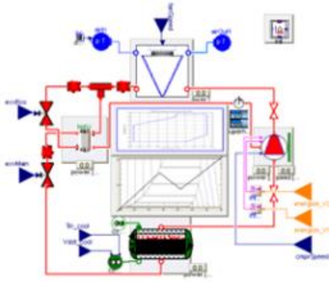
Building system simulation



Model-based control design and verification




HVAC refrigerant cycle chiller and heat pump design



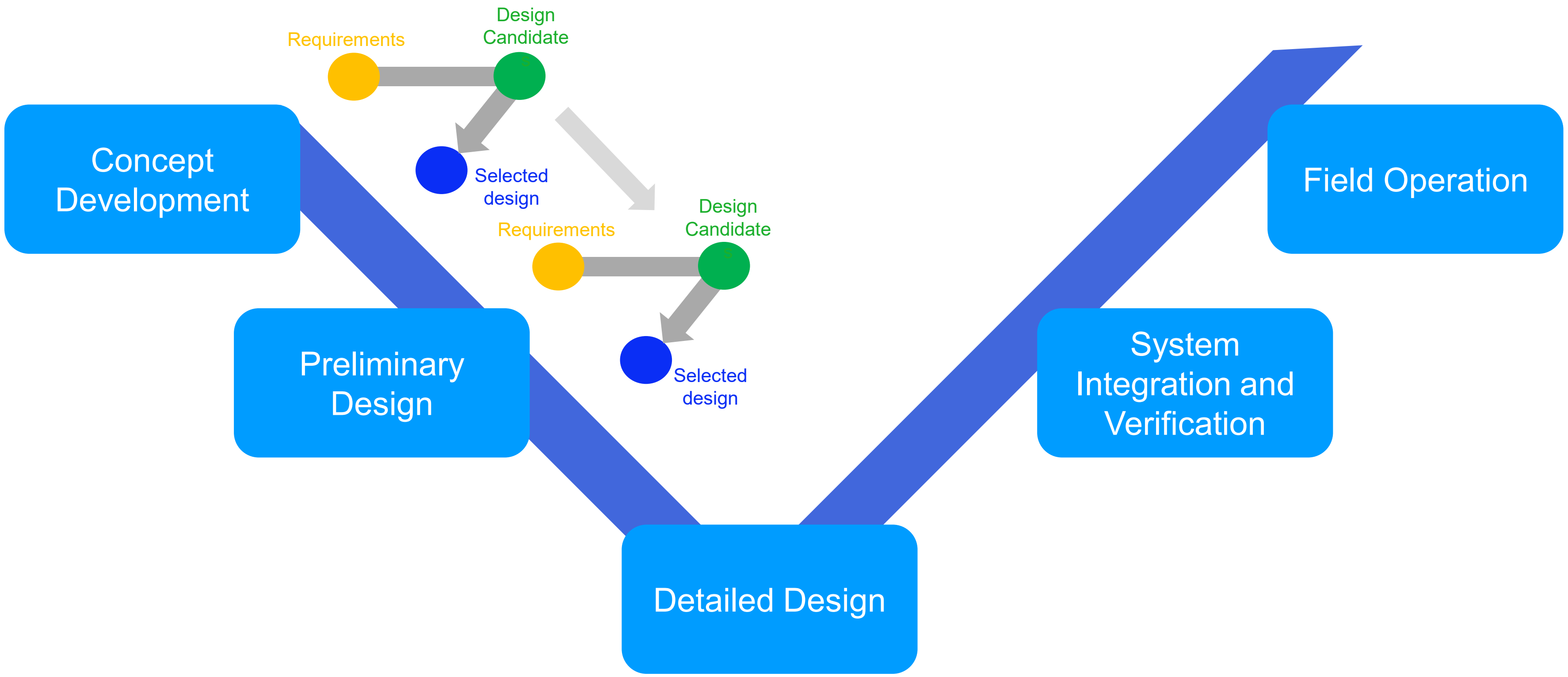
- Dynamic
- Steady-state
- Simulation
- Optimization
- Control design
- Robust design
- Verification

# Systems Engineering

Across the Product Life Cycle

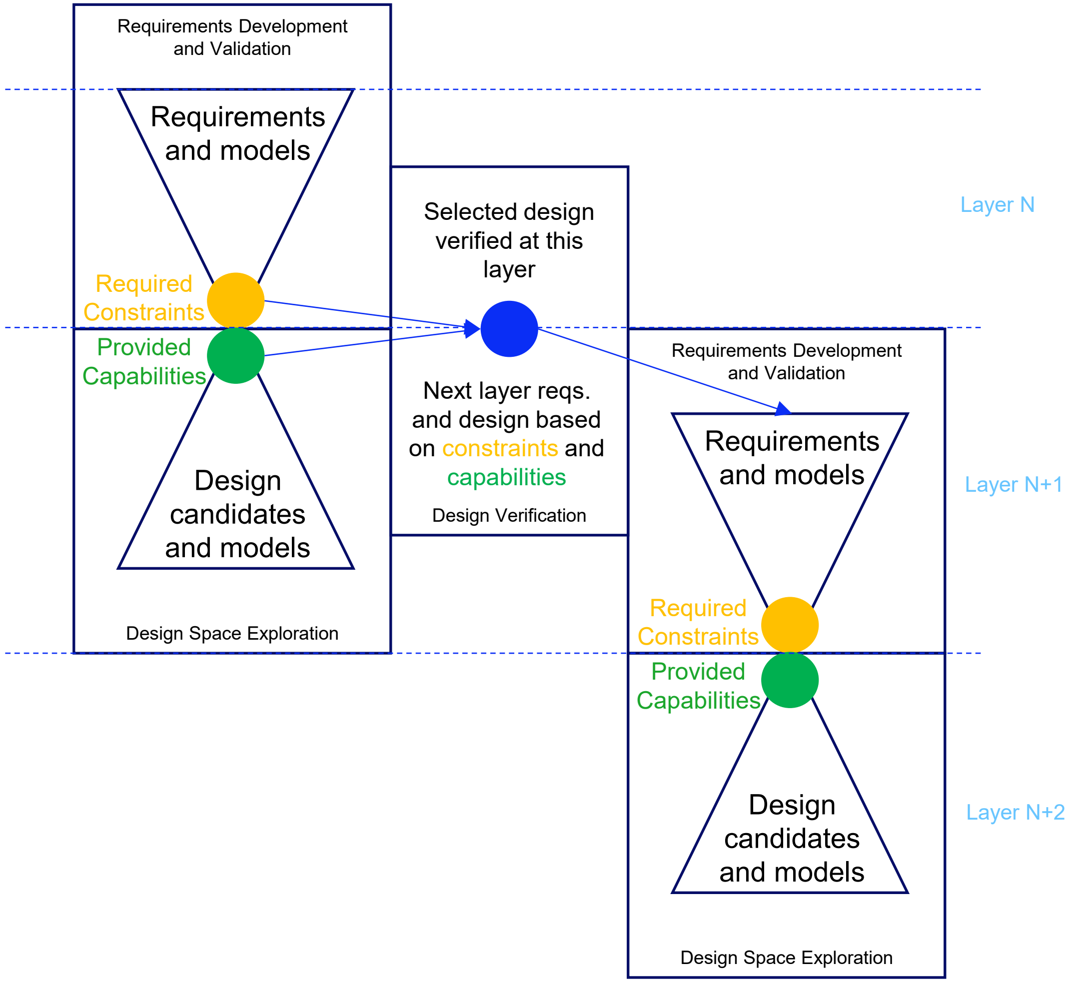
# What is Systems Engineering?

***Systems engineering*** is the integrated product view and overall management of what will be delivered including components, communications and controls along with the coordinated product design including requirements elicitation and analysis, product development methodologies and allocation of requirements to subsystems and the validation, verification and certification.

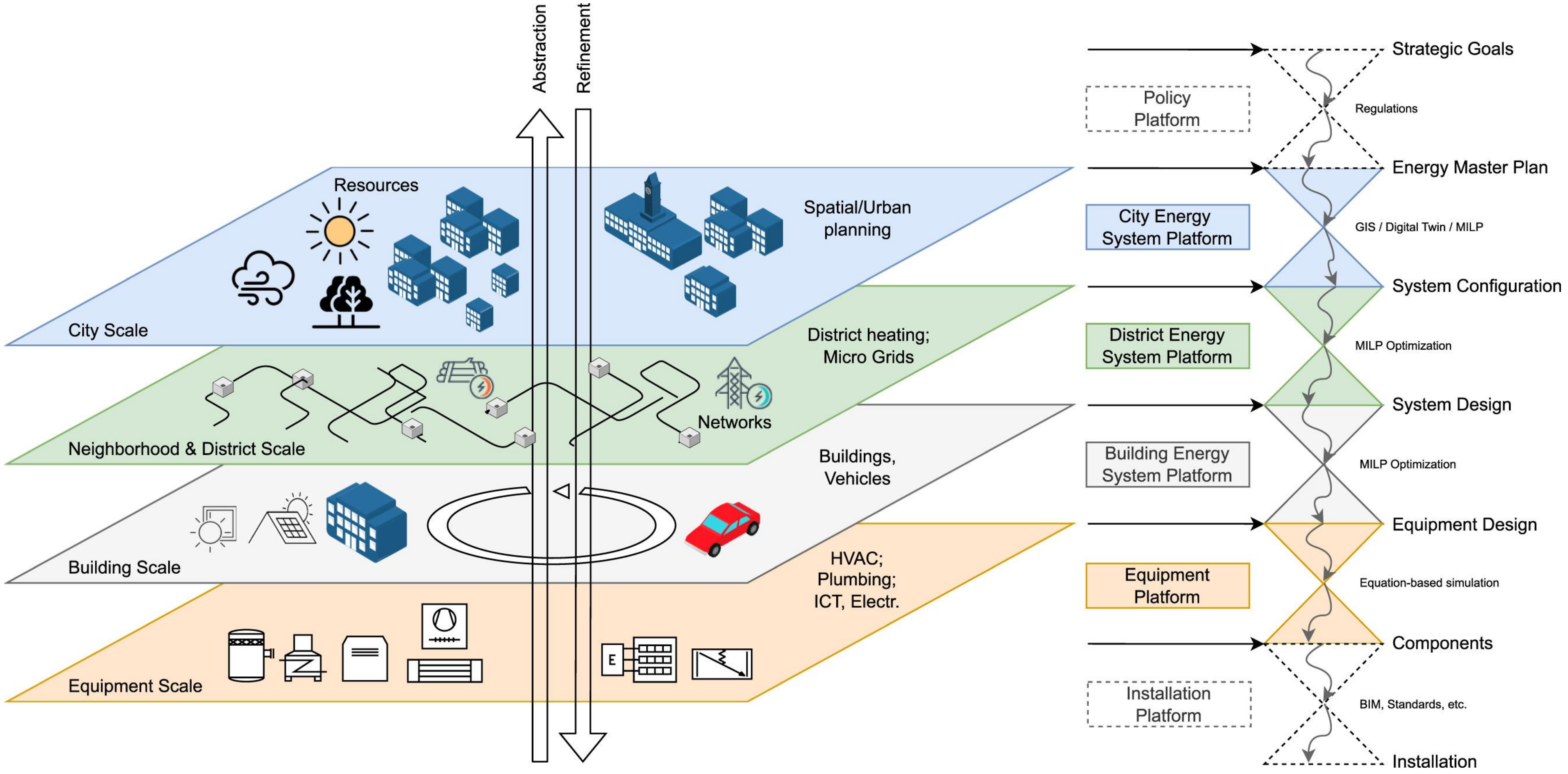


# Platform-based Design – Principles

- Starting at the highest level of abstraction
- Carrying out the design as a sequence of refinement steps
- At each layer specify requirements (“desired behaviors”) and architectures (“delivered behaviors”) and verify that these are satisfied
- Use of models to verify the designs (incremental V&V) at each layer – preventing “large loop” oscillations in the “V” model

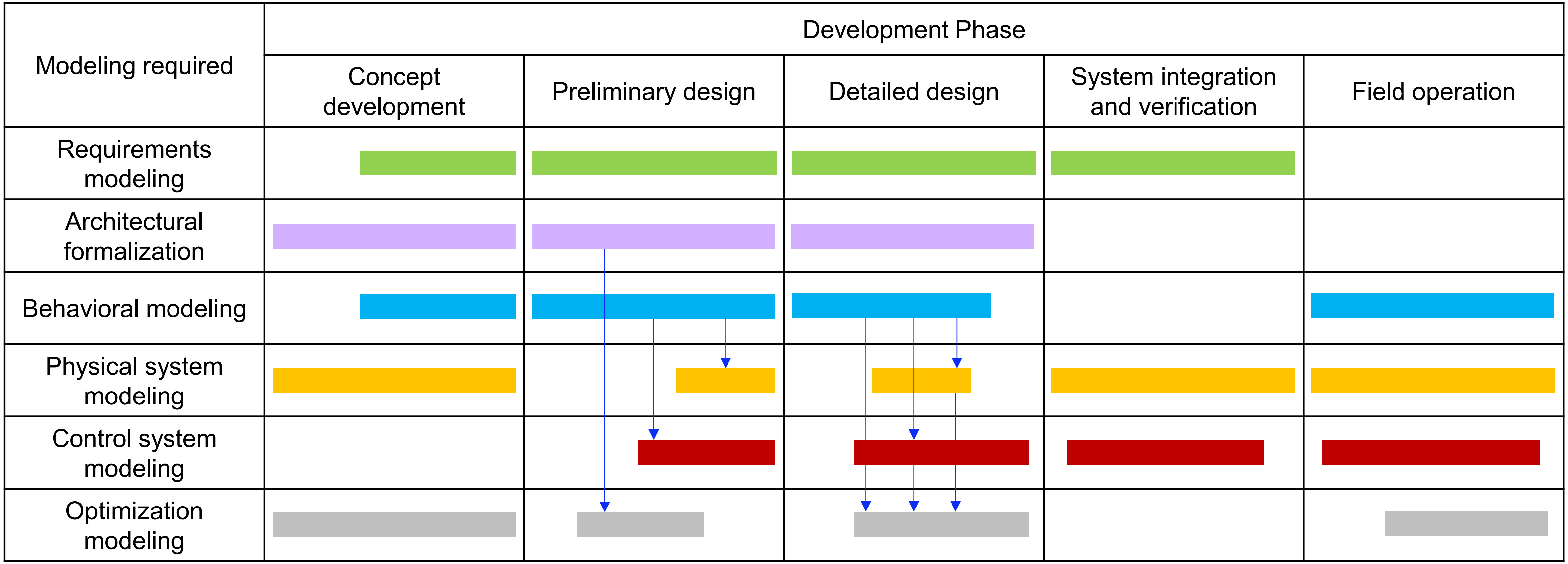


# Abstraction and Hiding Complexity – Layered Design




Matthias Sulzer, Michael Wetter, Robin Mutschler and Alberto Sangiovanni-Vincentelli. Platform-based design for energy systems. Applied Energy, 352, 2023.

# Modeling for X through the V model




- Use of models at each level to help make design decisions
- Not one model – the type and fidelity changes at each layer of design
- Different tools/languages – SysML, Modelica, FMI, Python/Pyomo, Simulink, MILP/NLPs

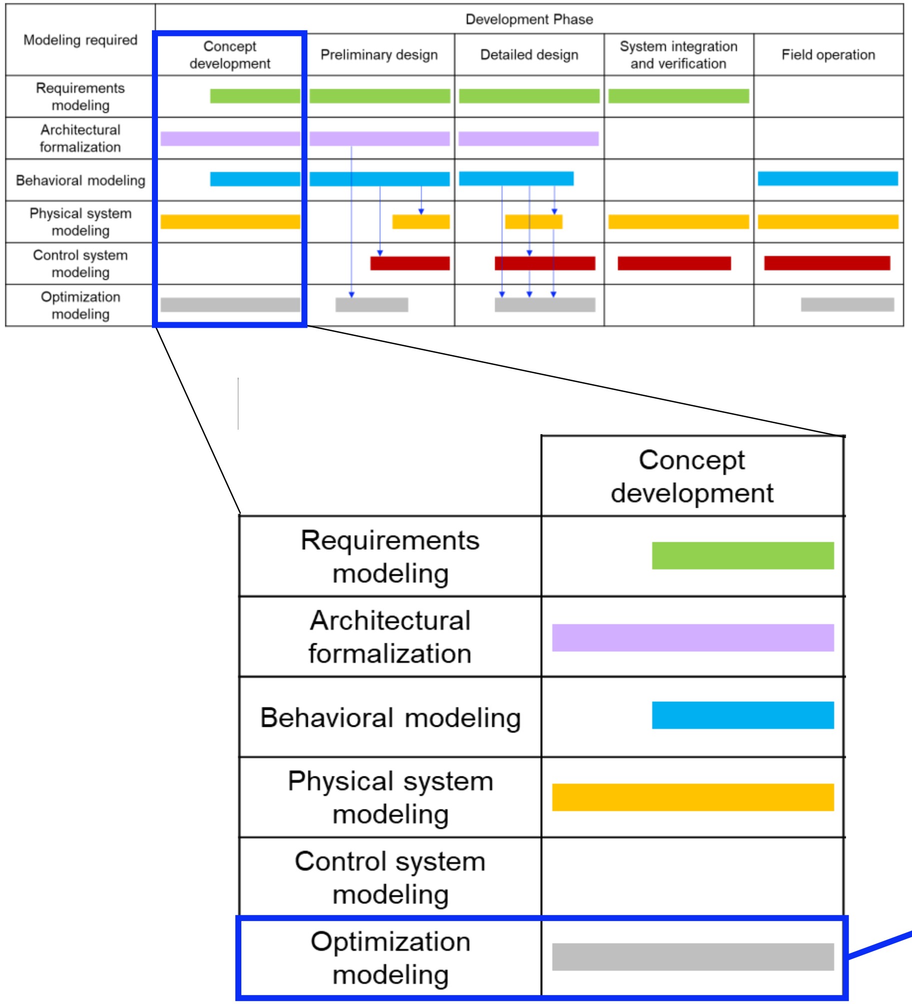
# Design Space Exploration – Problems Classes in Optimization

| Constraints | Variables | | |
|---|---|---|---|
| | $R^n$ | $R^n, \{0,1\}^n$ | Stochastic variables |
| Linear algebraic<br>$Ax = b$ | **Linear Programming (LP)**<br>Production planning, Financial portfolio optimization. | **Mixed-Integer Linear Programming (MILP)**<br>Assignment problems, Unit committment. | **Stochastic Programming**<br>Optimization under uncertainty. |
| Non-linear algebraic<br>$f(x) = 0$ | **Non-linear Programming (NLP)**<br>Min/max capcity problem, Set-point optimization. | **Mixed Integer Non-linear Programming (MINLP)**<br>Staging of equipment, Assignment. | … |
| Linear differential equation<br>$\dot{x} = Ax + Bu$ | **Linear Dynamic Optimization**<br>Linear Quadratic Regulation (LQR), Model Predictive Control (MPC). | **Mixed-Integer Linear Dynamic Optimization**<br>Optimal contol of switched systems, e.g., Mixed Logical Dynamic (MLD) | … |
| Non-linear differential equation<br>$\dot{x} = f(x, u)$ | **Non-linear Dynamic Optimization**<br>Non-linear Model Predictive Control (NMPC) | **Mixed Integer Non-linear Dynamic Optimization**<br>Optimal control with non-linear dynamics and discrete decisions, e.g., equipment on/off | … |
| Partial differential equations<br>$w_t = \alpha w_{xx}$<br>$w(t, 0) = 0$ and $w_x(t, L) = u(t)$ | … | … | … |

# District Heating and Cooling

Case Study

# Concept Development – Mixed Integer Programming




PYOMO

CPLEX

**Mixed-Integer Linear Programming (MILP)**
Assignment problems, Unit committment.

**Mixed Integer Non-linear Programming (MINLP)**
Staging of equipment, Assignment.

| Constraints | Variables | | |
|---|---|---|---|
| | $R^n$ | $R^n, \{0,1\}^n$ | Stochastic variables |
| Linear algebraic $Ax = b$ | **Linear Programming (LP)** Production planning, Financial portfolio optimization. | **Mixed-Integer Linear Programming (MILP)** Assignment problems, Unit committment. | **Stochastic Programming** Optimization under uncertainty. |
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| Partial differential equations $w_t = \alpha w_{xx}$ $w(t,0) = 0$ and $w_x(t,L) = u(t)$ | … | … | … |

# District Heating and Cooling Study – Greenville

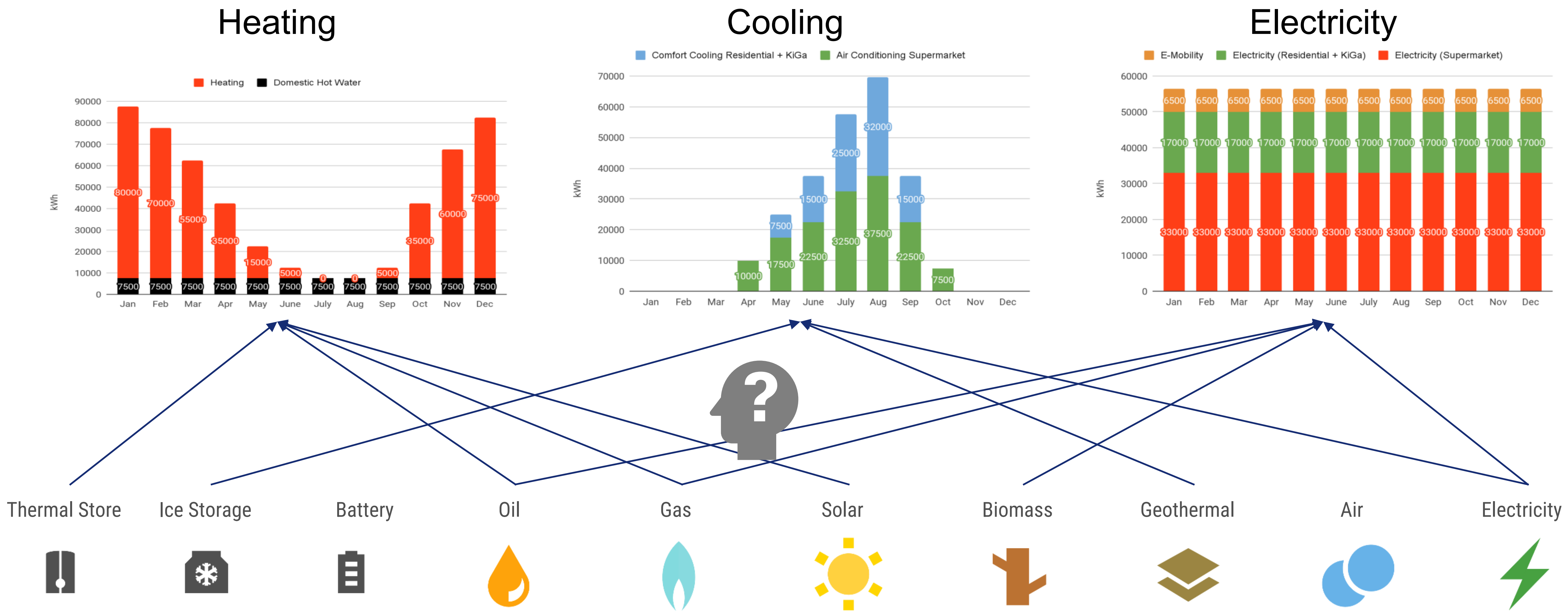
| Energy | Price |
| --- | --- |
| Electrical energy | 0.35 € / kWh |
| PV feed-in | 0.05 € / kWh |
| Gas | 0.20 € / kWh |
| Biomass / wood | 0.20 € / kWh |

| Energy | $CO_2$ emissions |
| --- | --- |
| Electrical energy | 370 $g_{CO2}$ / kWh |
| Gas | 220 $g_{CO2}$ / kWh |
| Biomass / wood | 30 $g_{CO2}$ / kWh |
| PV | 50 $g_{CO2}$ / kWh |
| Solar Thermal | 5 $g_{CO2}$ / kWh |


OBJECTIVE: guarantee a **reliable/stable**, **sustainable** and **affordable** energy supply.

# Requirements - Loads

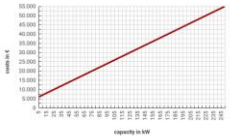
## HOW TO MEET ENERGY DEMAND ?



# Equipment Alternatives

## Boiler / CHP

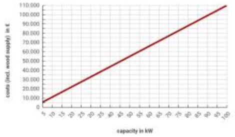
### Vitodens / Vitocrossal




| Gas boiler | |
|---|---|
| Thermal | 90% |
| Costs | 5.000 € + 200 €/kW |

*All given numbers are not specific to Viessmann products

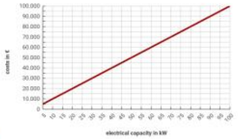
### Vitoligno




| Biomass boiler | |
|---|---|
| Thermal | 80% |
| Costs | 600 €/kW |
| Wood supply (wood chips, pellets) | 500 €/kW |

*All given numbers are not specific to Viessmann products

### Vitobloc

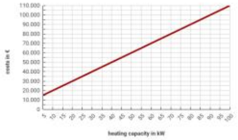



| Cogen (gas) | |
|---|---|
| Thermal | 55% |
| Electric | 40% |
| CHP Costs | 1.000 €/kWel |

*All given numbers are not specific to Viessmann products

## Heat-pump

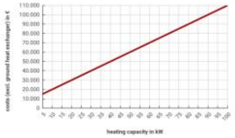
### Vitocal -A




| Air Source Heat Pump | |
|---|---|
| Costs | 10.000 € + 1.000 €/kW |
| SPF @ 65 °C<br>SPF @ 35 °C | 2,5<br>3,5 |

*All given numbers are not specific to Viessmann products

### Vitocal -G

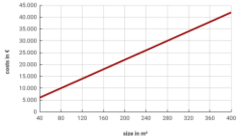



| Ground Source Heat Pump | |
|---|---|
| Costs | 10.000 € + 1.000 €/kW |
| Ground source heat exchanger | 1.000 €/kW heat |
| SPF @ 65 °C<br>SPF @ 35 °C | 3,0<br>4,5 |

*All given numbers are not specific to Viessmann products

## Solar

### Solar Air-Brine Collector



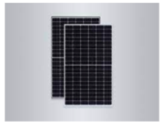

| ST (Solar Thermal) | |
|---|---|
| Yield @ambient temperature | 800 kWh/m² |
| Costs | 2.000 € + 100 €/m² |

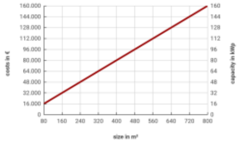
monthly yield in kWh per 40 m²

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1000 | 2000 | 3000 | 3000 | 4000 | 4000 | 4000 | 4000 | 3000 | 2000 | 1000 | 1000 |

*All given numbers are not specific to Viessmann products

### Vitovolt





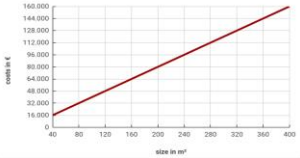

| PV (Photovoltaics) | |
|---|---|
| Yield | 200 kWh/m² (= 1.000 kWh/kWp) |
| Costs | 200 €/m² (= 1.000 €/kWp) |

monthly yield in kWh per 80 m²

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 500 | 1000 | 1500 | 1500 | 2000 | 2000 | 2000 | 2000 | 1500 | 1000 | 500 | 500 |

*All given numbers are not specific to Viessmann products

### Vitosol




| ST (Solar Thermal) | |
|---|---|
| Yield @75 °C (district heating) | 400 kWh/m² |
| Yield @50 °C (decentral) | 500 kWh/m² |
| Yield @25 °C | 600 kWh/m² |
| Costs | 400 €/m² |

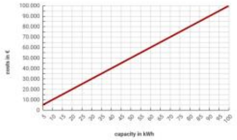
monthly yield in kWh per 40 m²

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 75 °C | 500 | 1000 | 1500 | 1500 | 2000 | 2000 | 2000 | 2000 | 1500 | 1000 | 500 | 500 |
| 50 °C | 750 | 1250 | 1750 | 1750 | 2500 | 2500 | 2500 | 2500 | 1750 | 1250 | 750 | 750 |
| 25 °C | 1000 | 1500 | 2000 | 2000 | 3000 | 3000 | 3000 | 3000 | 2000 | 1500 | 1000 | 1000 |

*All given numbers are not specific to Viessmann products

## Storage

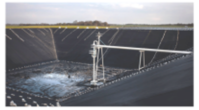
### Vitocharge

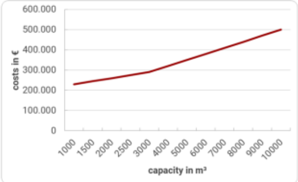



| Battery | |
|---|---|
| costs | 1.000 €/kWh |

*All given numbers are not specific to Viessmann products

### Seasonal thermal Storage



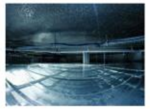


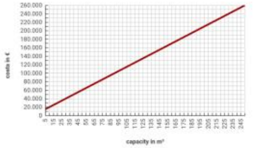

Prices and dimensions for seasonal storage (> 1 month)

| Seasonal thermal storage | |
|---|---|
| capacity | 20 kWh/m³<br>60 kWh/m³ (discharging with HP) |
| Costs | 25 €/m³ + 100.000 € |

*All given numbers are not specific to Viessmann products

### Ice storage



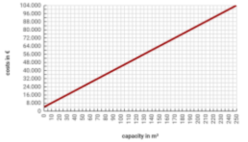



| Ice storage | |
|---|---|
| capacity | 100 kWh/m³ |
| Costs | 10.000 € + 1.000 €/m³ |

Solar absorber + ice storage as only source
Rule of thumb: 1 kW HP heating capacity requires 4 m³ ice and 3 m² unglazed solar collector

*All given numbers are not specific to Viessmann products

### Vitocell




| Thermal storage | |
|---|---|
| **mandatory for heat pump, solar thermal and pellets**<br>Collector: 0,1 m³/m² \| Pellet & HP: 0,05 m³/kW | |
| costs | 4.000 € + 400 €/m³ |

Prices and dimensions not applicable for seasonal storage (> 1 month)

*All given numbers are not specific to Viessmann products

# Objectives

1 Annualized cost

2 Annualized $CO_2$ emissions

3 Primary energy use

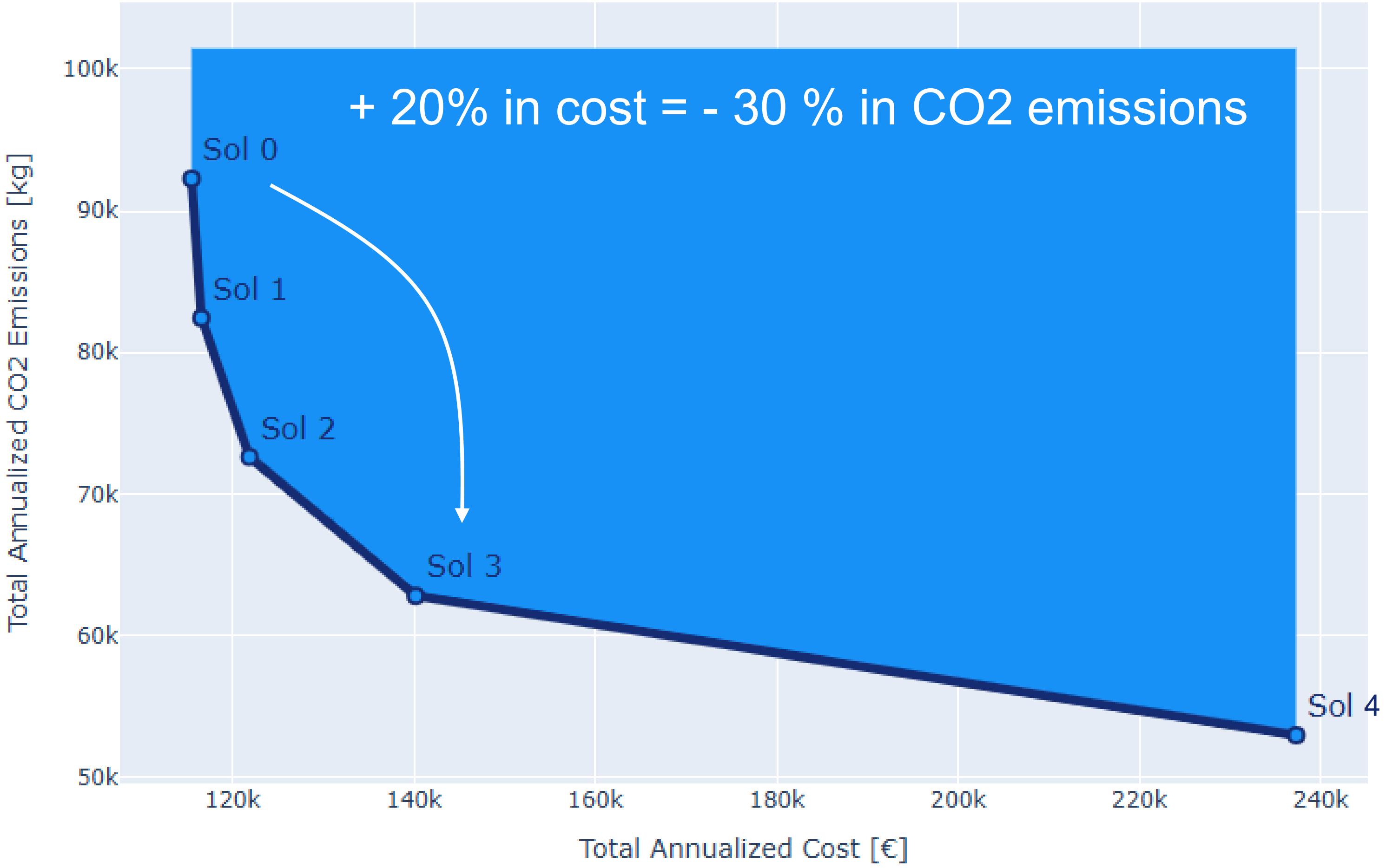
4 Share of renewable energy

5 Return On Investment

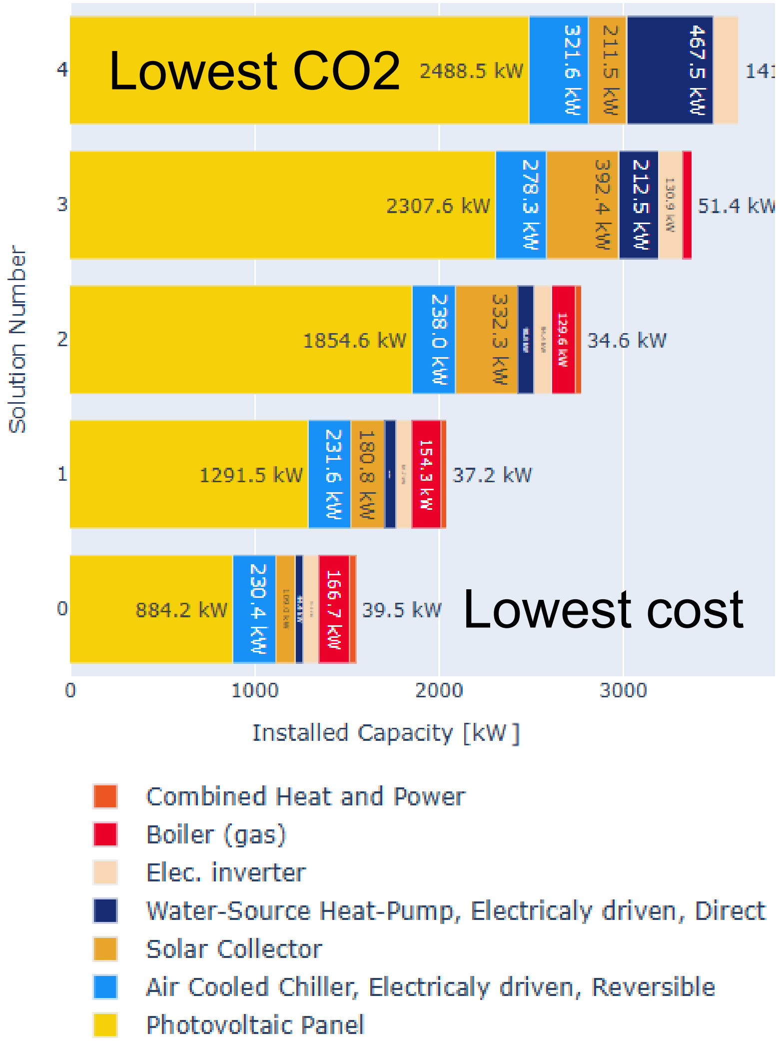
Need for consultation and dialogue

# Solution Trade-off – Mixed Integer Programming

## PARETO FRONT (Cost vs. Emissions)

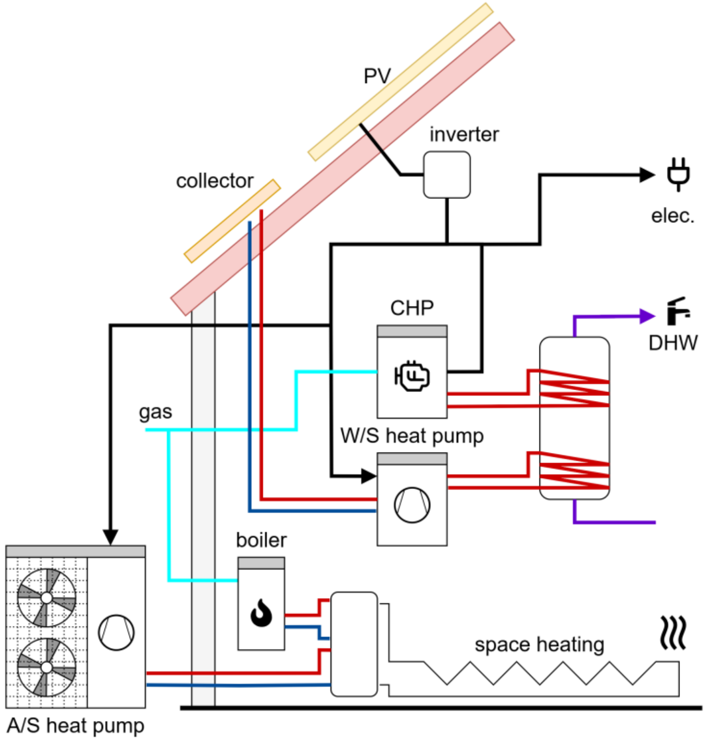



## Capacity of energy converters



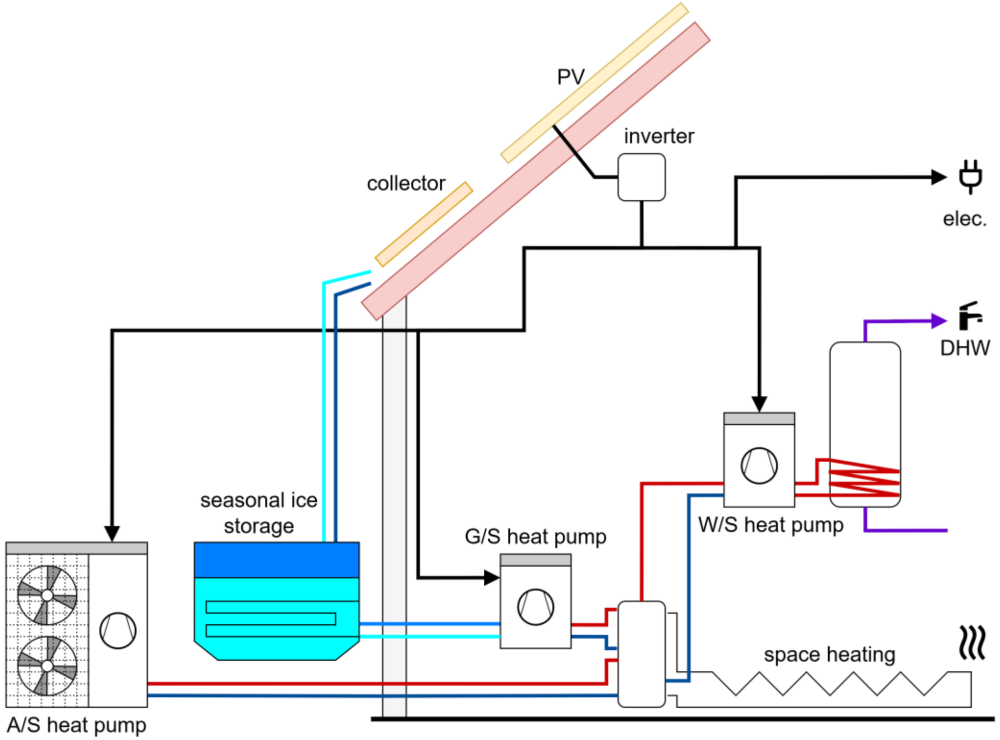
# Trading off Architectures and Technologies

## Solution 0




- Renewable electricity (PV panel)
- Renewable heat (solar collector + air source)
- Locally produced/consumed heat & electricity (gas CHP)
- Back-up gas boiler (peak demand and low OAT)

## Solution 3




- Renewable electricity (PV panel)
- Renewable heat (solar collector + air source)
  - ✓ **High share** reinforced by a seasonal <u>ice storage</u>
- No gas import

# Challenges

- Scale of optimization problem for large plants – Mixed Integer Programming
- Transition from topology and selection to control and dynamics – parameter consistency across layers
- Impact of uncertainty on system robustness
- Tooling – multiple platforms and tools
- Accessibility of expert modeling and optimization technology for a large group of application engineers

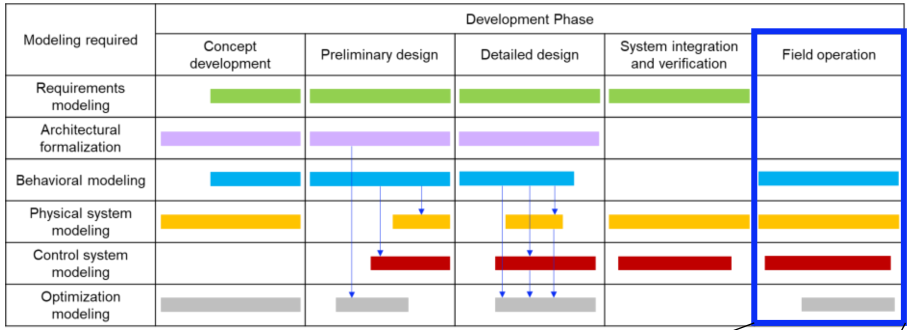
***Key Performance Indicators***

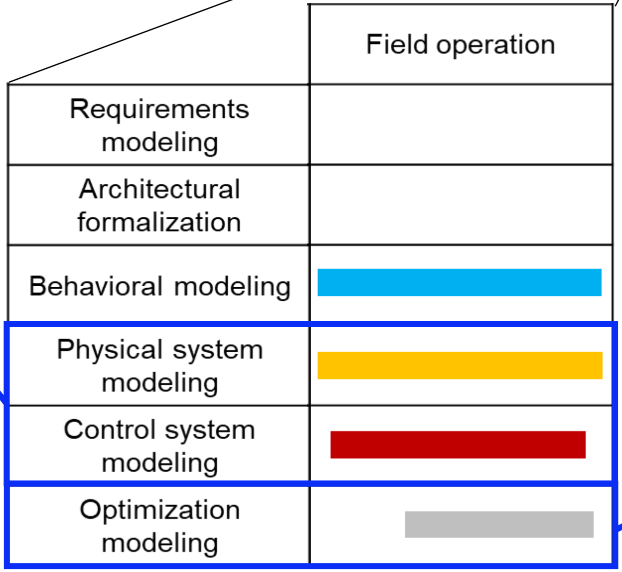
1. **Cycle times**: days to weeks (not months to years)
2. **Skillset required**: application engineers (not experts)
3. **Scalability**: highly repeatable (not on-offs)

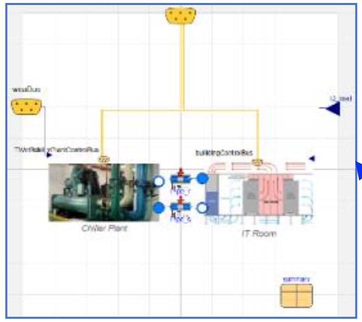
# Data Center Energy Optimization

Case Study

# Field Operation – Mixed Integer Programming and Dynamics




**Mixed-Integer Linear Programming (MILP)**
Assignment problems, Unit committment.

**Mixed Integer Non-linear Programming (MINLP)**
Staging of equipment, Assignment.

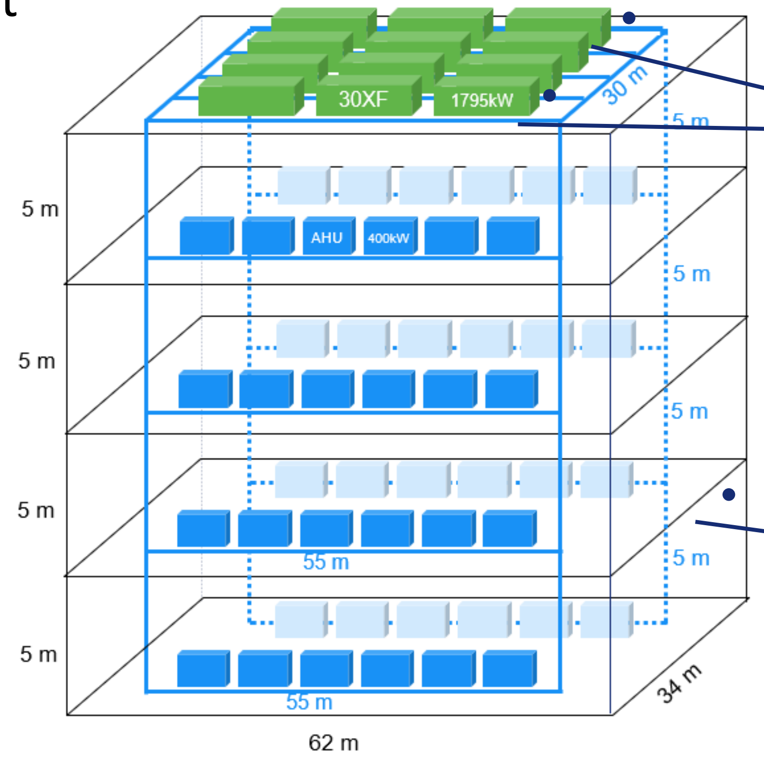
PYOMO

CPLEX

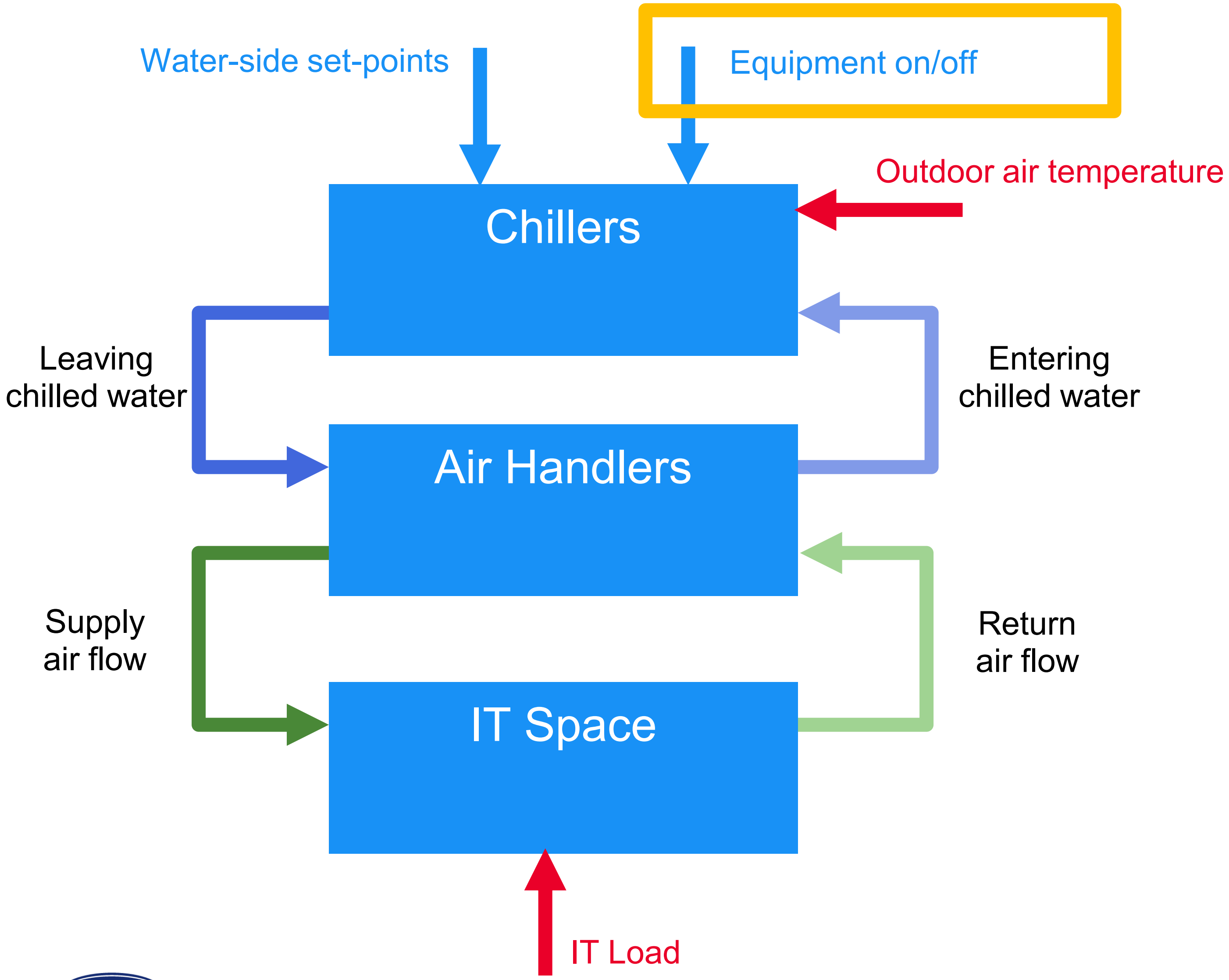
| Constraints | Variables | | |
|---|---|---|---|
| | $R^n$ | $R^n, \{0,1\}^n$ | Stochastic variables |
| Linear algebraic $Ax = b$ | **Linear Programming (LP)** Production planning, Financial portfolio optimization. | **Mixed-Integer Linear Programming (MILP)** Assignment problems, Unit committment. | **Stochastic Programming** Optimization under uncertainty. |
| Non-linear algebraic $f(x) = 0$ | **Non-linear Programming (NLP)** Min/max capcity problem, Set-point optimization. | **Mixed Integer Non-linear Programming (MINLP)** Staging of equipment, Assignment. | … |
| Linear differential equation $\dot{x} = Ax + Bu$ | **Linear Dynamic Optimization** Linear Quadratic Regulation (LQR), Model Predictive Control (MPC). | **Mixed-Integer Linear Dynamic Optimization** Optimal contol of switched systems, e.g., Mixed Logical Dynamic (MLD) | … |
| Non-linear differential equation $\dot{x} = f(x,u)$ | **Non-linear Dynamic Optimization** Non-linear Model Predictive Control (NMPC) | **Mixed Integer Non-linear Dynamic Optimization** Optimal control with non-linear dynamics and discrete decisions, e.g., equipment on/off | … |
| Partial differential equations $w_t = \alpha w_{xx}$ $w(t,0) = 0$ and $w_x(t,L) = u(t)$ | … | … | … |

# Data Center System Architecture

- 12 chillers (air-cooled)
- 4x24 = 96 AHUs (200 kW each) for IT equipment
- 4 IT rooms (floors)




# Energy Optimization – Problem Statement




**Objective**

- Predict energy savings
- Minimize total thermal energy consumption
- Support IT load requirement
- Consider OAT based on geography

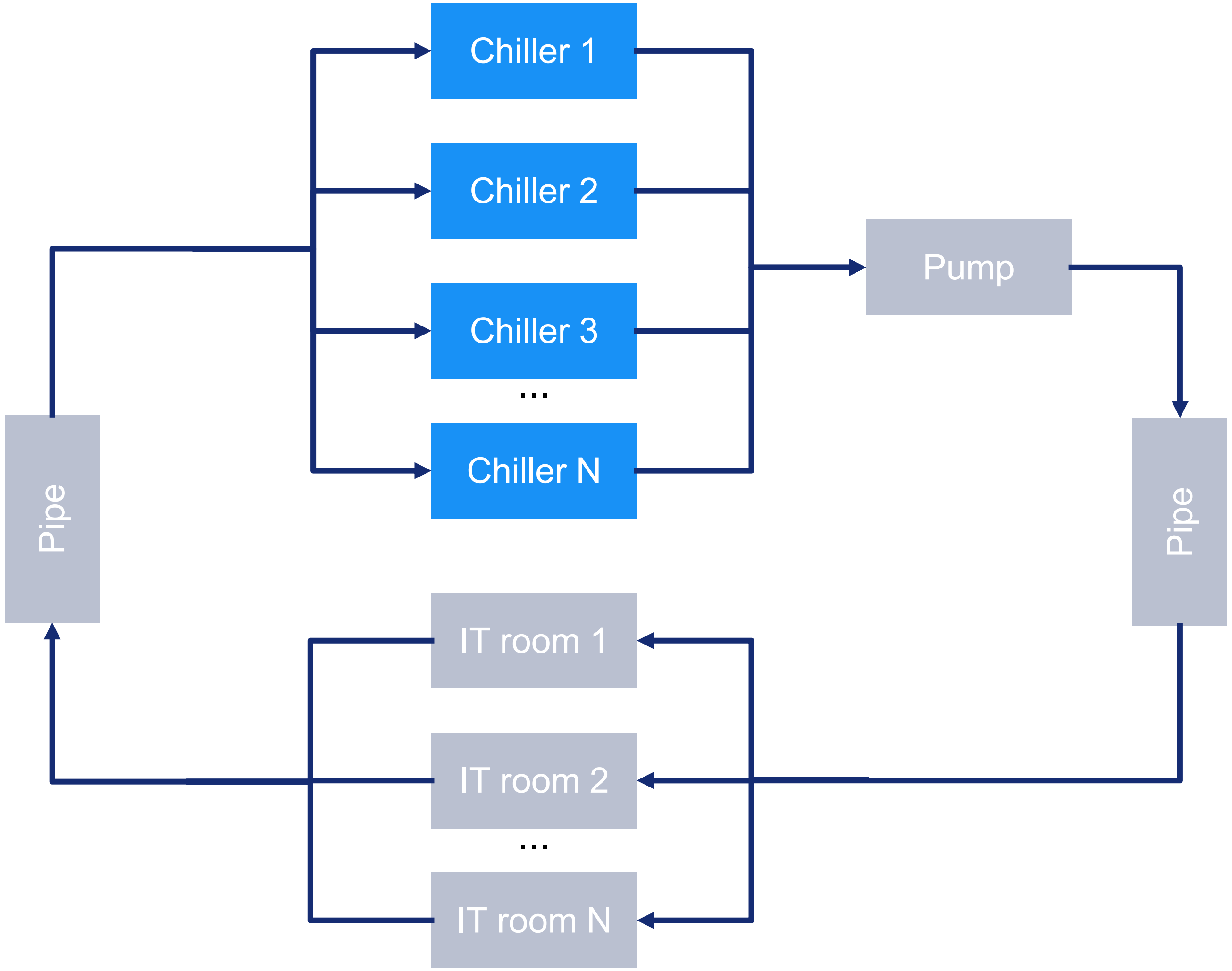
**What to optimize – advices?**

- ***How many chillers should be running***
- ***Chiller capacity allocation***

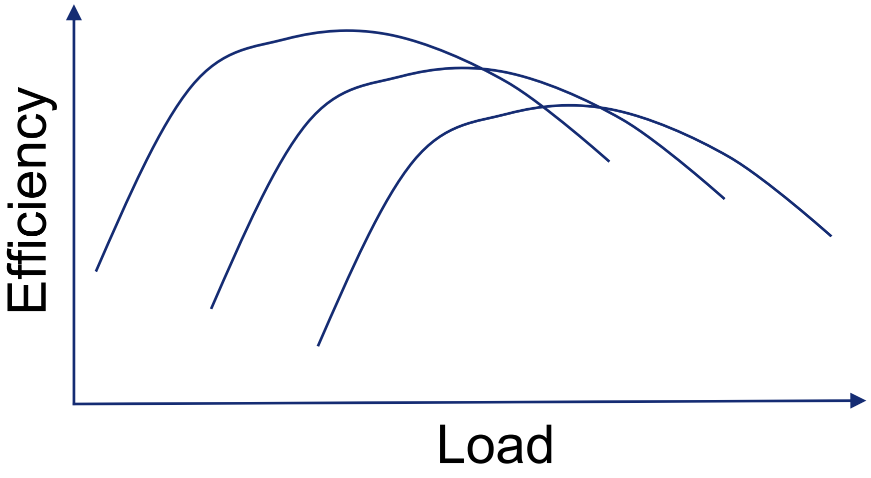
**Modeling approach**

- Identify equipment performance
- Build system model

# Decision Problem – Chiller Staging




- Chillers may be same or different
- Weather and IT load vary
- Efficiency depends on chiller load
- ***Decide how many chillers to run***
- ***Decide what capacity to allocate to each chiller***



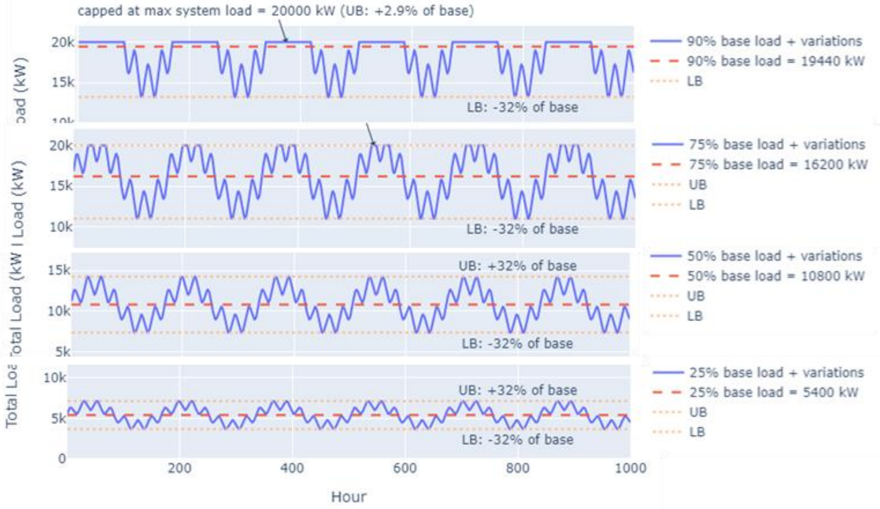
# Load and Weather Data

**Constant Load:**

- 25%
- 50%
- 75%
- 90%

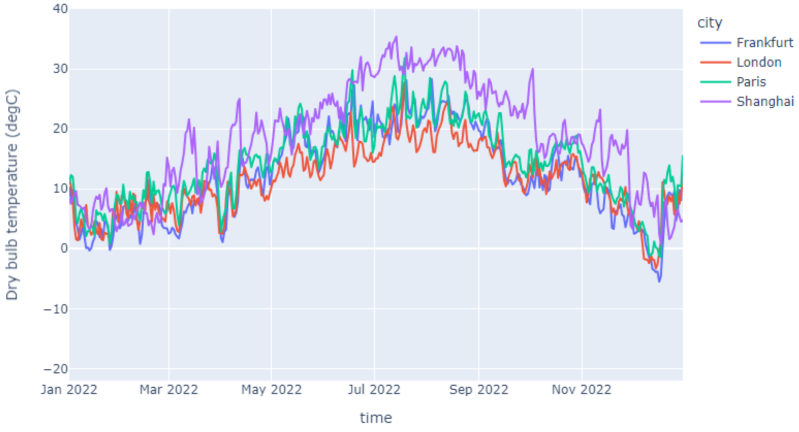

**Varying Load:**

- 25%
- 50%
- 75%
- 90%



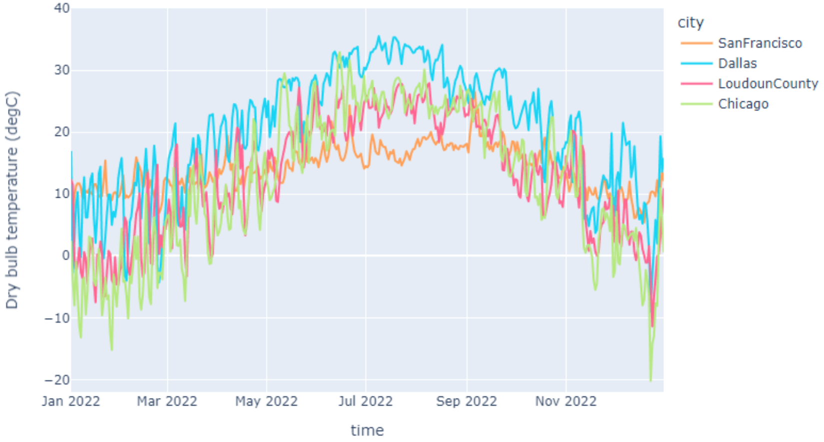

**EU & Asia:**

- Frankfurt
- London
- Paris
- Shanghai

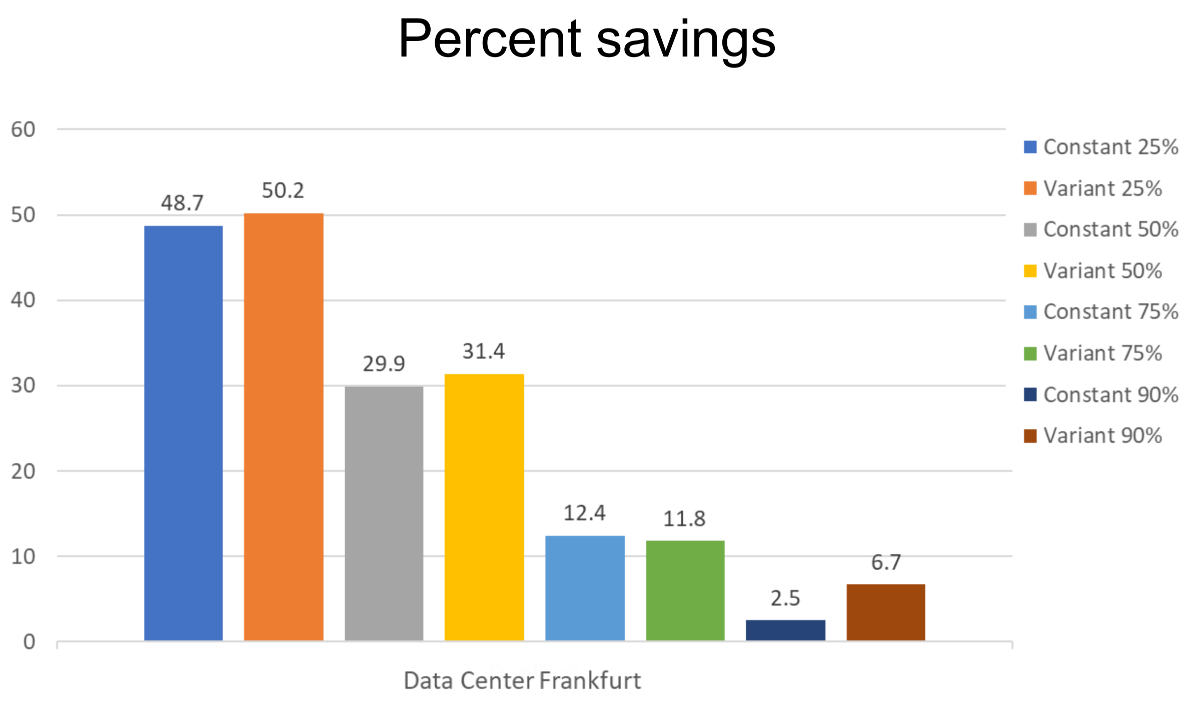



**NA:**

- San Francisco
- Dallas
- North Virginia
- Chicago

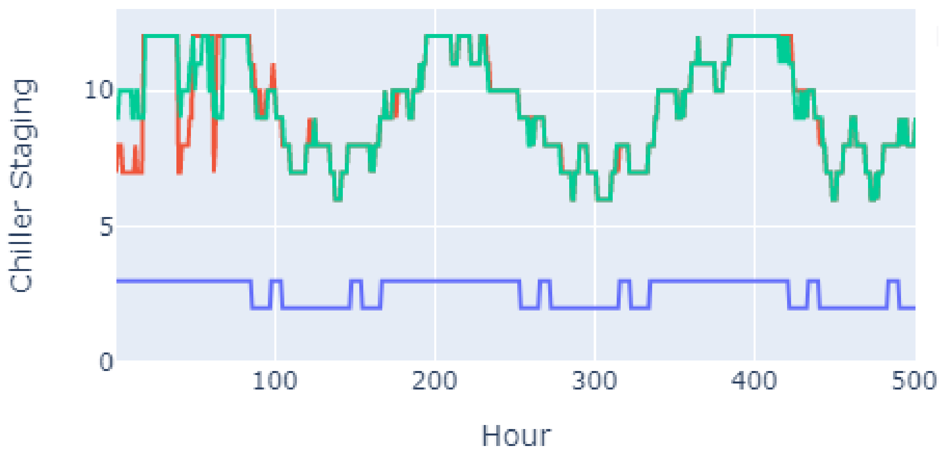


# Energy Savings Compared to Baseline




Optimized solution tends to ***run more chillers than baseline staging rules***

***Match peak efficiency points of chillers***

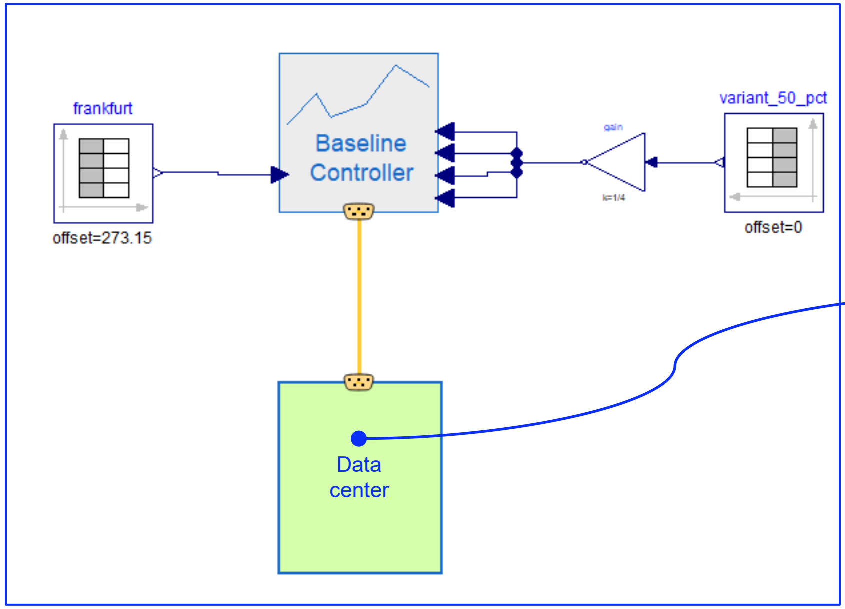



**25% Variant Load**

# Modelica System Model – Buildings Library

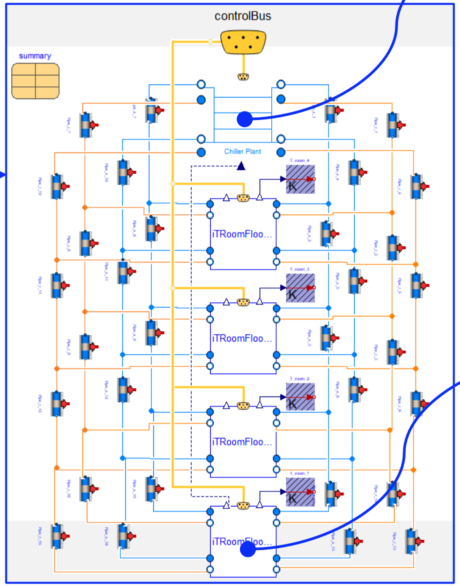
## Top level model

The controller and the data center is connected through a bus. The IT load is assumed to be evenly distributed across all floors.



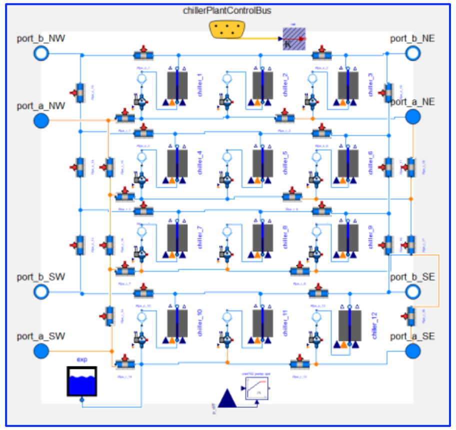

## Data center model

The chiller plant is connected to 4 IT rooms through raiser pipes at four corners.



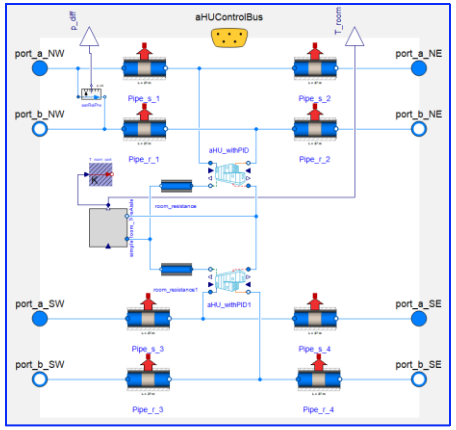

## Chiller plant model

Some pipes are ignored to simplified the model.




## IT room floor model

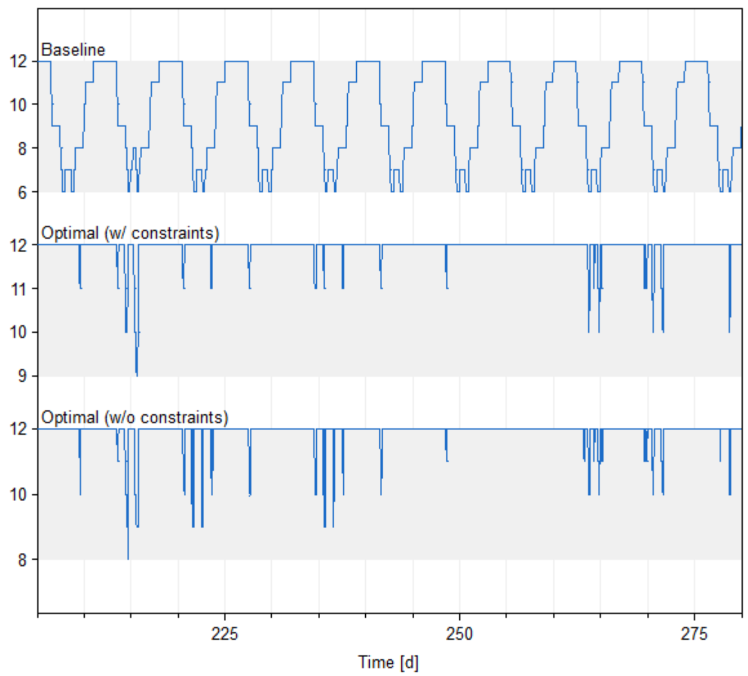
The AHUs on the same row are lumped into a single model.



# Annual Energy Simulation with Modelica and Buildings Library

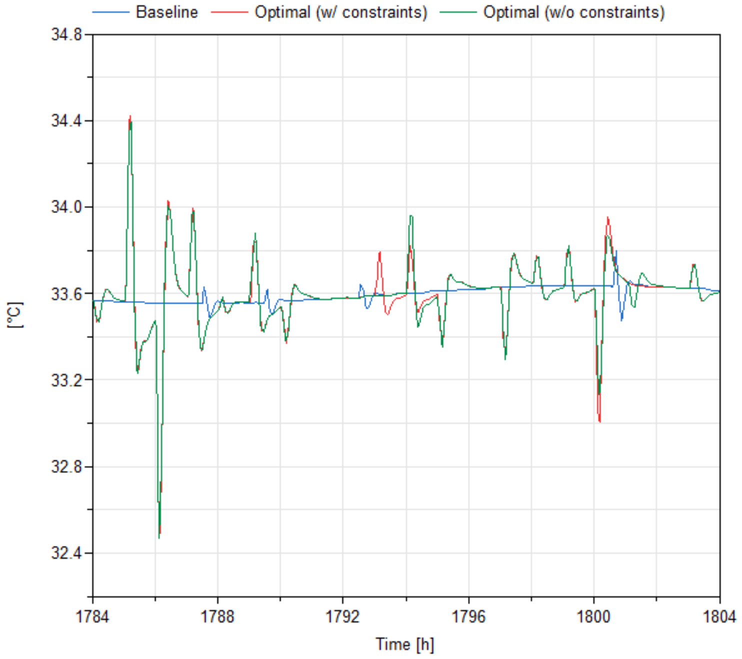
## Results for 75% load

### Chiller staging



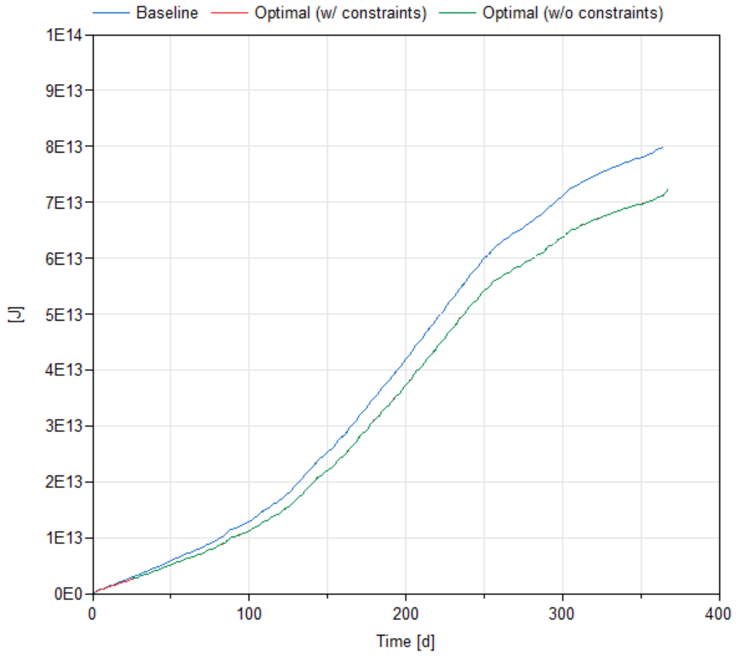

Optimal chiller staging

### AHU RAT




Air temperature fluctuate in a median range because of the LWT fluctuations

### Power consumption




Energy consumption.

# More challenges – Data Centers Energy Optimization

- Consistency between Modelica simulation models and Pyomo optimization models (MILP/NLP)
- Robustness and scalability of dynamic simulation with large scale thermal plants (initialization, numerics, speed)
- Component uncertainty and propagation to system level KPIs
- Tooling – multiple platforms and tools
- Accessibility of expert modeling and optimization technology for a large group of application engineers

***Key Performance Indicators***

1. **Cycle times**: days to weeks (not months to years)
2. **Skillset required**: application engineers (not experts)
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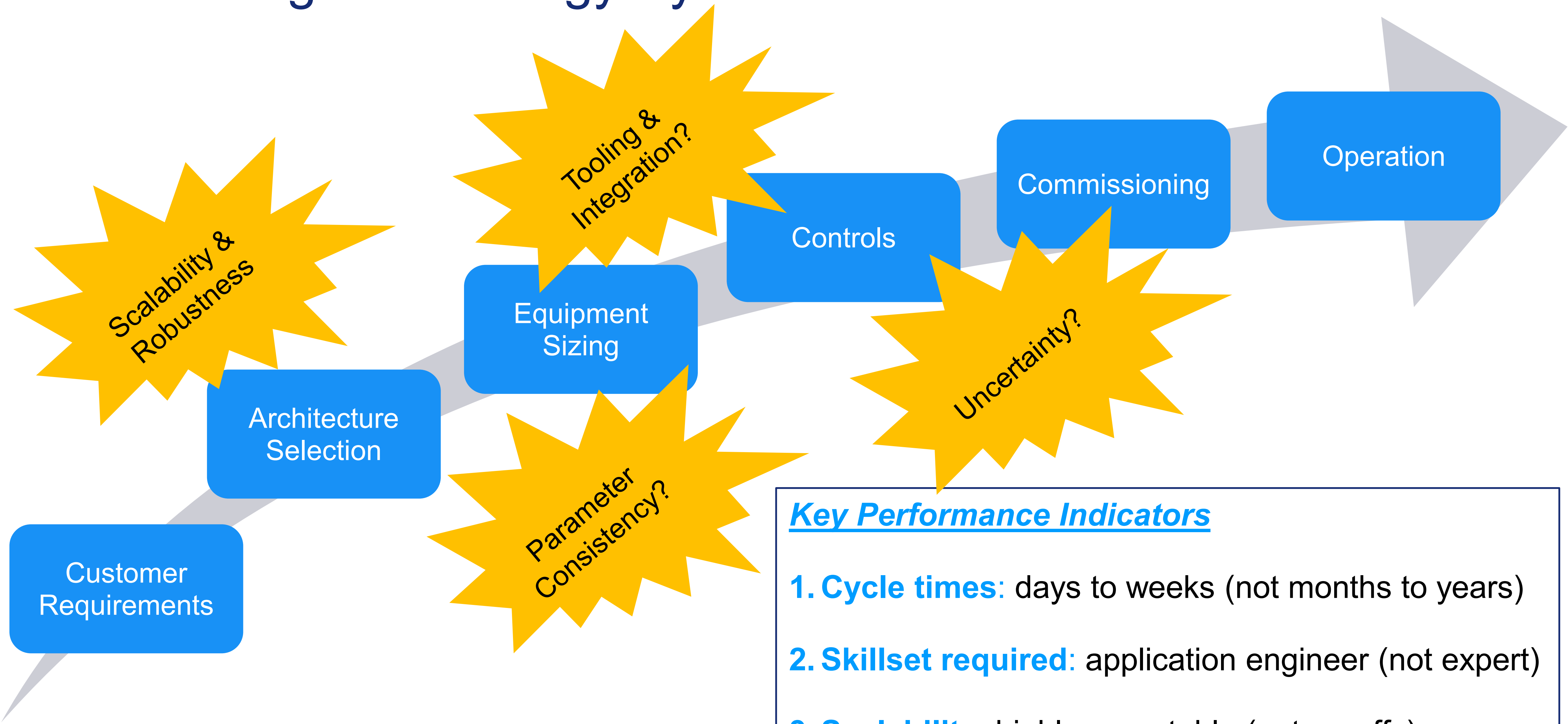
# Summary of Challenges

# Vision – Integrated Energy Systems at Scale




***Key Performance Indicators***

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# Looking Forward

# What about…

- …ML/AI for accelerated model creation?
- …digital twins for autonomous control?
- …oFMI for tooling integration?

Topics for another talk – come discuss!

# Key Points

- ***Modelica and FMI continue to bring significant value to Carrier*** in our product design – and has done so for 25 years!
    - Thank you!
- ***Design, control and operation of Integrated Energy Systems (IES) is fundamentally different*** from equipment (chillers)
    - Heterogeneity, scale, interconnections – and no labs
- ***Efficient IES exists*** – but they are often ***one-offs***, they take ***months to years*** to build even for ***skilled experts***
    - Need speed in creation and operation
- ***Systems engineering and platform-based design*** offers process to formally verify that standardized designs align with requirements
    - Tools and methodology exist but is not widely used in the energy sector
- ***Modeling, simulation and optimization is a (the) key enabler*** – actions required to mitigate challenges for IES – work ahead
    - Heterogeneity of computations, scale to very large systems, uncertainty management