Lecture

Introduction to graph-based bottom-up planning

Infratrain 2021

Energy system modeling with sector coupling

Technische Universität Berlin

DIW BERLIN

Agenda

1. **Course structure and introduction**
2. **Basics of bottom-up planning models**
3. **Basics of graph-based approach**

Schedule

Time	Mon 11.10	Tue 12.10	Wed 13.10	Thu 14.10	Fri 15.10
9:00 - 10:30		**Code along** Parameters, variables, and constraints in bottom-up planning models	**Code along** Storage, multi-temporal capacity expansion and time-series representation		Group Work
11:00 – 12: 30	Welcome	**Integrated session** Project and paper discussion	Group Work	**Integrated session** Project and paper discussion	Group Work
13:30 – 15:00	**Lecture** Introduction to graph-based bottom-up planning	**Lecture** Overview of exemplary applications for graph-based bottom-up planning	**Lecture** Advanced features based on interests (e.g. retrofitting, stochastic optimization, technology deployment, solution algorithm)	Group Work	Final presentations
15:30 – 17:00	**Code along** Program setup, data files and plotting with AnyMOD.jl	Guest lecture	Group Work	Group Work	Final presentations
Evening	**Integrated session** Software Troubleshooting		Fun Evening		

Survey and introduction round

Scan this QR code to join

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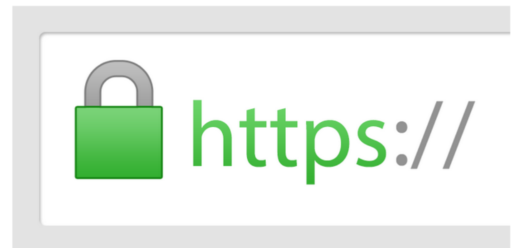

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Capacity expansion models

Scope

- Investigate how a portfolio of technical systems can be deployed to satisfy an exogenously set energy demand
- Considered systems include <u>generation and storage technologies</u> and <u>exchange infrastructure</u>
- Integrates decision on capacity expansion and subsequent dispatch of capacities to meet demand
- Might cover a single time-step of capacity expansion (<u>snapshot year</u>) or multiple consecutive time-steps (<u>pathway</u>)
- Might cover a single energy carrier or sector (e.g. electricity) or multiple sector at once to cover their interaction

Method

- Linear optimization problem (with continuous variables)
  - Objective function: minimization of system costs
  - Subject to constraints (technical, environmental, political, …)

→ Since LP models solve comparatively <u>fast</u>, a <u>great scope and level of detail</u> is possible

Basics of linear optimization

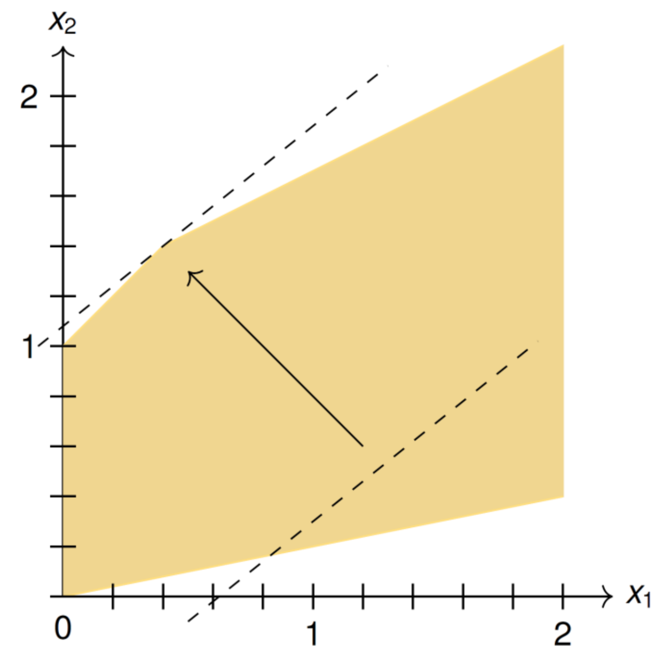
Sets: $\mathcal{I}, \mathcal{J}$

Variables: X_i, Z

Parameters: $u_i, a_{i,j}, c_j$

Objective $\min Z = \sum_{i=1}^{\mathcal{I}} u_i X_i$

Constraints
$$\begin{cases} \sum_{i=1}^{\mathcal{I}} a_{i,j} X_i \leq c_j, \; j \in \mathcal{J} \\ X_i \in \mathbb{R}, \; Z \in \mathbb{R} \end{cases}$$



Definitions for framework, model, and scenario

Abstract mathematical formulation and interface	Sets and mappings among sets	Parameter data
Examples : general definition of sets, algorithms for generation of equations	**Examples :** energy carriers, technologies, assigning energy carriers to technologies	**Examples :** demand, emission limits, efficiencies …

Framework → Model → Scenario

based on definitions by the Open Energy Modelling Initiative

Applying definitions to a linear optimization problem

$$\mathcal{I} = \{1, 2, 3, 4\}$$

$$\mathcal{J} = \{1, 2\}$$

$$a = \begin{pmatrix} 30 & 20 & 60 & 20 \\ 40 & 30 & 10 & 50 \end{pmatrix}$$

$$u = \begin{pmatrix} 500 & 400 & 200 & 100 \end{pmatrix}$$

$$c = \begin{pmatrix} 110 \\ 990 \end{pmatrix}$$

Model → **Scenario**

Model:

$$\begin{aligned} \max Z = u_1 \; X_1 + u_2 \; X_2 + u_3 \; X_3 + u_4 \; X_4 & \\ a_{1,1} X_1 + a_{2,1} X_2 + a_{3,1} X_3 + a_{4,1} X_4 & \leq c_1 \\ a_{1,2} X_1 + a_{2,2} X_2 + a_{3,2} X_3 + a_{4,2} X_4 & \leq c_2 \end{aligned}$$

Scenario:

$$\begin{aligned} \max Z = 500 \; X_1 + 400 \; X_2 + 200 \; X_3 + 100 \; X_4 & \\ 30 \; X_1 + 20 \; X_2 + 60 \; X_3 + 20 \; X_4 & \leq 110 \\ 40 \; X_1 + 30 \; X_2 + 10 \; X_3 + 50 \; X_4 & \leq 900 \end{aligned}$$

Typical in- and outputs of bottom-up planning models

	Input parameters	Result outputs
Capacity expansion	▪ Investment costs ▪ Upper capacity limits	▪ Costs and installed capacities • Generation technologies • Storage technologies (energy and power) • Exchange infrastructure
	▪ Discounting rates ▪ Budget constraints	
Dispatch of capacity	▪ Variable costs ▪ Efficiency and availability	▪ Variable costs ▪ Generated, stored and exchanged energy quantities
	▪ Demand for energy ▪ Emission limits ▪ Import prices	▪ Unmet demand ▪ Emissions

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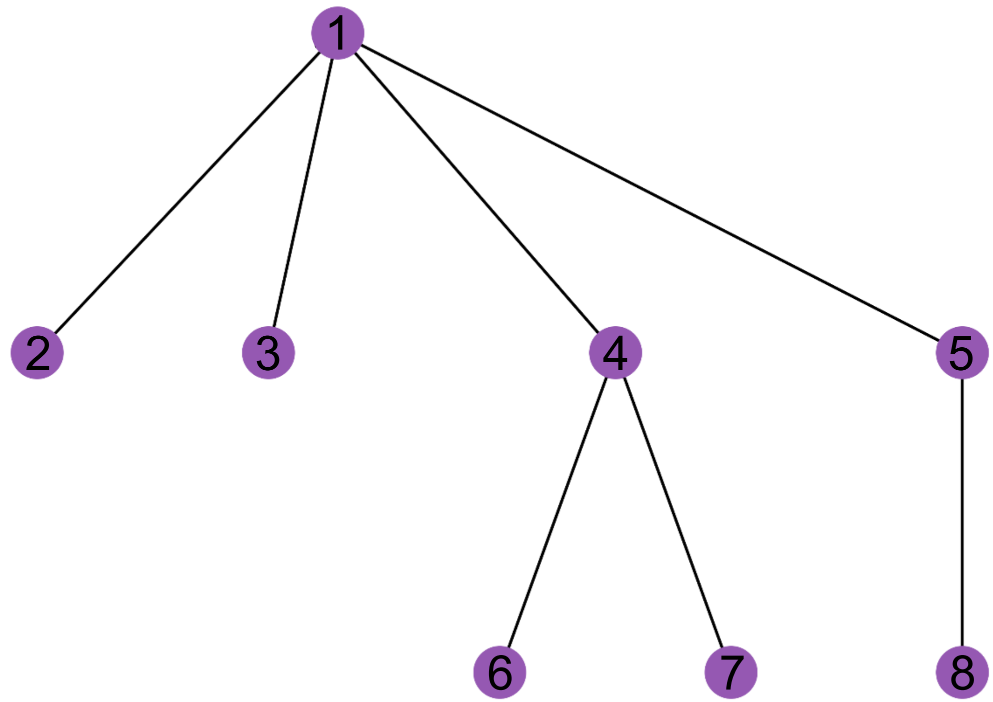
3. **Basics of graph-based modelling**

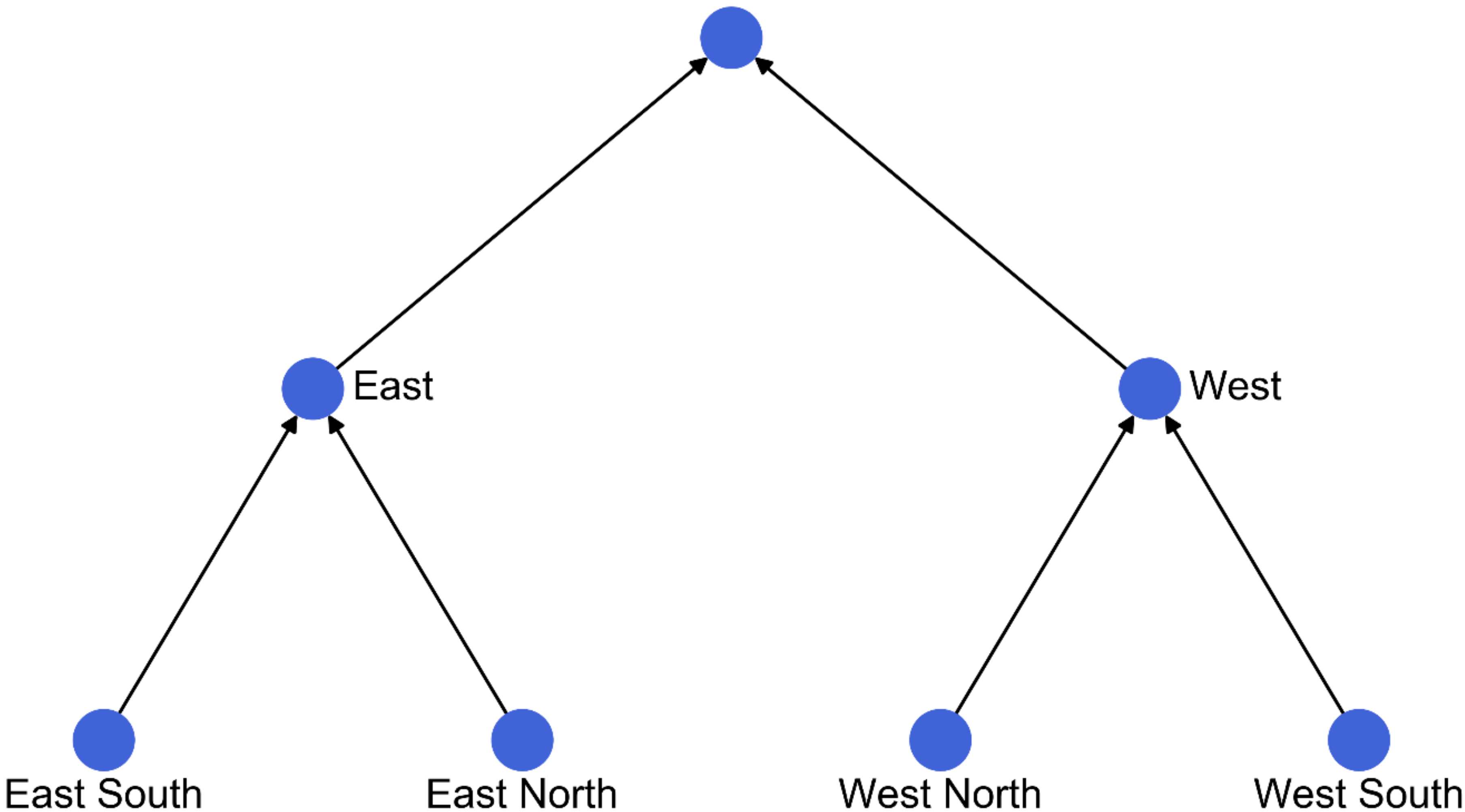
Basics of graph theory

Definitions

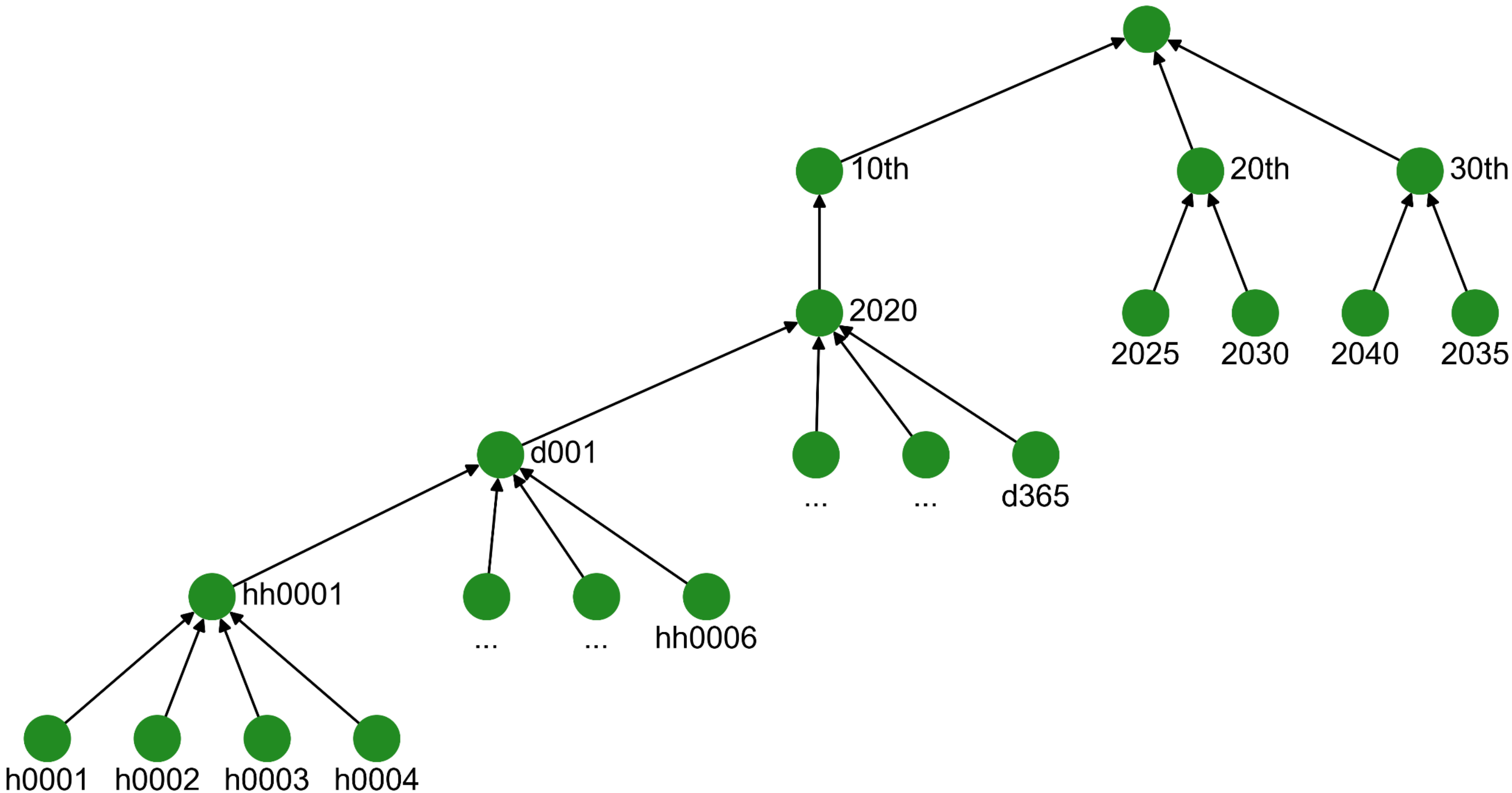
- A graph is defined by **vertices** and **edges**
- Edges can either be directed or undirected
- In a **tree** any two vertices are connected by exactly one path
- In a **hierarchical** (or rooted) tree one vertex is defined to be the **root**
- The number of vertices on the path from any vertex to the root is termed **depth**
- All vertices on the path from a vertex to the root are **ancestors** to the root (**descendants** are defined vice versa)
- A vertex without any descendants is termed **leaf**



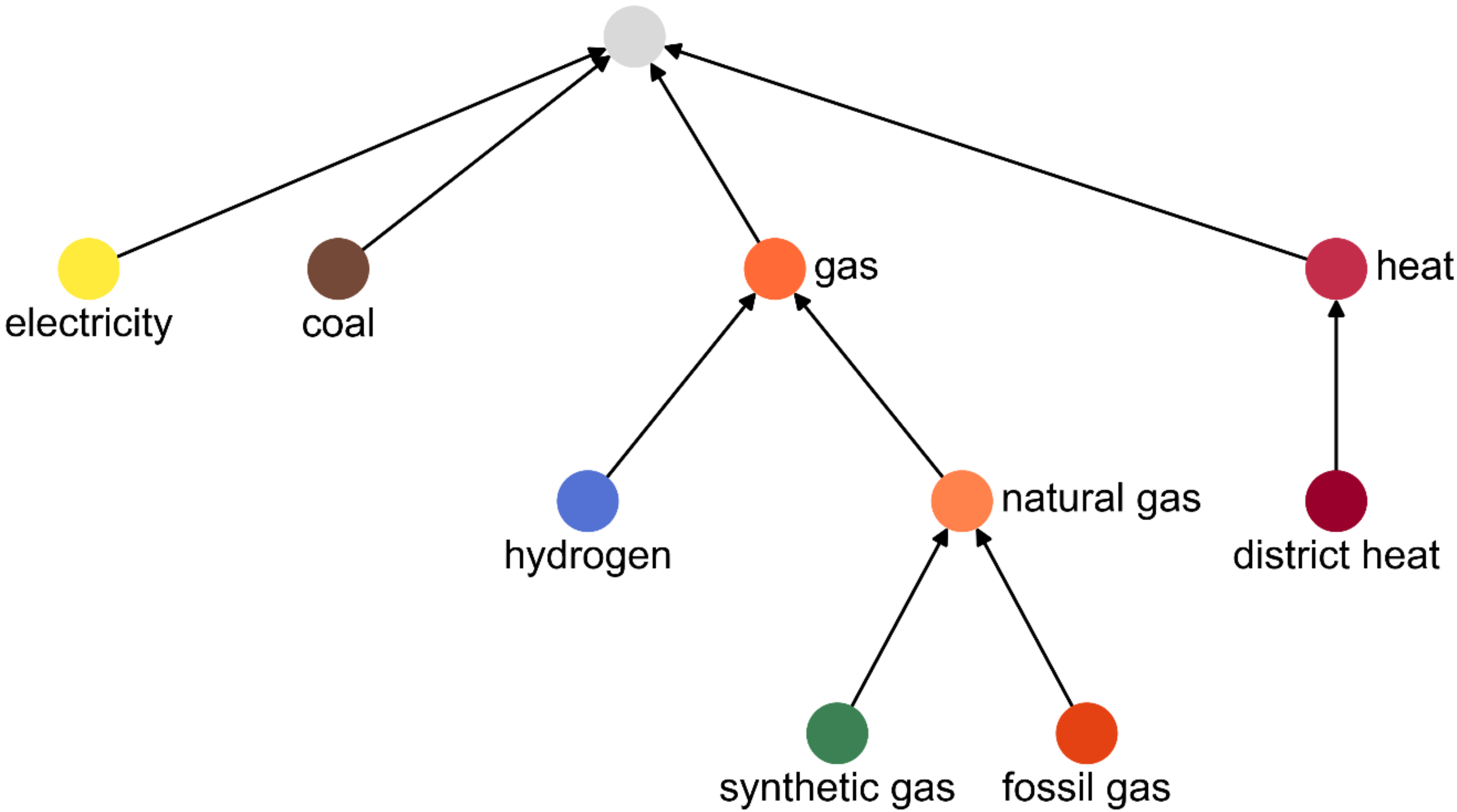
Hierarchical tree of regions



Hierarchical tree of time-steps



Hierarchical tree of carriers



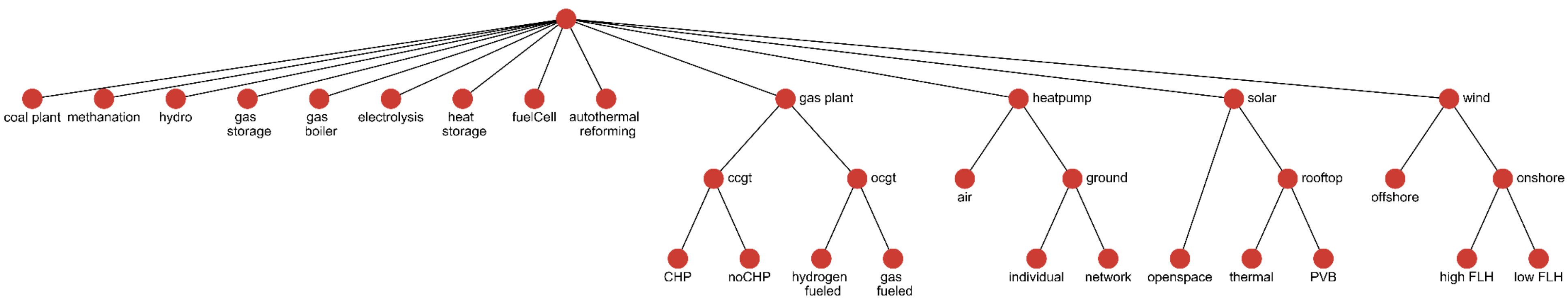
Defining the resolution for each carrier

carrier with depth 1	carrier with depth 2	carrier with depth 3	temporal		spatial	
			dispatch	expansion	dispatch	expansion
electricity			5	2	1	1
heat	district heat		4	2	2	2
gas	natural gas	synthetic gas	3	2	1	1
gas	natural gas	fossil gas	3	2	1	1
gas	hydrogen		3	2	1	1
coal			2	2	1	1

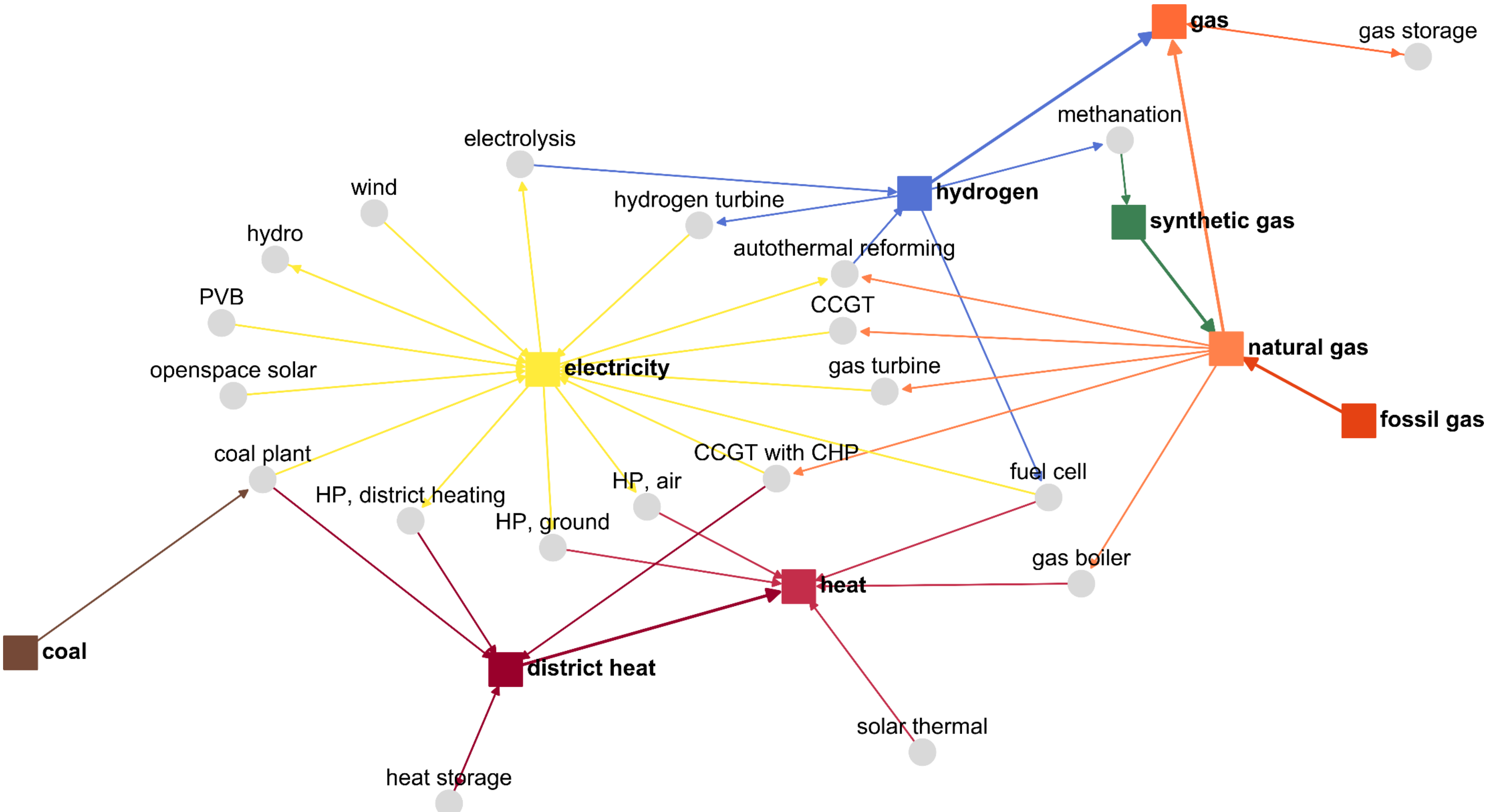
- **Temporal resolution of dispatch** is an implicit assumption on a carrier's inherent flexibility
- Appropriate resolution depends on
  - Physical properties of the carrier
  - Corresponding spatial resolution
  - Scope of research

→ Can achieve a more accurate <u>and</u> computationally less intensive representation

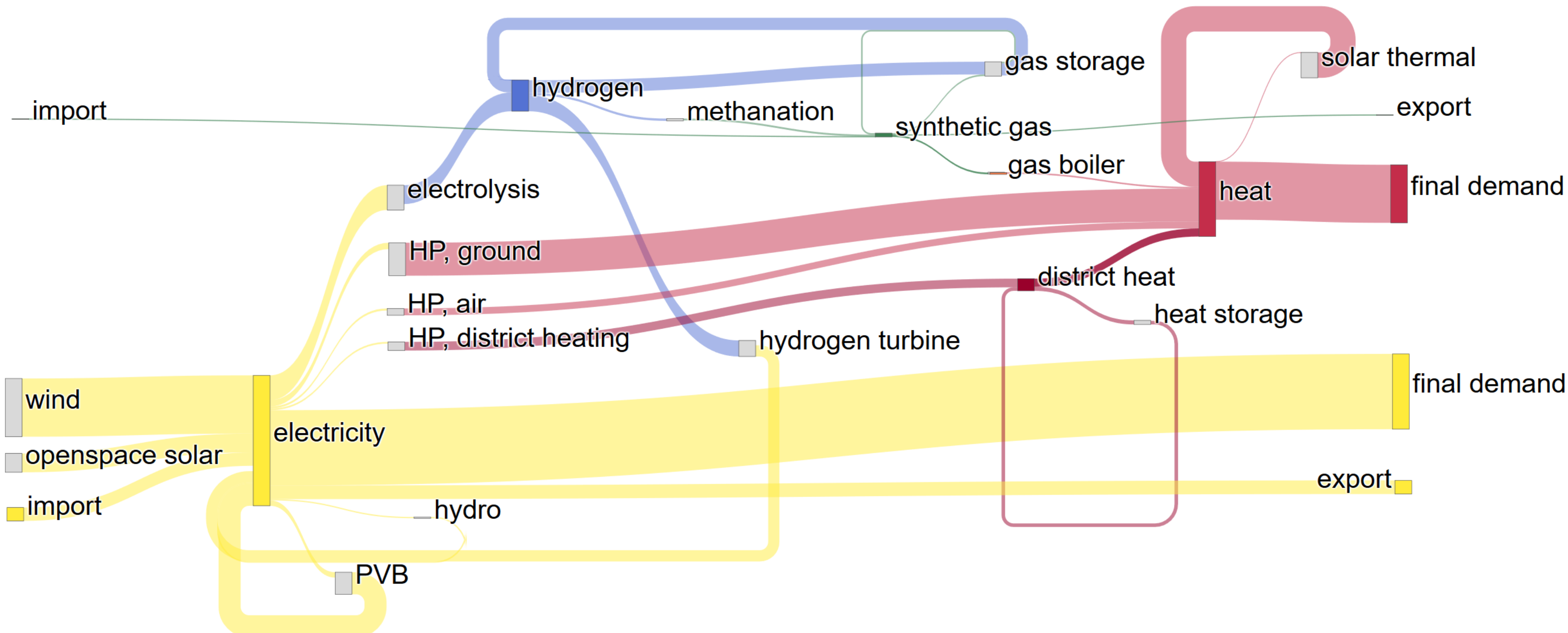
Hierarchical tree of technologies



Qualitative energy flow graph



Quantitative energy flow graph for 2040



Example technology: CCGT power plant with CHP