ENERGY SYSTEMS

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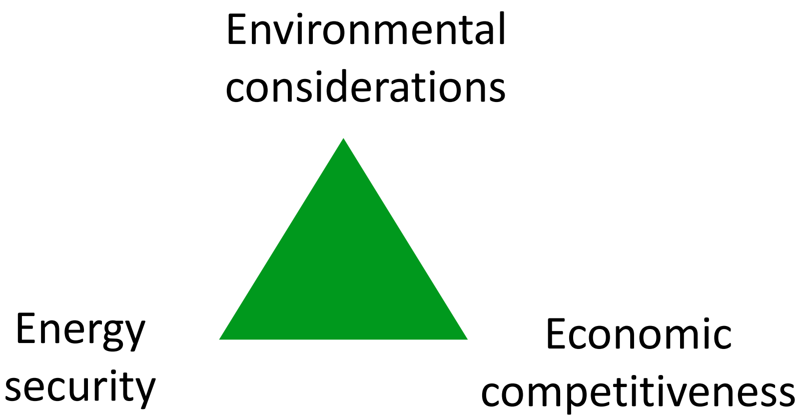
1 Energy planning with energy models

The essence of energy planning is preparing for an uncertain future in a comprehensive, organized and transparent manner.

Energy planning is about dealing with trade-offs:



Energy modelling provides is about the analysis and evaluation of a set of different possible futures – providing insights, not answers.

Different actors require different answers and thus different approaches (no one size fits all).

1 Energy planning with energy models

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Traditional questions…	… + increasingly
• Security • Affordability • Resilience of energy supply	• Environmental and climate concerns
Trends in the role of energy modelling	**Contemporary development shows increase in**
• Increased role for modelling in energy research • Increased complexity in models	• Sectoral scope (flexibility from sectors) • Variability and temporal detail (intermittency) • Spatial detail (distributed generation and renewable potential)

1 Physical energy system

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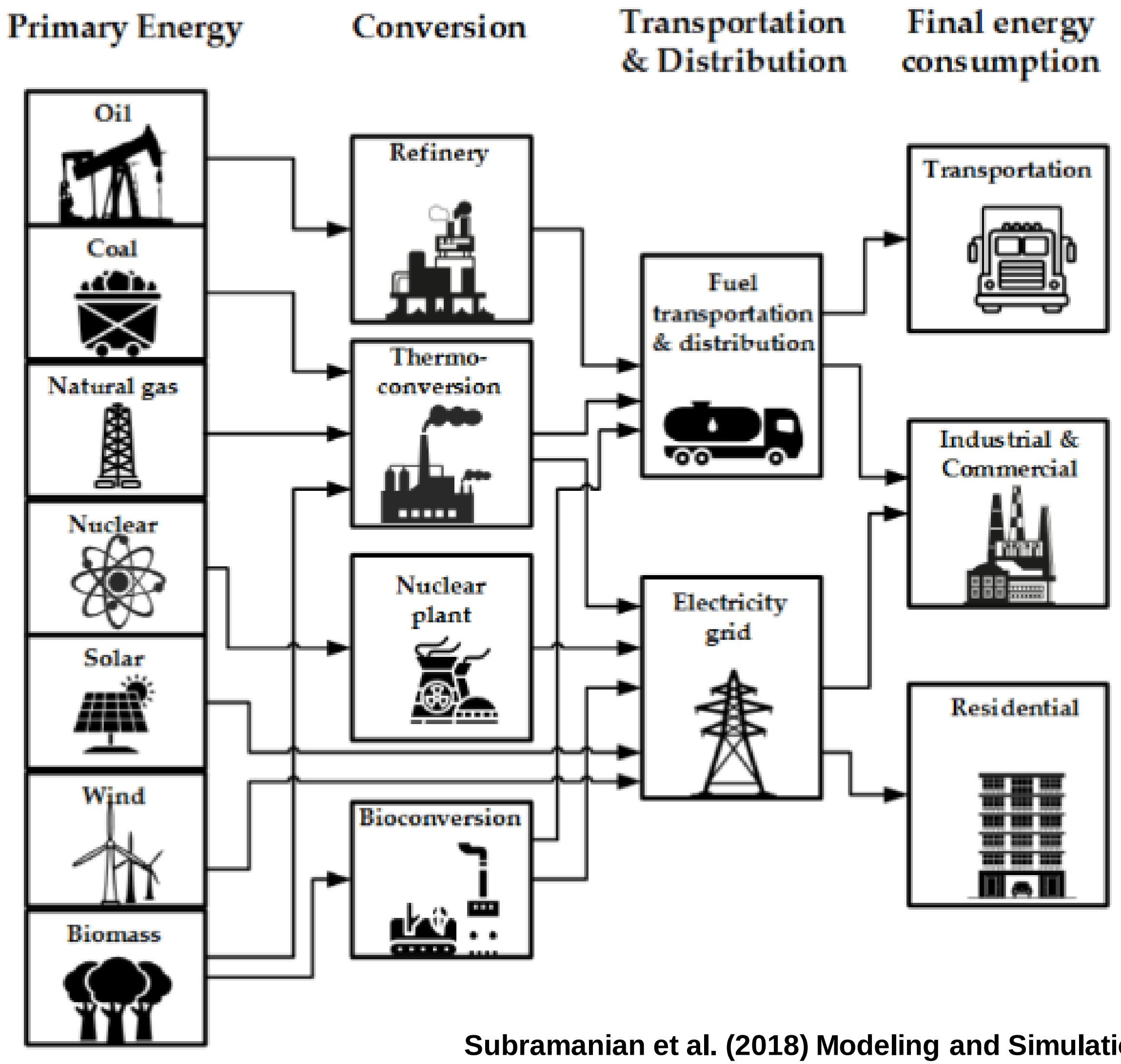
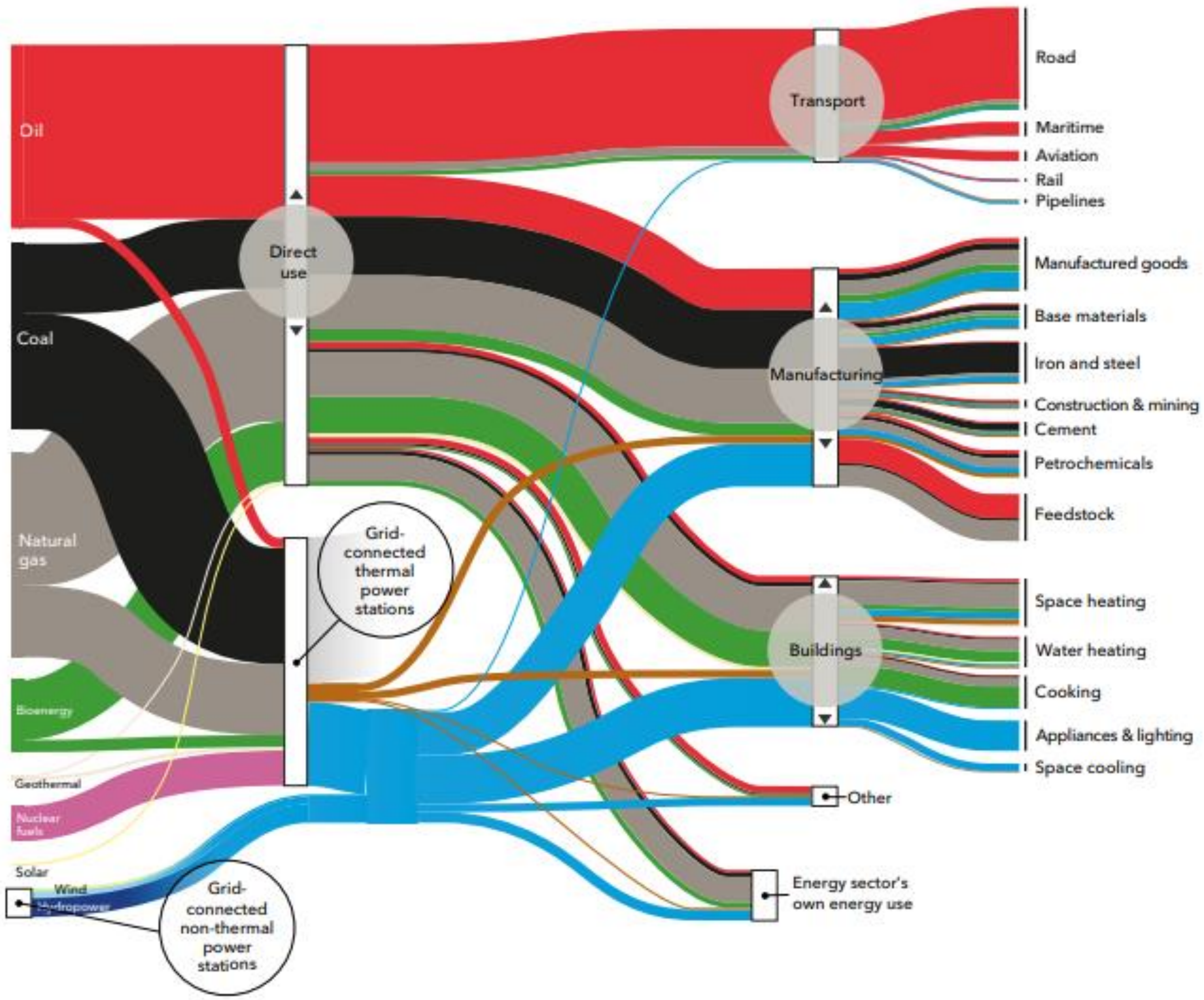


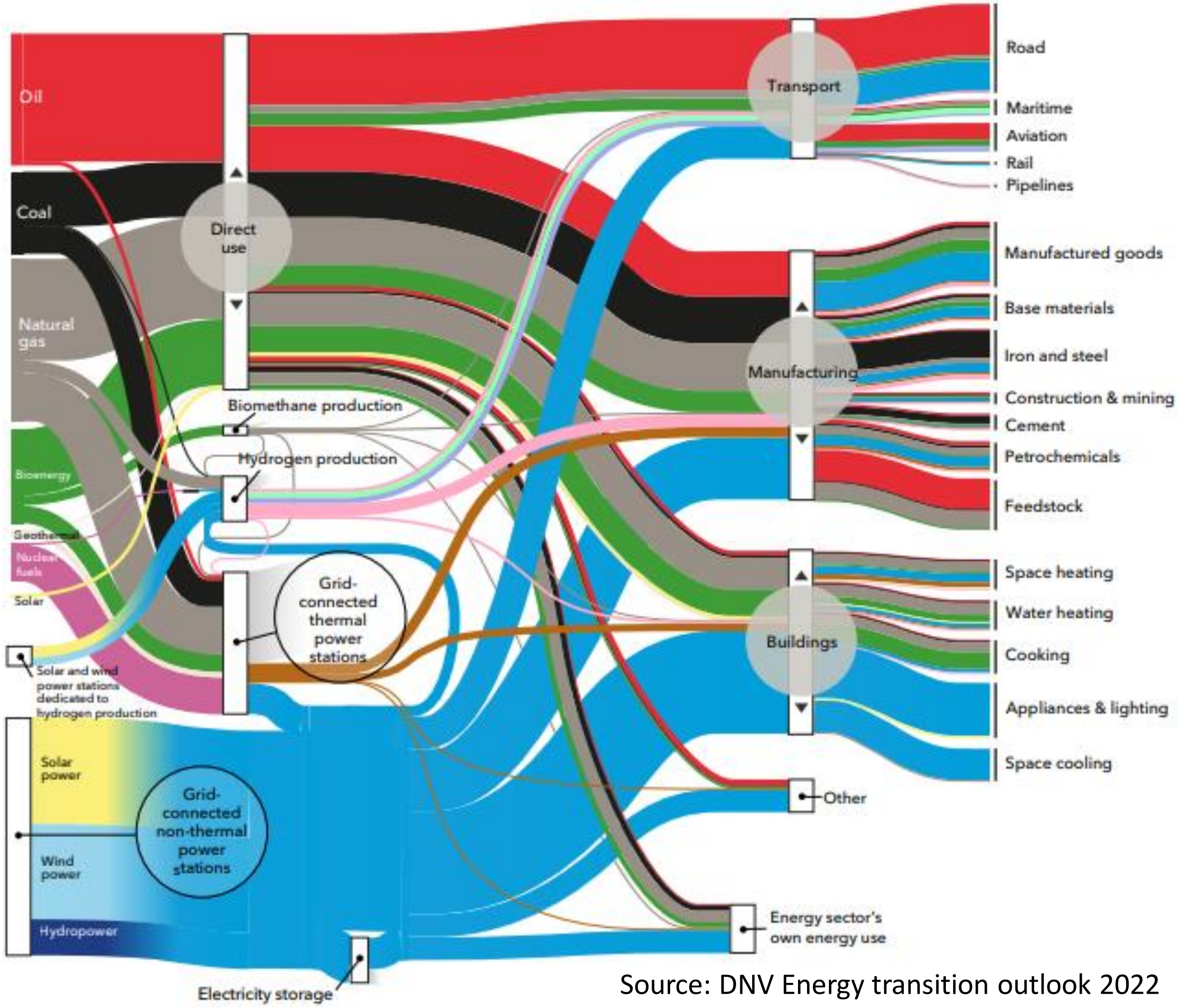
Subramanian et al. (2018) Modeling and Simulation of Energy Systems: A Review

1 World energy flows 2020 vs. 2050

Primary Transformation Distribution Demand Final Use



Primary Transformation Distribution Demand Final Use



Source: DNV Energy transition outlook 2022

1 Many roads to low carbon energy systems

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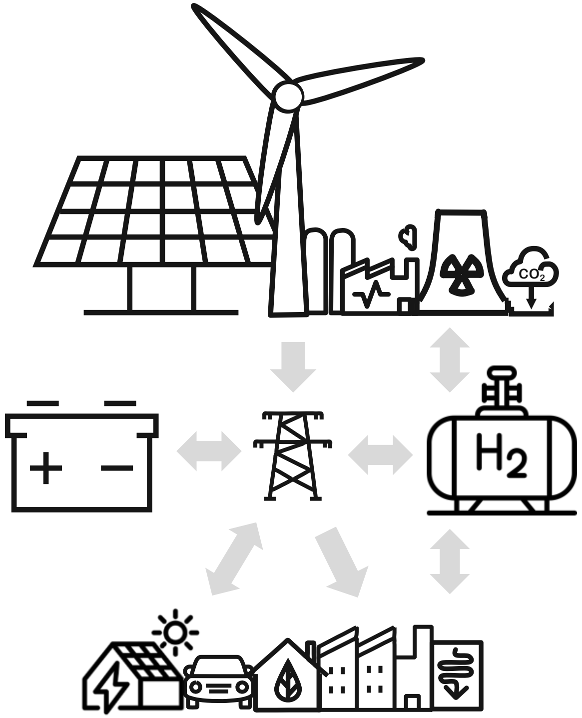
GENERATION

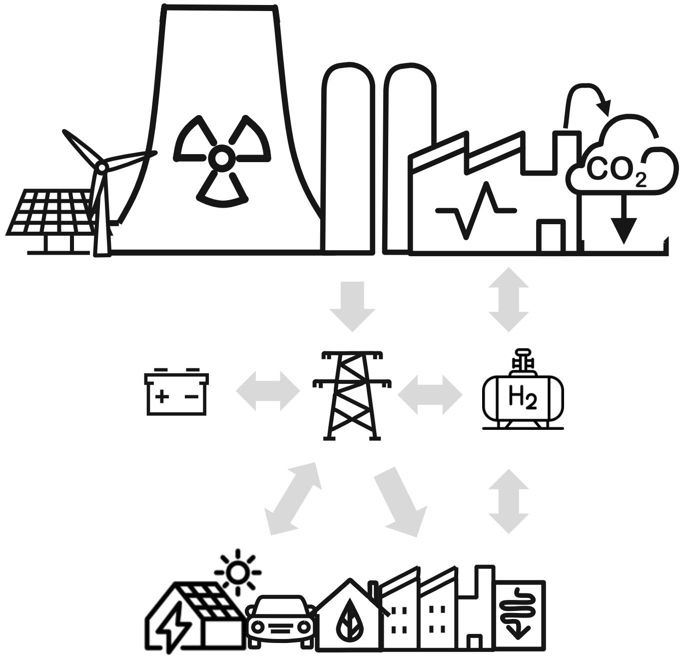
SYSTEM

END-USE

VRE centered system



Nuclear + CCS centered system



TYPES OF ENERGY SYSTEM MODELS

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2 Model = mathematical representation of the system

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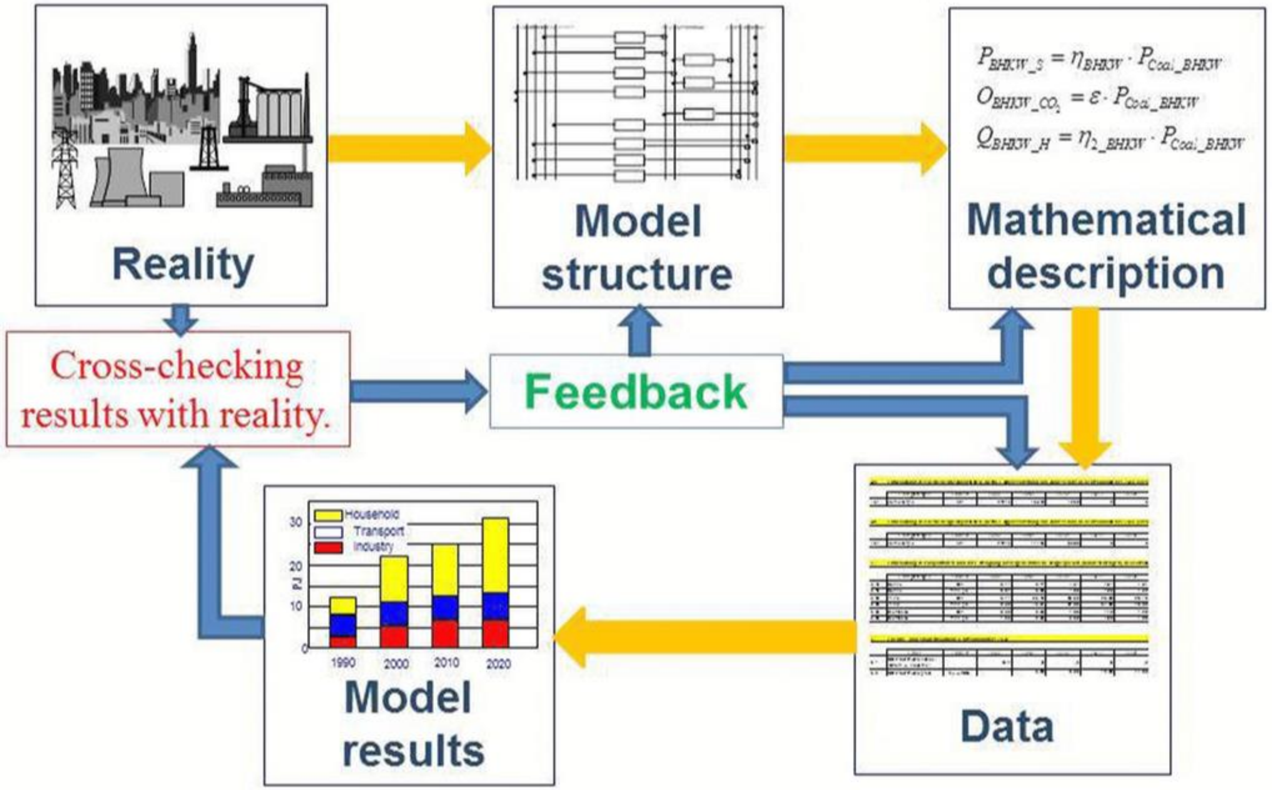
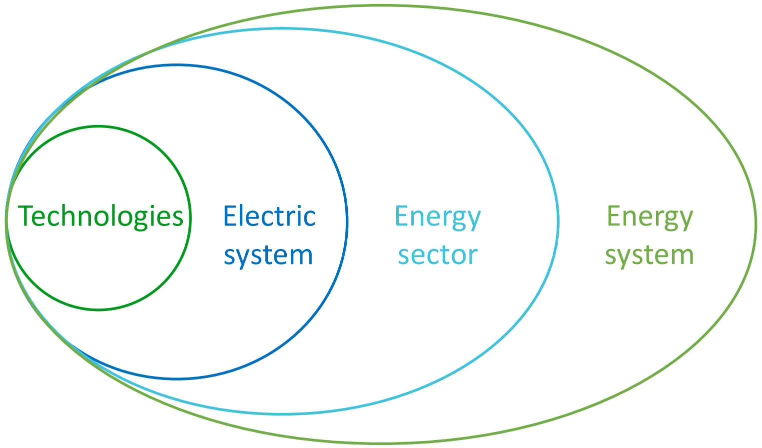
Depicting reality inside an energy system model



Defining system boundaries:

- Full energy system or subsystem?
- Data availability?
- Technology representation: Detail and diversity?
- Level of interaction with other systems



Source: Gargiulo & Gallachoil (2013) Long-term energy models: Principles, characteristics, focus, and limitations

2 Classifying energy system models…

…by methodology

…by purpose

…by sectoral coverage

…by resolution and level of detail

…by programming technique and mathematical logic

Source: Cao et al. (2016) Raising awareness in model-based energy scenario studies-a transparency checklist

2 Modelling methodologies

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Optimization

Simulation

Econometric

Economic / partial equilibrium

Input-output

Spreadsheet

Other: Markov Chain, integrated assesment, long-term energy scenarios, agent-based, heuristic, geospatial, machine learning

+ hard or soft linked hybrid models

Note that the categories are often overlapping, e.g. simulation models include optimization elements, optimization includes geospatial model etc.

2 Models by purpose: Optimization vs. simulation

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Optimization models are typically used as a range of **scenarios**

- The purpose of modelling is **possible evolution without estimation of likelihood**
- or **normative** (system only achievable by certain actions / target-seeking)

Simulation models are more typically be used for **forecasting**

- The purpose of modelling is **predictive** (how the system will likely be)

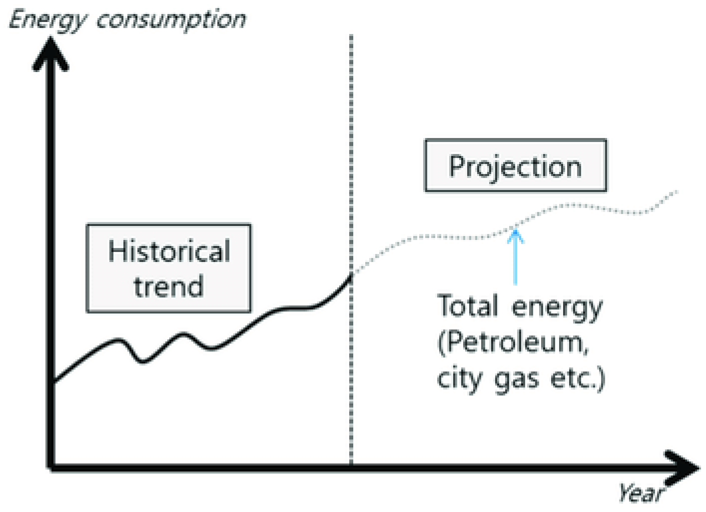
Explorative (plausible)			Normative			Predictive (Outlooks)		
What might happen?			What future we want?			What future we expect?		
Plausible future	Plausible future	Plausible future	Preferable future	←gap→	”Business as usual”	”Best case”	Baseline	”Worst case”

Different energy scenario approaches

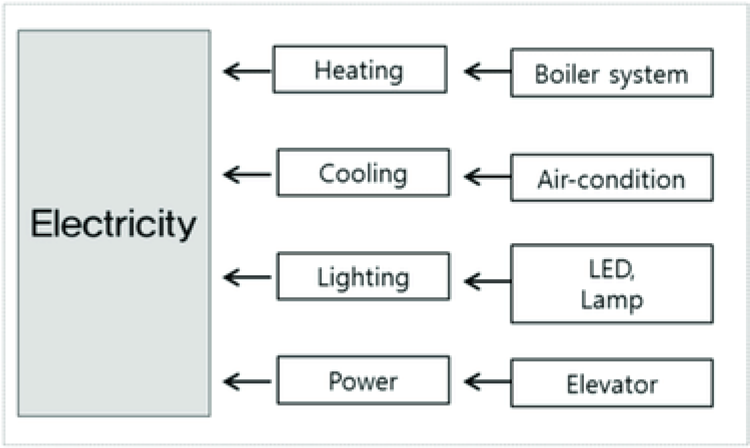
+ is the model providing a snapshot or a pathway?

Image source: Klemm & Vennemann (2021) Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches

2 Top-down vs. bottom-up



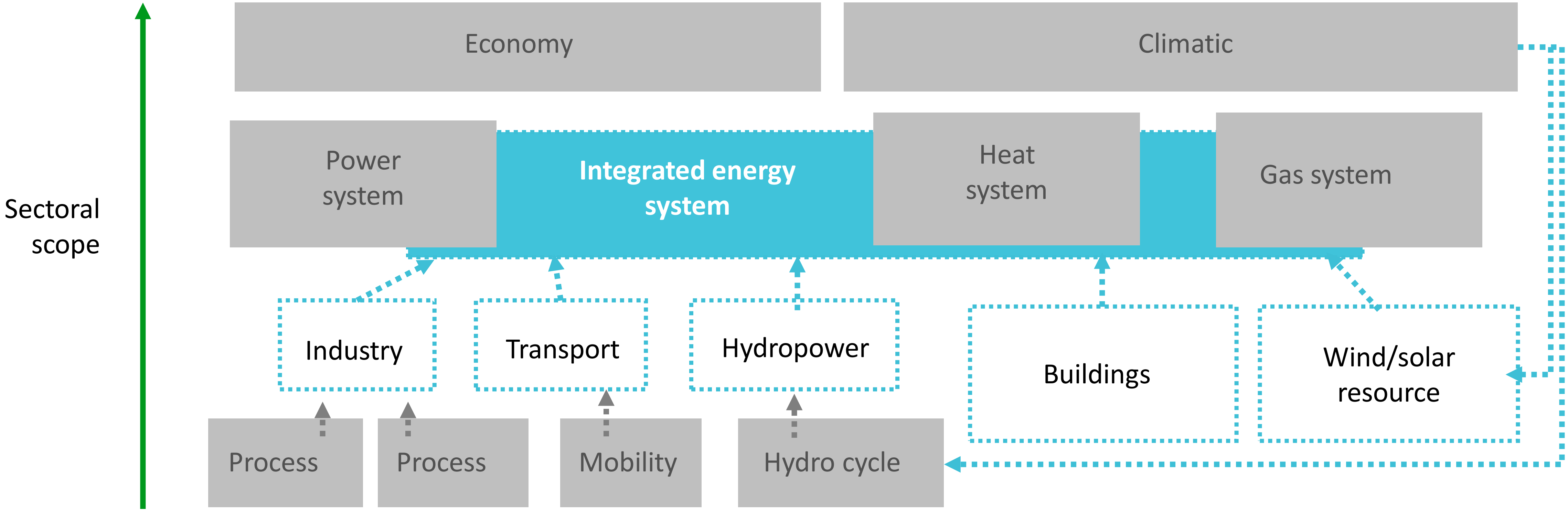
Top-Down Modeling
begins with a high-level view of the entire energy system, offering simplicity and applicability for long-term planning and policy analysis, with a focus on aggregated data and broader trends.



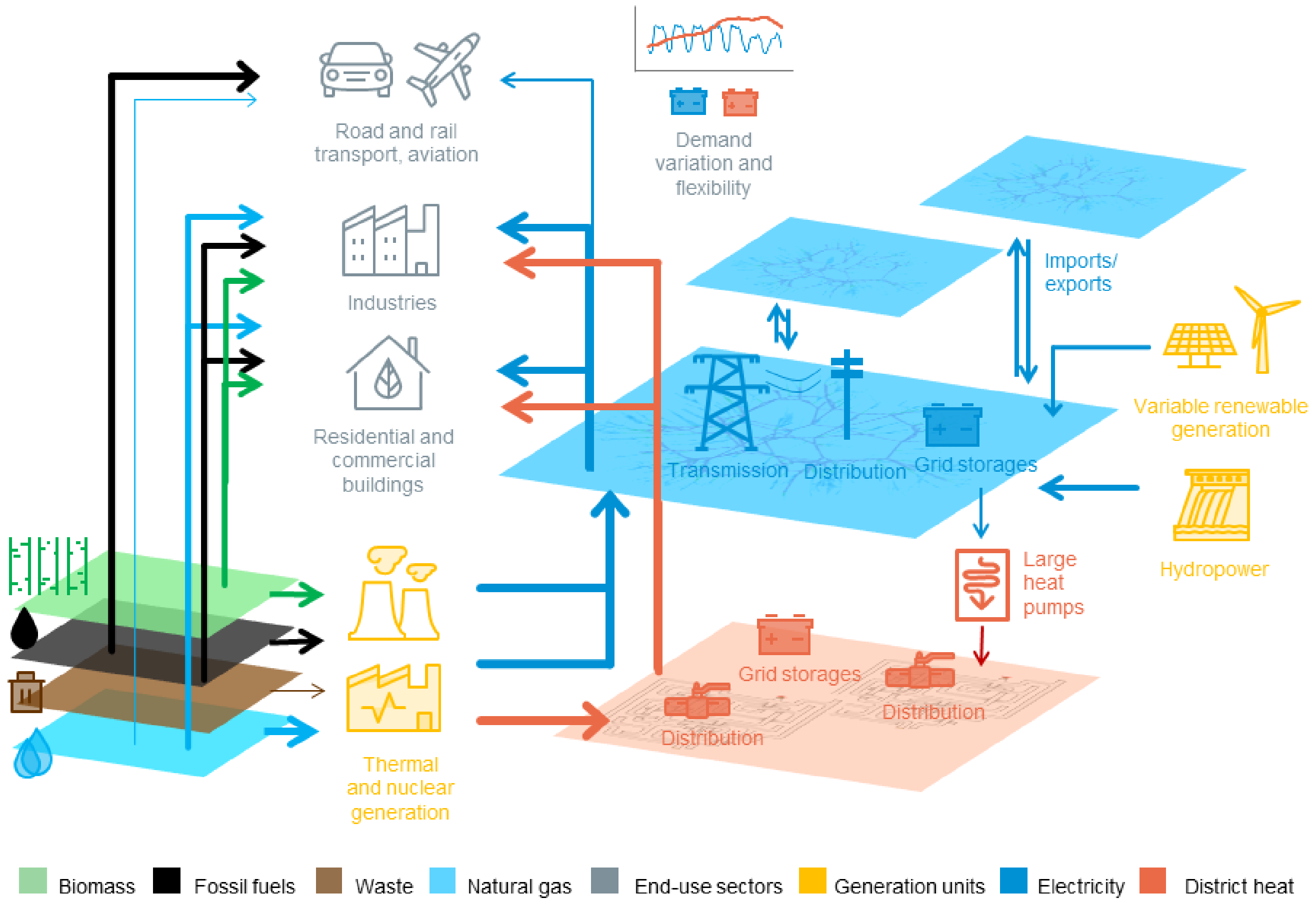
Bottom-Up Modeling
starts with detailed analysis of individual components and processes, providing granularity and suitability for specific technologies and local assessments.

Image source: Ha et al. (2016) Energy Demand Forecast Models for Commercil Buildings in South Korea

2 Models by sectoral scope



2 Integrated energy system optimization model



Key operation of the energy system relates to **balancing supply and demand at each time instant**.

This requires **cost-optimal dispatch decision** of generation units, optimal use of storages and power interconnectors and possible demand response under the technical, market and regulatory restrictions.

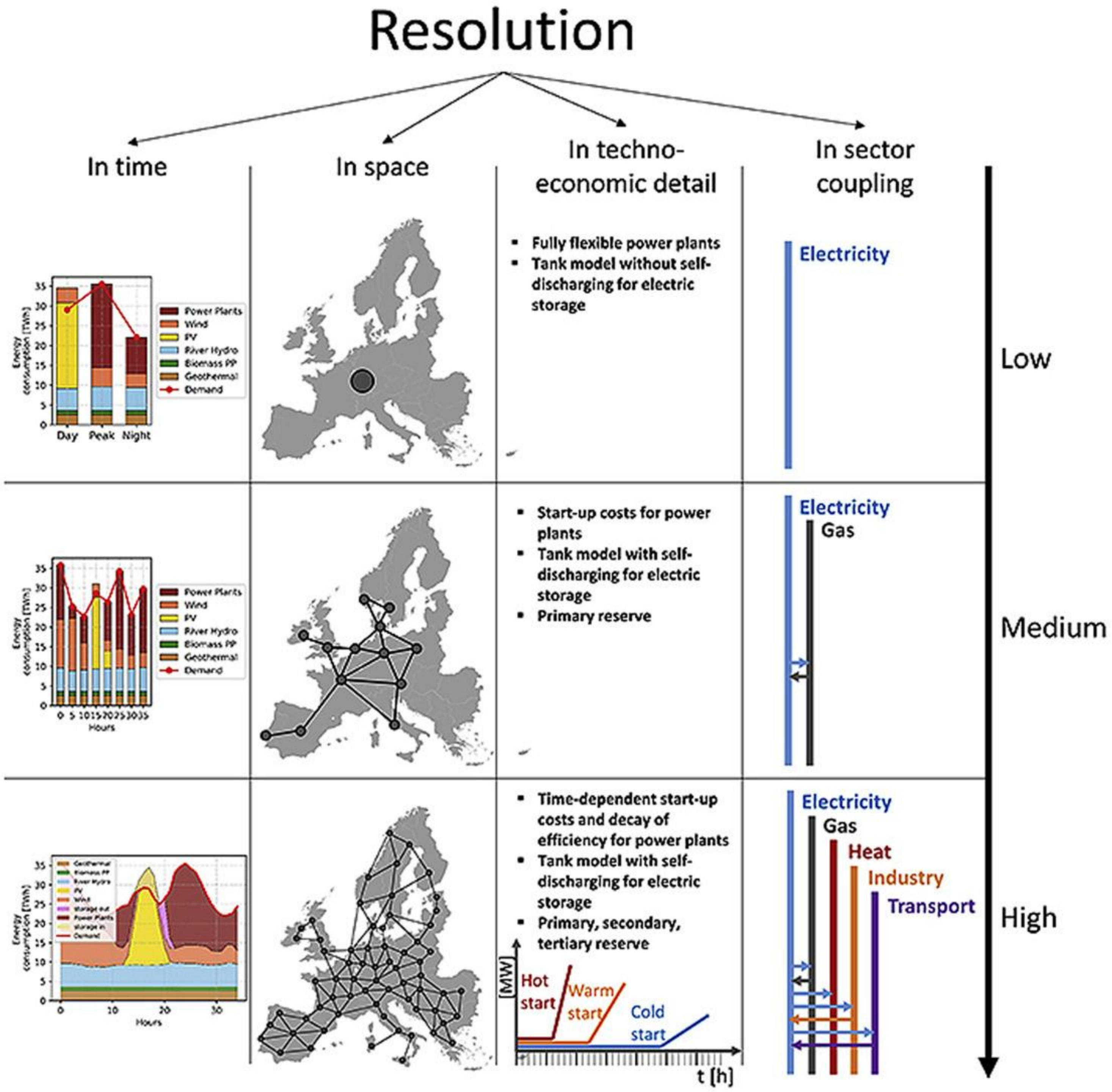
Planning of the energy system seeks optimal investments under uncertain future conditions. As the system grows increasingly complex, simultaneous consideration of many energy sectors becomes necessary.

2 Examples of resolution

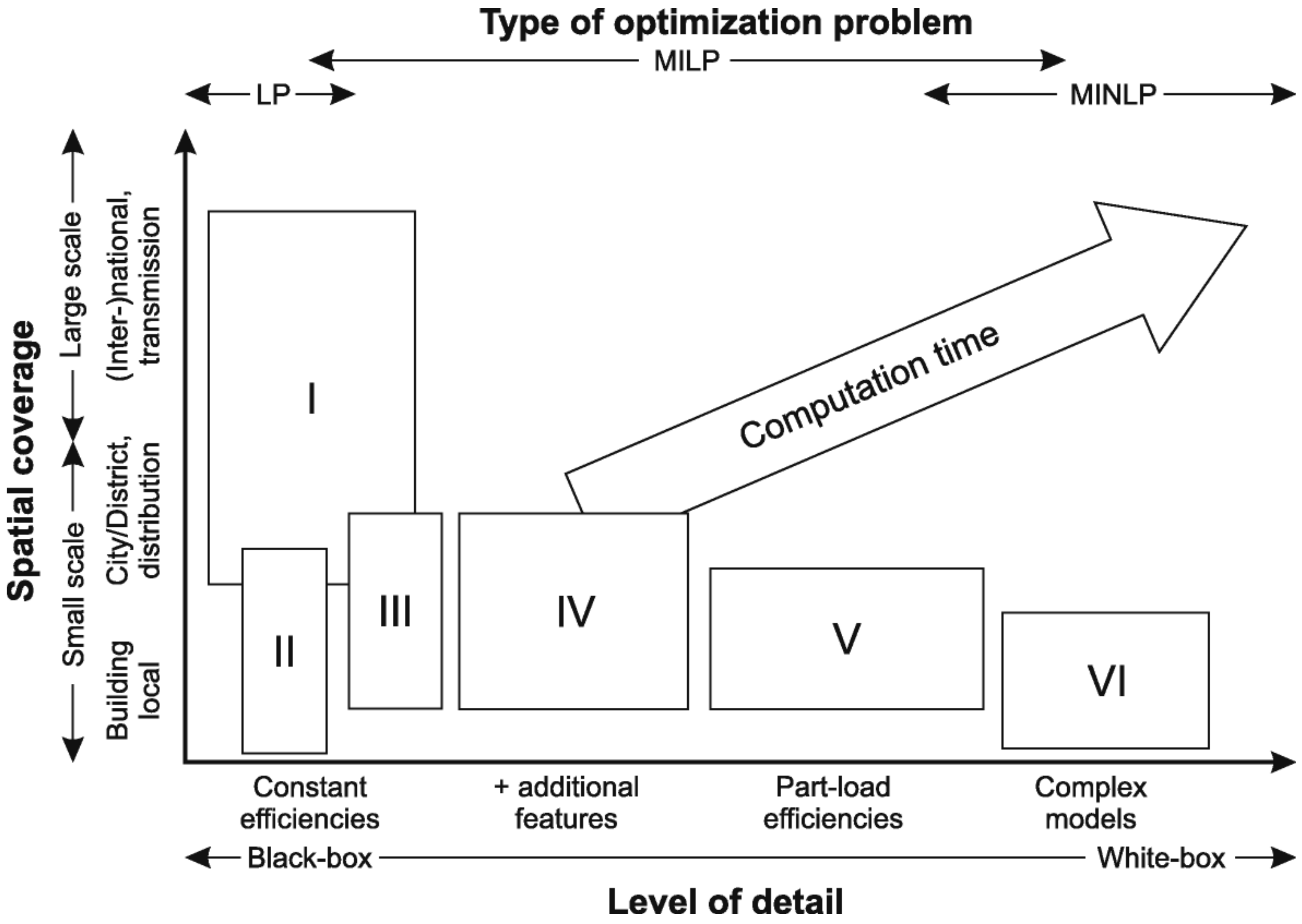
Time resolution from sub-hourly to annual

Spatial resolution from plant level to continental

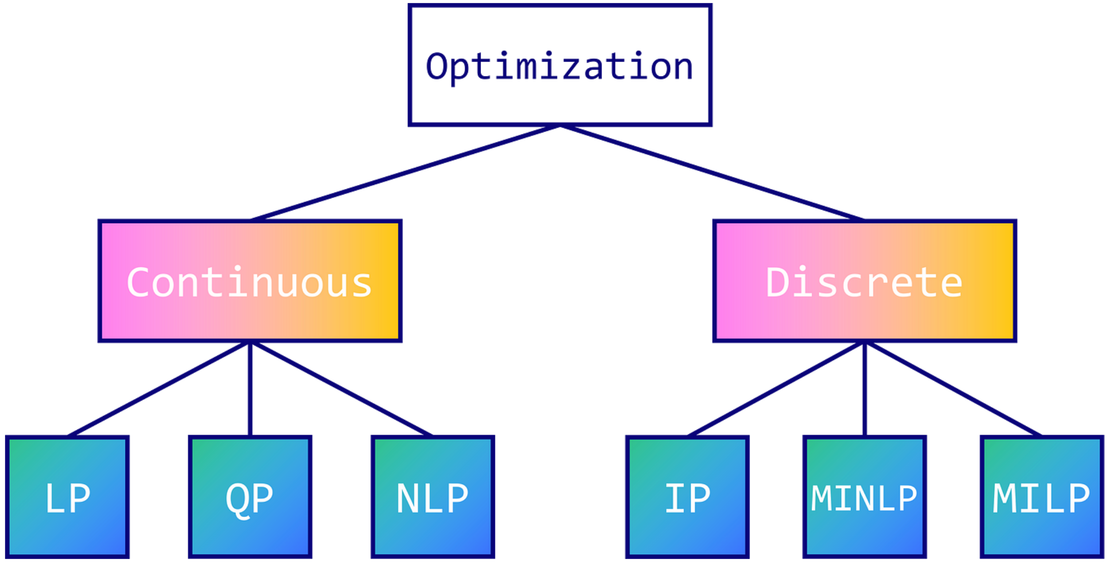
Techno-economic detail from linear aggregated to dynamic



2 Trade-off of resolution and computation time

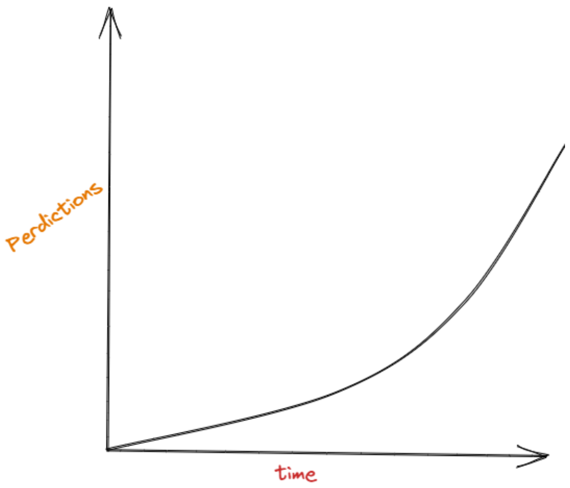
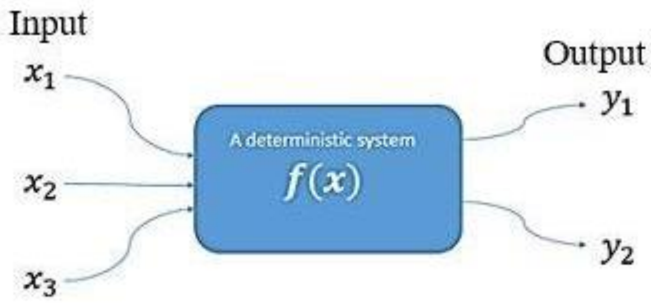
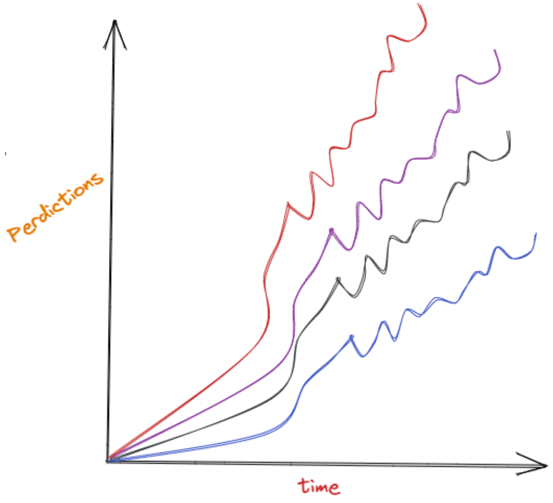
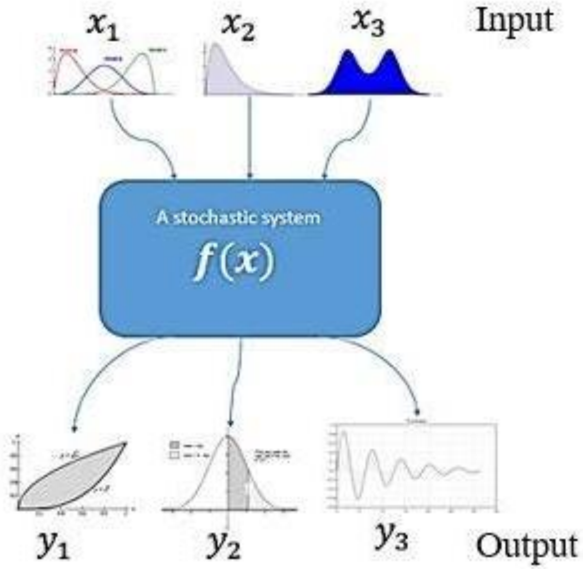


2 Linear and integer optimization programming



Method	Objective function	Constraints	Decision variables
Linear programming	Linear	Linear	Real numbers
Nonlinear programming	Can be nonlinear	Can be nonlinear	Real numbers
Integer linear programming	Linear	Linear	Integers
Mixed integer linear programming	Linear	Linear	Integers or real numbers
Integer nonlinear programming	Can be nonlinear	Can be nonlinear	Integers
Mixed integer nonlinear programming	Can be nonlinear	Can be nonlinear	Integers or real numbers

2 Stochastic vs. deterministic

	Reality	Model
Deterministic		
Stochastic		

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3 Why not have it all? Key constraints in all energy modelling

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1. **Data.** Availability and quality
2. **Uncertainty.** From inadeaqate knowledge / stochastics. Technological assumptions
3. **Resolution and computational limits.** Complexity and dimensionality, temporal and spatial resolution, time horizon, model integration and interoperability
4. **Model vs. reality.** Policy and regulatory constraints, behavioral factors, trade-offs and conflicting objectives, model calibration and validation
5. **Impact.** Communication and stakeholder engagement

As useful as modelling can be, we must accept something is always left in the dark: e.g. interannual variation, large or small scale, politically unviable options…

3 Additional constraints in optimization modelling

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1. Accounting for nonlinearities or linearizing complex interactions and feedbacks, such as market dynamics or behavior
2. Mixed-integer optimization slower to solve
3. Number of variables in complex energy systems – solver scalability
4. Accounting for variable renewable energy integration

3 Summary of optimization vs. simulation

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Optimization Models:

Advantages: Provide optimal solutions for specific objectives (e.g., cost minimization, emission reduction). Efficient for well-defined problems. Can handle large-scale systems. Can be used for optimization under uncertainty.

Limitations: Relies heavily on assumptions and simplifications. Might not capture the full complexity of real-world systems. Sensitive to input data and model parameters. Difficult to include some dynamic and behavioral aspects.

Simulation Models:

Advantages: Capture dynamic behavior over time. Can represent complex interactions and feedback loops. Suitable for analyzing the impact of policies and external shocks. Can include behavioral and technological heterogeneity.

Limitations: Computationally intensive for large-scale systems. Model calibration and validation might be challenging. May not find an explicit optimal solution for certain objectives.