Energy system integration

Modelling for energy systems design and integration

Lecture

Seth van Wieringen

5-12-2025

About me

Seth van Wieringen, energy modeller and consultant at Witteveen+Bos

2014 Started studying in Twente

Mechanical engineering

2021 Graduated from UTwente (SET and ME)

Thesis: cost-optimal energy systems under uncertainty

2022 Scenario study Nuclear Energy

On the role of nuclear energy in the energy system, commissioned by the Dutch parliament

2024 Energy mix and market dynamics of CO2-free energy 2035

With a strong focus on the NPE and the effects of it's targets under various scenarios

Content

Part 1	break	Part 2
45 minutes	*15 minutes*	*45 minutes*

Overview of modelling approaches

1. Need for modelling
2. Overview of approaches
3. ESI with models in practice

Understanding energy models

1. Modelling level of detail
2. Subsystems and components
3. Example case optimisation
4. Setting up a simple model

Energy system integration

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Need for modelling

Need for modelling – **driving factors**

- **The Dutch climate agreement**
  - Requires the integral Infrastructure outlook **(model study)**
  - Sets targets for renewability of energy
- **European Renewable Energy Directive** (RED III, 2018/2001/EU)
  - Requires carbon neutral electricity by 2035 and sets targets for industry
- **Transitioning from the current system to a fully renewable is complex**
  - New and unknown dynamics and dependencies
  - There is no real-life example on continental scale

What should policy makers and energy planners do to transition the energy system?

Need for modelling – **driving factors**

- **Typical research questions**
  - What targets should be set for offshore wind production?
  - What policies are best suited to reach our goals?

    (subsidies, incentives and market design)
  - What decarbonisation routes are best?
    - Optimal system integration?
    - Least cost for industry?
    - **Least societal cost?**

→ **Driven by this and above: ESI with optimisation models**

Need for modelling – **driving factors**

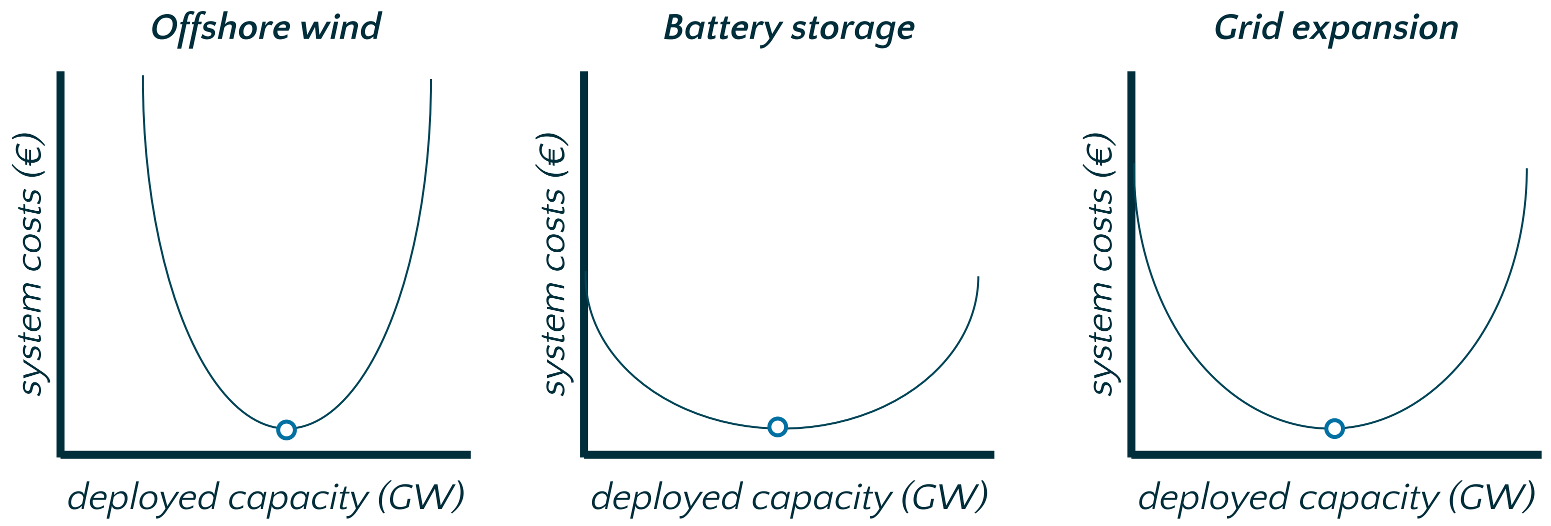
What should policy makers and energy planners do to transition the energy system?

- Intermittency and uncertainty complicates renewable energy grid planning.
- High renewable penetration increases system complexity.
- Integration challenges: various energy carriers and numerous energy system configurations.

How do we support this process using modelling?

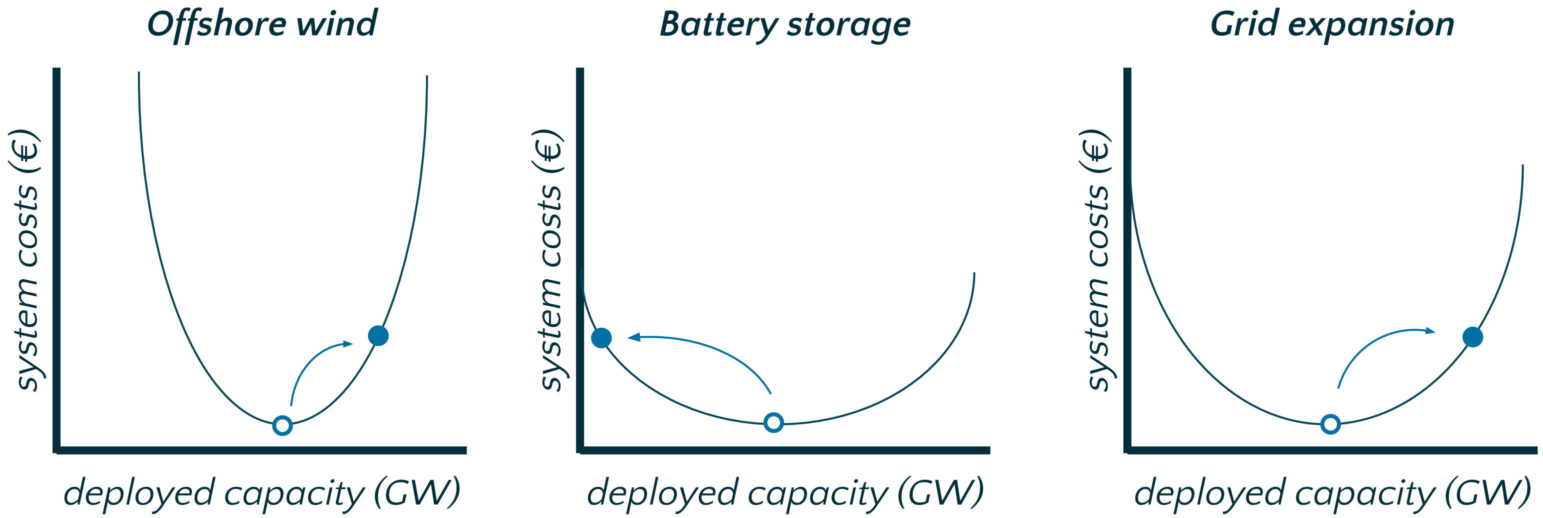
- Represent energy system components correctly
- Explorative use of modelling, investigate system dynamics

Need for modelling – **driving factors**



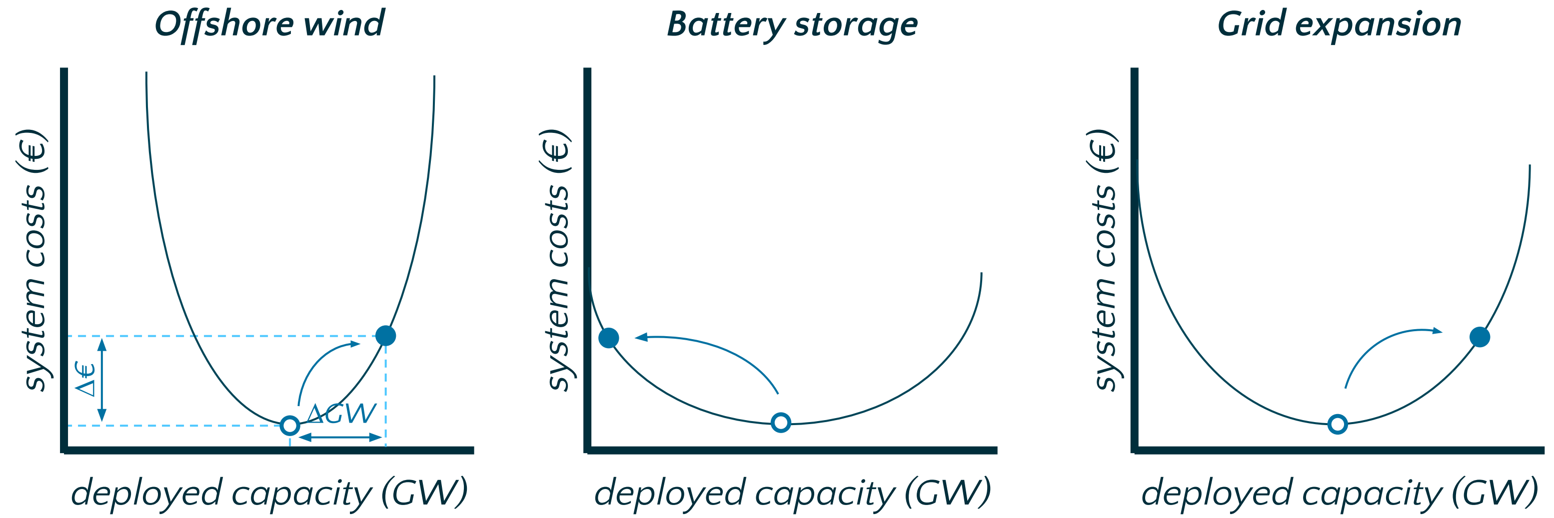
○ ***Optimal*** *system configuration/integration*

Need for modelling – **driving factors**



- ***Optimal*** *system configuration/integration*
- ***Alternative*** *system configuration/integration*

Need for modelling – **driving factors**



Optimal *system configuration/integration*

Alternative *system configuration/integration*

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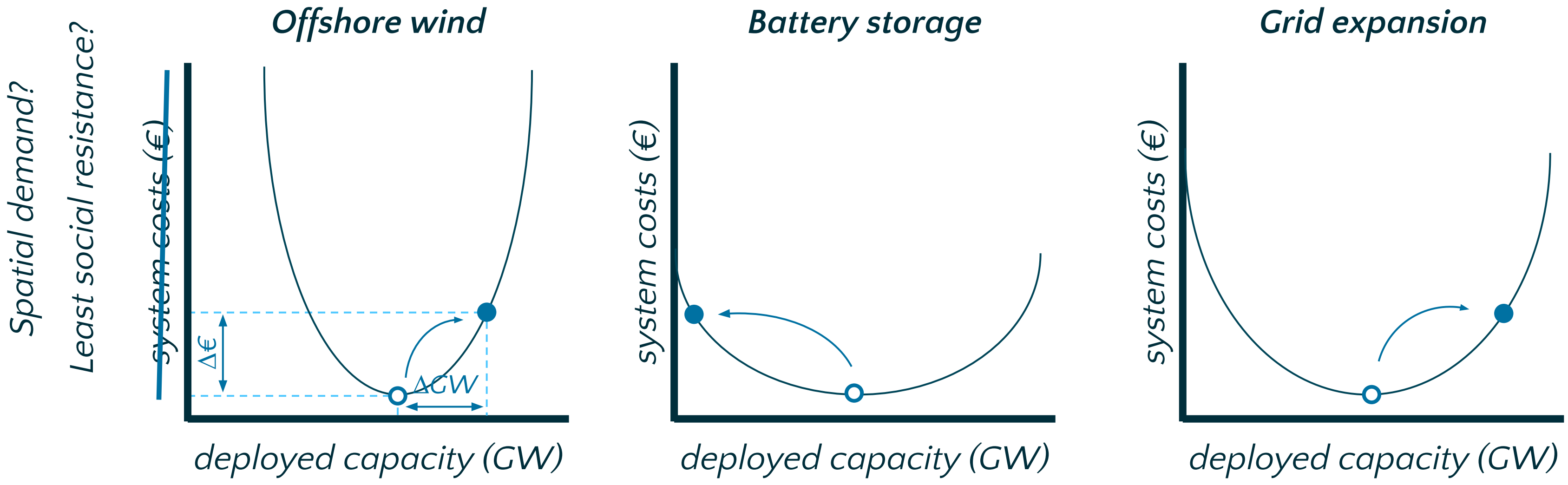
Need for modelling – **driving factors**



○ ***Optimal*** *system configuration/integration*

● ***Alternative*** *system configuration/integration*

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Overview of modelling approaches

Modelling approaches overview

Three most used modelling approaches for **energy planning**:

1.	Simulation	25%
2.	Optimisation	40%
3.	Agent based modelling	25%
4.	*Other*	*10%*

Academics

Modelling approaches overview

Three most used modelling approaches for **energy planning**:

1. Simulation **>50%**
2. Optimisation 30%
3. Agent based modelling 10%
4. *Other 10%*

In practice

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Modelling approaches overview

- **Perspective**

  Top down vs. bottom-up

- **Model type**

  Simulation, agent-based, system dynamics, IAM and optimisation

- **Model based research approaches**

  Scenario analysis, system/actor dynamics, sensitivity analysis and exploratory modelling

- **Model choices**

  Boundary conditions, endo/exogenous elements, temporal and spatial resolution

ABM

Modelling approaches overview

- **Perspective**

  Top down vs. **bottom-up**

- **Model type**

  Simulation, **agent-based**, system dynamics, IAM and optimisation

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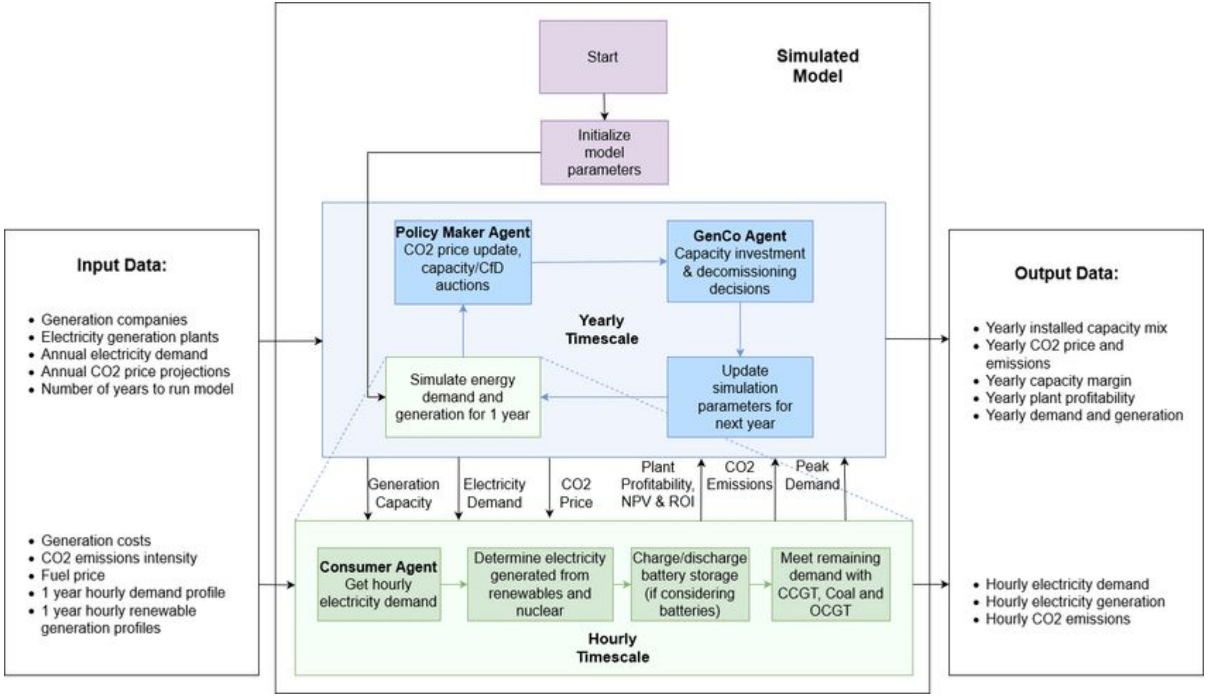
ABM

Modelling approaches overview



When to use ABM

1. System dynamics cannot be defined or are unknown
2. Good insight in individual (agentic) choices

Example research questions:

1. What is the resulting dynamic of a complex and agentic system?
2. How can we influence certain agents to reach the desired system state?

Examples in energy system modelling:

1. Energy markets modelling (game theory, imperfect/untransparent market dynamics)
2. Policy design targeting specific actors in the energy system (grid fees)

ESI with ABM

Advantages

1. Represents individual agents in the system and effect on them
2. Can provide insight into system dynamics as sum of agent actions even if top level dynamics are unknown

Disadvantages

1. Does not 'plan' towards a desired state, instead, it is a result of dynamics
2. Computationally very expensive at energy systems scale

Simulation models

Modelling approaches overview

- **Perspective**

  Top down vs. bottom-up

- **Model type**

  Simulation, agent-based, **system dynamics,** IAM and optimisation

- **Model based research approaches**

  Scenario analysis, sensitivity analysis and explorative modelling

- **Model choices**

  Boundary conditions, endo/exogenous elements, temporal and spatial resolution

ESI with simulation models

Advantages

1. Detailed representation of dynamics
2. Delivers explainable insights coupled with scenario analysis

Disadvantages

1. Places a lot of decisions variables outside of model function (e.g. loads of assumptions)
2. Insights as strong as input

Optimisation models

Modelling approaches overview

- **Perspective**

  Top down vs. bottom-up

- **Model type**

  Simulation, agent-based, **system dynamics, IAM and optimisation**

- **Model based research approaches**

  Scenario analysis, sensitivity analysis and explorative modelling

- **Model choices**

  Boundary conditions, endo/exogenous elements, temporal and spatial resolution

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ESI with optimisation models

Advantages

1. More complex dynamics can be placed inside model
2. Delivers outcomes based on boundaries and dynamics, not a cognitively biased storyline

Disadvantages

1. Less detailed for specific dynamics when compared to simulation
2. Result is based only on the objective function which might not align with real-world objective

Energy system integration

Modelling for energy systems design and integration

ESI modelling in practice

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Energy system integration in practice

Two examples

Grid outlook Netherlands

1. Simulation modelling
2. What are the demands on the grid system in 2040 and 2050?

TSO's, DSO's and various consultants

Netbeheer Nederland

National plan energy 2035

1. Optimisation modelling
2. What system and market dynamics around the NPE targets?

Witteveen+Bos and CE Delft

Ministry of Climate Policy and Green Growth

Energy system integration in practice

Two examples

Grid outlook Netherlands

National plan energy 2035

1) Gather assumptions
2) Define scenarios
3) Grid simulation
4) Data analysis
5) Reporting

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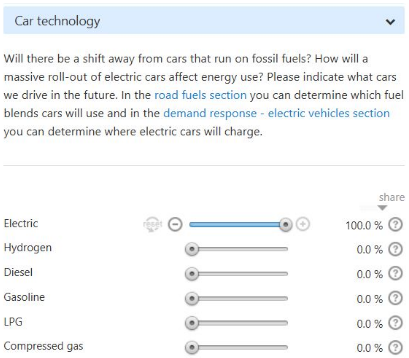
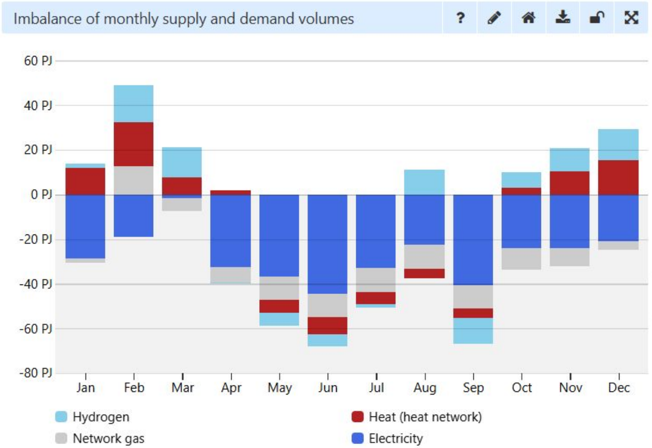
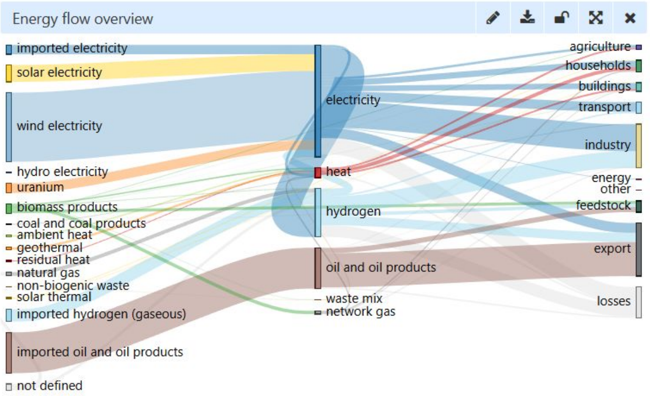
Grid outlook Netherlands

1) Scenario tooling in Energy Transition Model





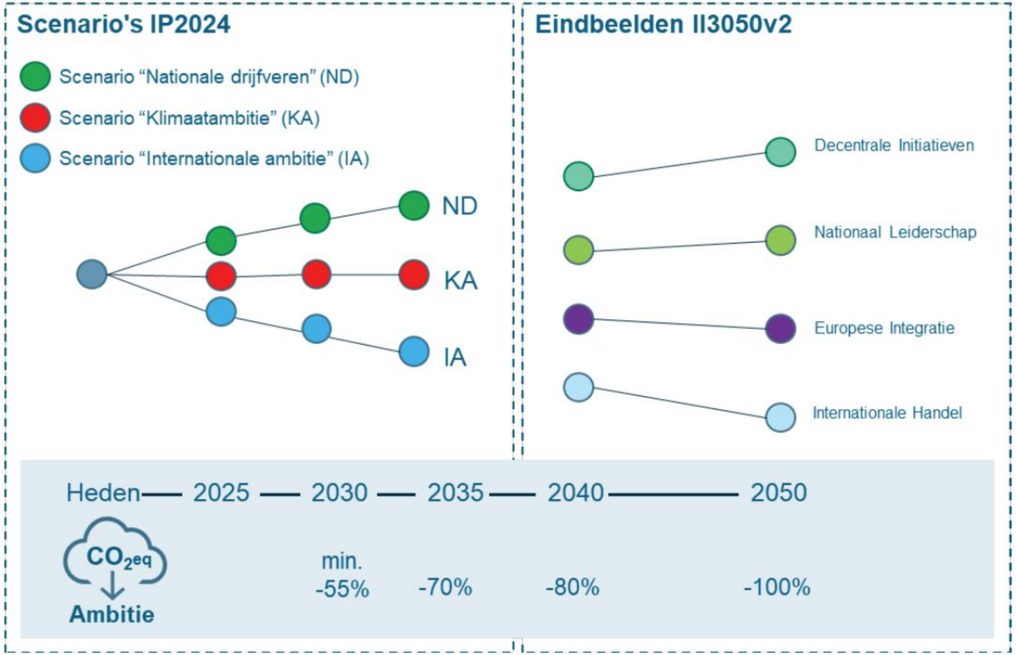


A) 850+ input assumptions

B) Analyse energy balance and flows

Grid outlook Netherlands

1) Scenario tooling in Energy Transition Model
2) Define scenarios based on distinct narratives

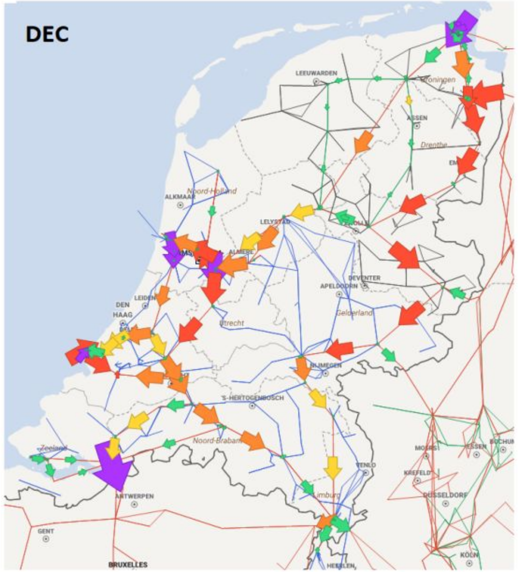


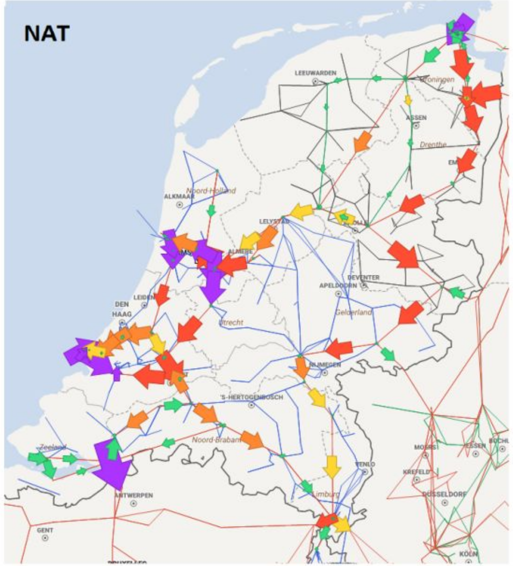
Grid outlook Netherlands

1) Scenario tooling in Energy Transition Model

2) Define scenarios based on distinct narratives

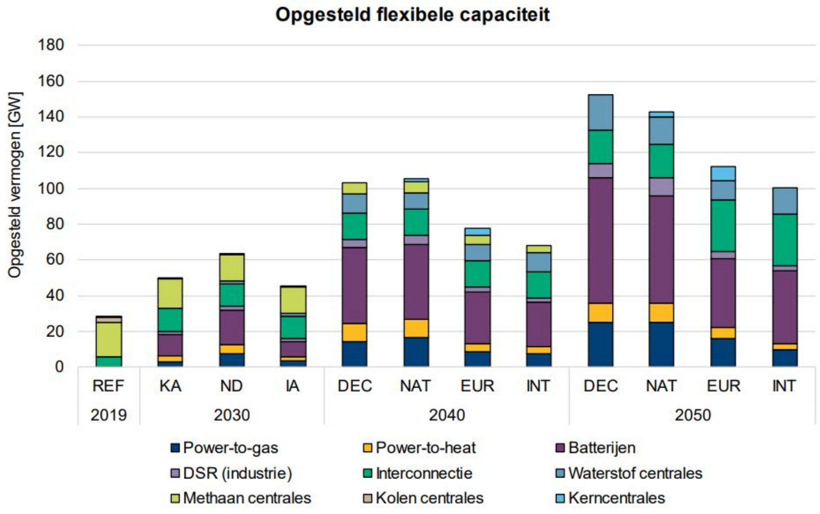
3) Grid simulation

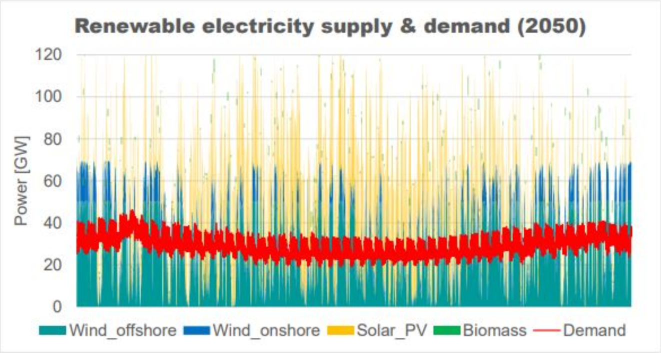


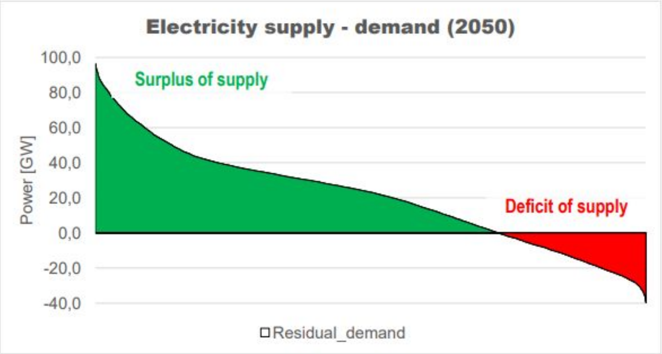


Grid outlook Netherlands

1) Scenario tooling in Energy Transition Model
2) Define scenarios based on distinct narratives
3) Grid simulation
4) Data analysis and interpretation







Grid outlook Netherlands

1) Scenario tooling in Energy Transition Model
2) Define scenarios based on distinct narratives
3) Grid simulation
4) Data analysis and interpretation
5) Reporting

… leads to:

- Grid investment planning
- Project development and tendering (e.g. offshore wind lots)
- Spatial planning (e.g. housing, industry lots and utilities)

Remember the goal!

1. **Discover and analyse optimal system integration configuration**

   This type of problem is a synthesis problem

   (= to co-optimize both the components and their interaction at the same time)

   1. *E.g. what is the optimal capacity of wind generation given grid connection and battery? When to charge? When to import energy? When to curtail? Etc.*

Remember the goal!

1. **Discover and analyse optimal system integration configuration**

   This type of problem is a synthesis problem
2. To do this, we should integrate all interactions and decision variables into the model, and co-optimize them in an integral approach:
    1. Storage
    2. Conversion
    3. Transport
    4. Generation
    5. Loads

Energy system integration in practice

Two examples

Grid outlook Netherlands

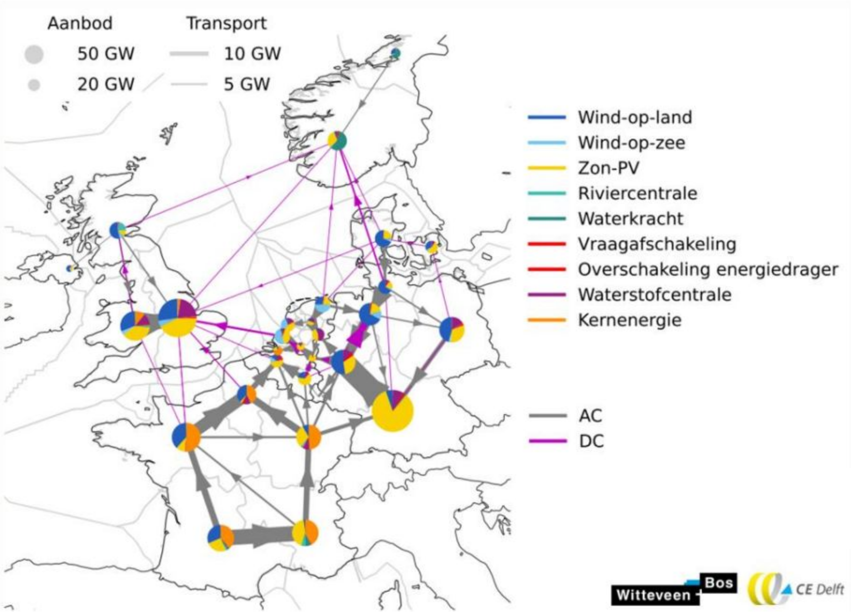
1) Gather assumptions
2) Define scenarios
3) Grid simulation
4) Data analysis
5) Reporting

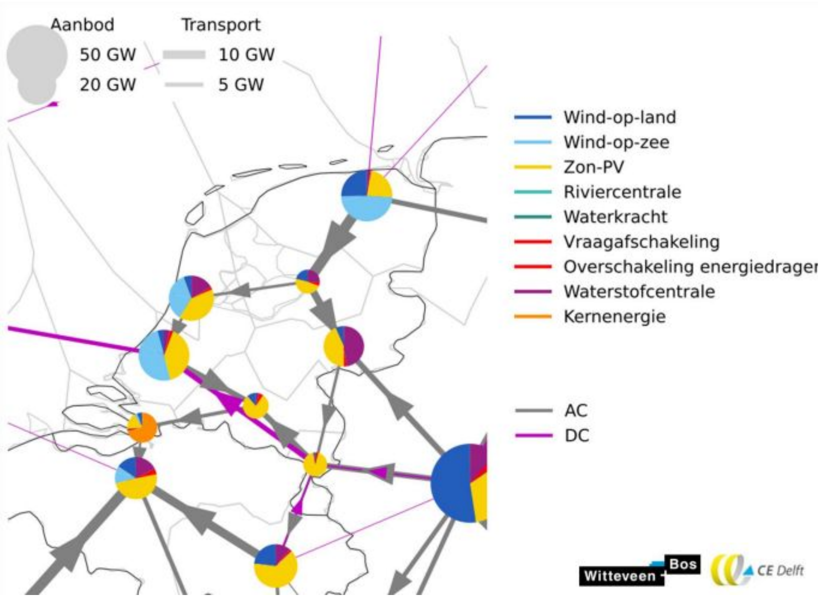
National plan energy 2035

1) Set up model configuration
2) Define scenario’s (boundaries)
3) Solve synthesis problem
4) Data analysis
5) Reporting

National plan energy 2035

Model configuration





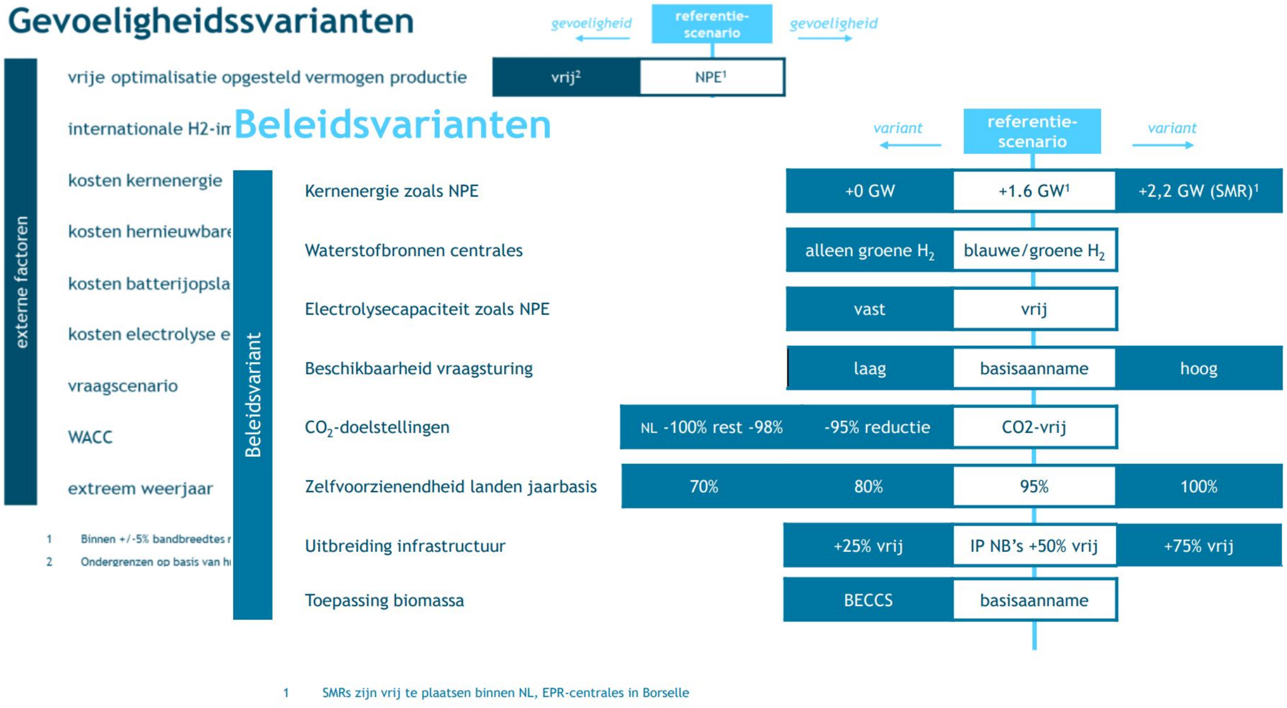
National plan energy 2035

Scenario definition

Sensitivity analysis!

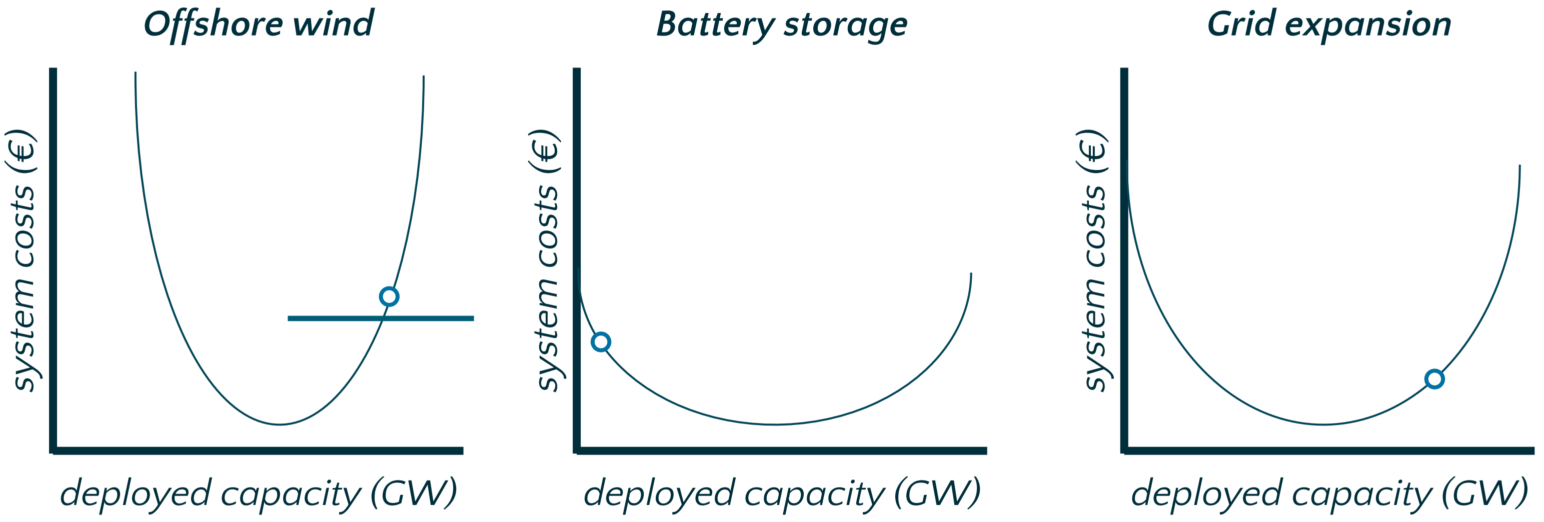
1 reference

30+ variants



National plan energy 2035

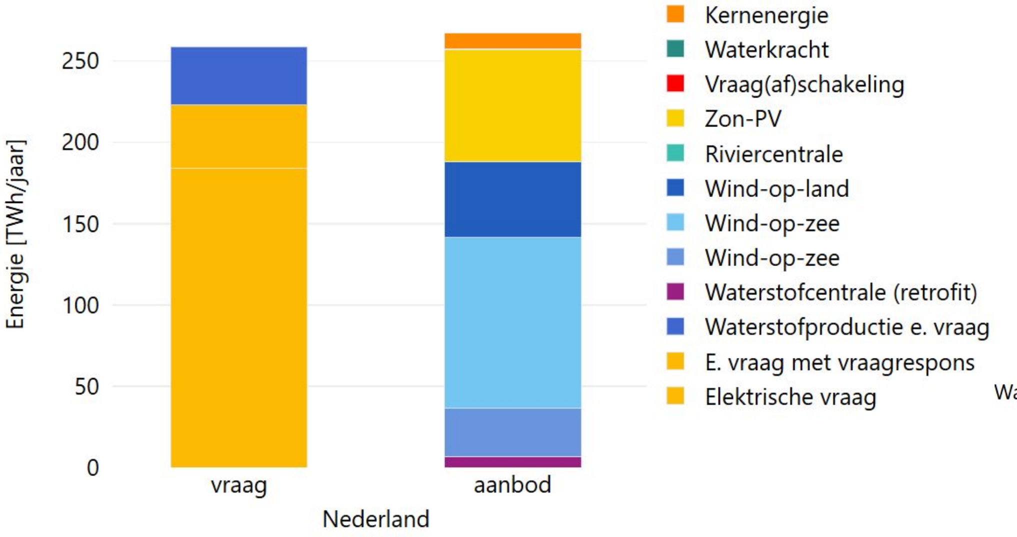
Solve synthesis problem

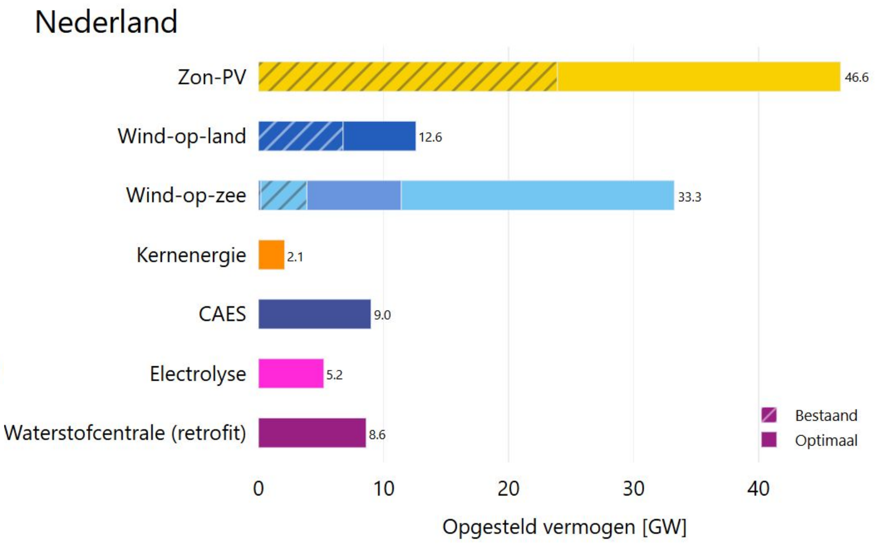


Optimal *system configuration/integration*
within boundary conditions of NPE

National plan energy 2035

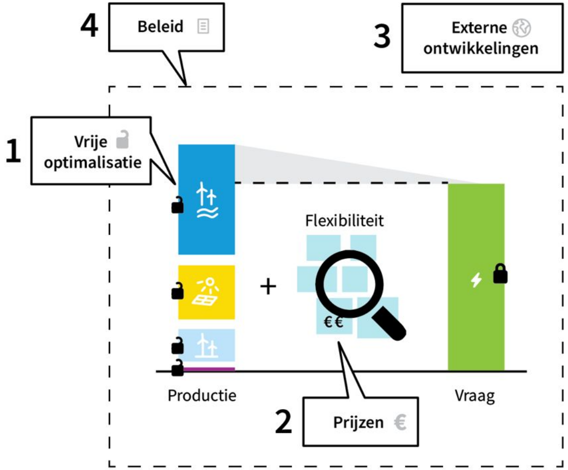
Data analysis

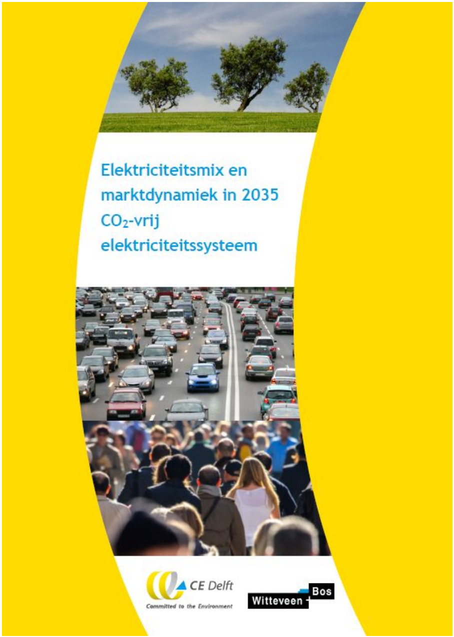




National plan energy 2035

Reporting





... leads to:

- Policy and market redesign
- Flex agenda (bill to the Parliament)
- Public insights for project developers and other energy experts

Energy system integration

Modelling for energy systems design and integration

Lecture

Part 2

Seth van Wieringen

5-12-2025

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Content

Part 1	break	Part 2
45 minutes	*15 minutes*	*45 minutes*

Overview of modelling approaches

1. Need for modelling
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Understanding energy models

1. Modelling level of detail
2. Subsystems and components
3. Example case optimisation
4. Setting up a simple model

Energy system integration

Modelling for energy systems design and integration

Modelling level of detail

Level of detail

1. Temporal resolution
2. Spatial resolution
3. Geographic coverage

Level of detail

1. Temporal resolution (time step)

<< 15 min	domain of grid operation and control systems
15 min	grid balancing
1 hour	generation, transmission, storage and energy carrier integration
3 hours	minimal resolution to represent renewable energy dynamics for grid planning

2. Spatial resolution
3. Geographic coverage

Level of detail

1. Temporal resolution
2. Spatial resolution

   1 node market model (per bidzone), local energy system (energy hub)

   8 nodes represent the pocket structure of the Dutch HV network (TenneT)

   50 nodes Actual Dutch HV network (TenneT)

   1000+ nodes Dutch electricity grid to 10/20 kV level (DSO, distribution)

1. Geographic coverage

Level of detail

1. Temporal resolution
2. Spatial resolution
3. Geographic coverage

Too small	Overestimate need for storage or back up power (autarky)
Too large	Computationally expensive so pressure on other details
Sweet spot	Depends on the research question and energy system scope

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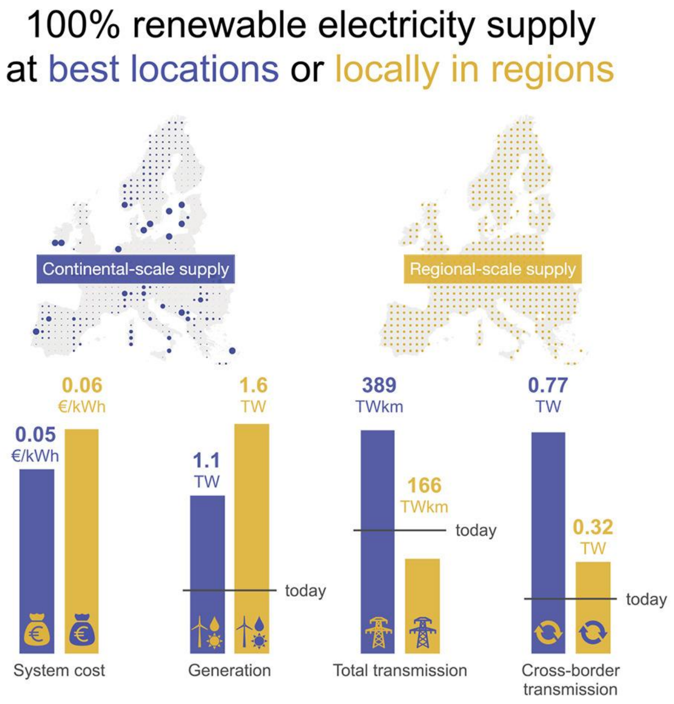
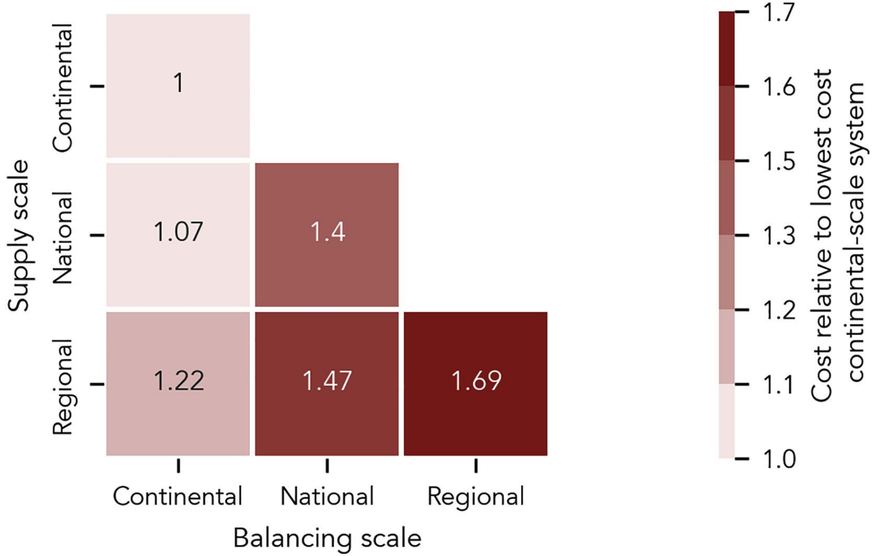
Level of detail

1. Temporal resolution
2. Spatial resolution
3. Geographic coverage

Goal: Balance these three to reflect your research questions and keep the problem computationally achievable

Level of detail – Geographic coverage





Trade-Offs between Geographic Scale, Cost, and Infrastructure Requirements for Fully Renewable Electricity in Europe
Tröndle, Tim et al.
Joule, Volume 4, Issue 9, 1929 – 1948

Level of detail – Geographic coverage

Why?

1. Interconnection is spatially analogous to storage (shift in space, not in time)
2. Renewable energy generation has poor correlation on continental scale

   The wind will always blow somewhere, if not; it must be sunny
3. Sharing of back-up power over regions
4. Autarkic systems are nearly always more expensive

   Only exception: grid connection extremely expensive (e.g. on top of a mountain)

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Optimisation modelling using LP

Optimisation using LP

- Linear programming
- Really one big matrix that represents (approximates) system dynamics, e.g.
  - *Wind turbines can't produce more than physically possible at time instance*
  - *Storage can't increase stored energy without withdrawing energy from grid*
  - *Load should be met at all times*
  - *Conservation of energy*

- Really sensitive to assumptions
  - Optimisation without sensitivity analysis is not optimisation *but a lucky guess*

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Approach – optimisation using LP

1. Represent all decisions variables as linear relations i.e. make a huge matrix
    1. Typical problem is > 1 million rows, > 10 millions columns

2. Represent dynamics of intermittent resources, storage and transport in (linearized equations)

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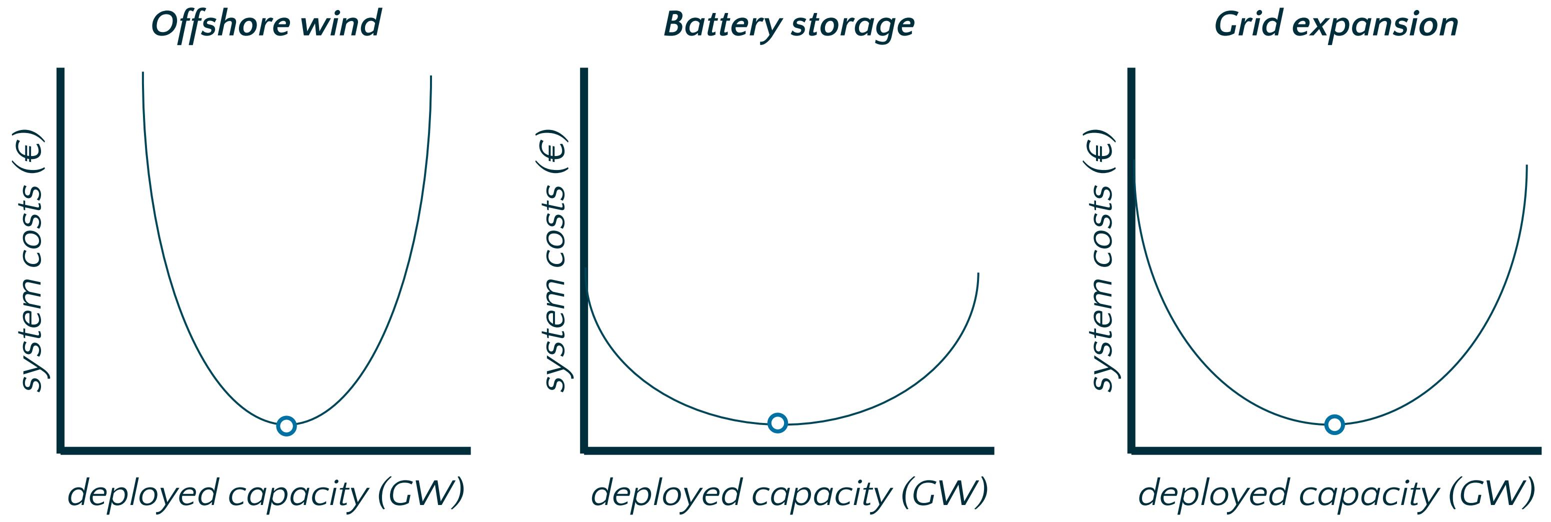
Visual representation – optimisation using LP



○ ***Optimal*** *system configuration/integration*

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Modelling subsystems

Subsystems

An energy system consists of various distinct subsystems that need to be modelled

1. **Renewable energy sources**	Wind, solar, hydro	Insert energy
2. **Dispatchable energy sources**	(Hydrogen) gas turbines	Insert energy
3. **Conversion**	P2H, P2gas	Modal change
4. **Transmission**	AC, DC, gas pipeline	Spatial change
5. **Storage**	Li-ion, flow, pumped hydro	Temporal change
6. **Loads**	Electricity demand	Extract energy

Subsystems – renewable energy generation

- **Renewable energy sources** Wind, solar, hydro

$$f\big(x(t)\big) = P(t)$$

Some transfer function of a time-dependent variable *yields* *Power generation over time*

Subsystems – renewable energy generation

- **Renewable energy sources** Wind, solar, hydro

- Why? We need to represent the intermittent and weather-dependent dynamics

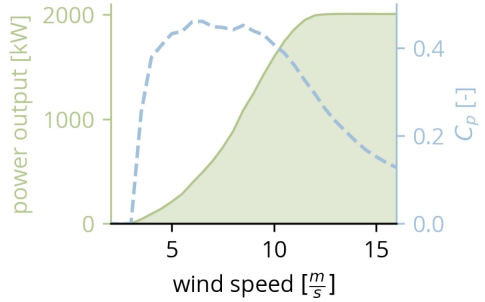
Subsystems – Example of wind

$$P_{wind} = \frac{1}{2}\rho A v^3 \eta c_p$$

Turbine specifications

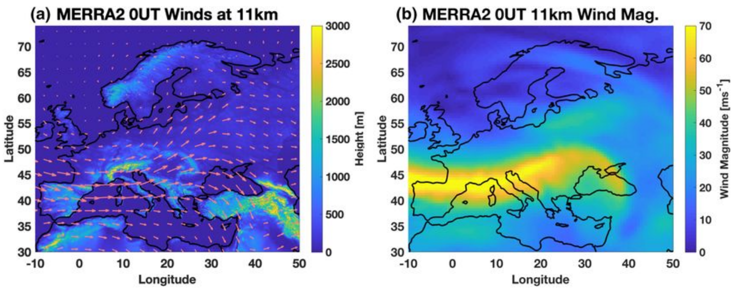
1. Hub height
2. Power curve
3. Rotor area

$$v(H) = \mathrm{v_{ref}} \frac{\ln (H/z_0)}{\ln (\mathrm{H_{ref}}/z_0)}$$



Time and space dependent variables

1. Density
2. Windspeed



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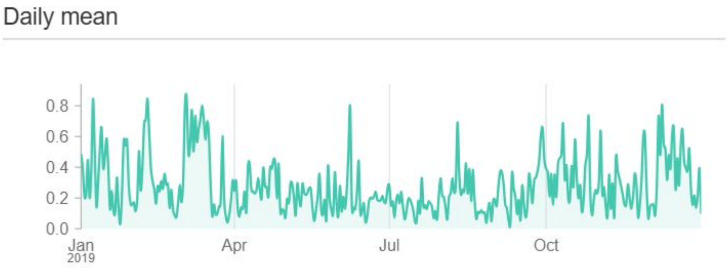
Subsystems – Example of wind

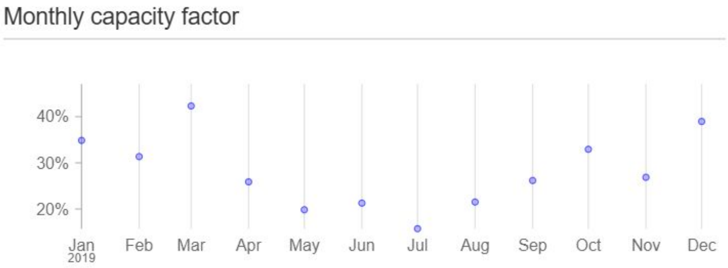
Select wind turbine (e.g. Vestas V90)

Select weather dataset (e.g. MERRA2 for 2012)

Apply sub model to implement dynamics (system-coupling)

Try it yourself!
https://renewables.ninja/





Subsystems – storage

Storage Li-ion, flow, pumped hydro

Energy stored $E(t) \leq E_{max}$ *Storage capacity*

with: t, time $\forall t \in [t_{min}, t_{max}]$

$E_t = E_{t-1} + \eta P_t$ *Charge/discharge x efficiency*

with: t, time $\forall t \in [t_{min} + 1, t_{max} - 1]$

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Case example optimisation

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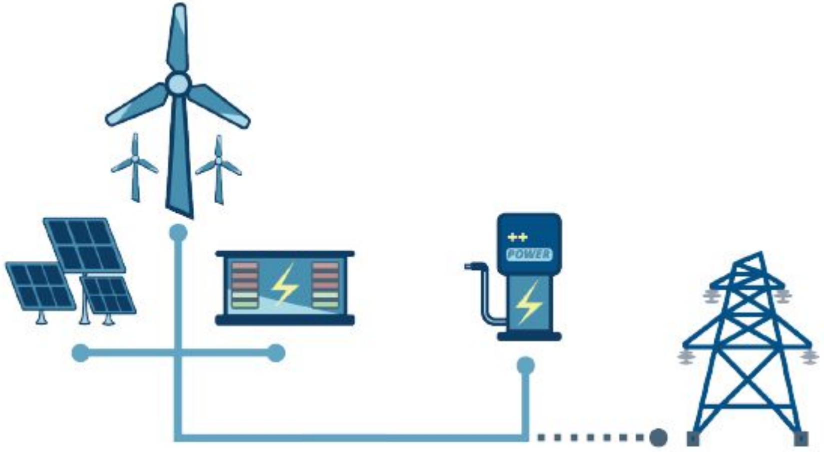
Case example optimisation

Overview

Energy hub

- Loading demand
- Decentral energy generation
  - Wind
  - Solar
- Battery storage
- Soft coupled to grid



Case example optimisation

Subsystems

An energy system consists of various distinct subsystems that need to be modelled

• **Renewable energy sources**	Wind, solar	Insert energy
• **Transmission**	AC	Spatial change
• **Storage**	Li-ion	Temporal change
• **Loads**	Electricity demand	Extract energy

Case example optimisation

Input parameters

- Charging demand curve must be fulfilled
- Grid price curve for import
- Cost of subsystems (storage, wind and solar)
- Timeseries for solar and wind
- Maximum grid capacity

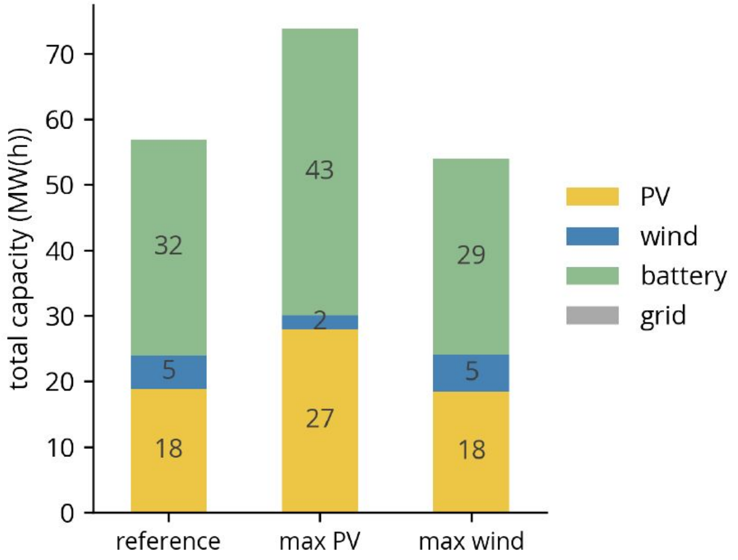
Case example optimisation

Input parameters

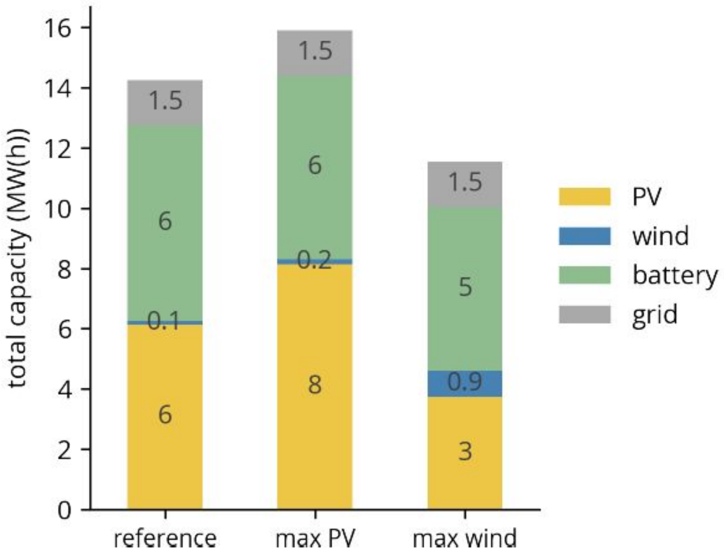
- Charging demand curve must be fulfilled <- **peak load 2.5 MW**
- Grid price curve for import <- **Future energy scenario**
- Cost of subsystems (storage, wind and solar) <- **Sweep over cost projection**
- Timeseries for solar and wind
- Maximum grid capacity <- **0 or 1.5 MW**

Results

0 MW grid



1.5 MW grid



Energy system integration

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Setting up a simple model

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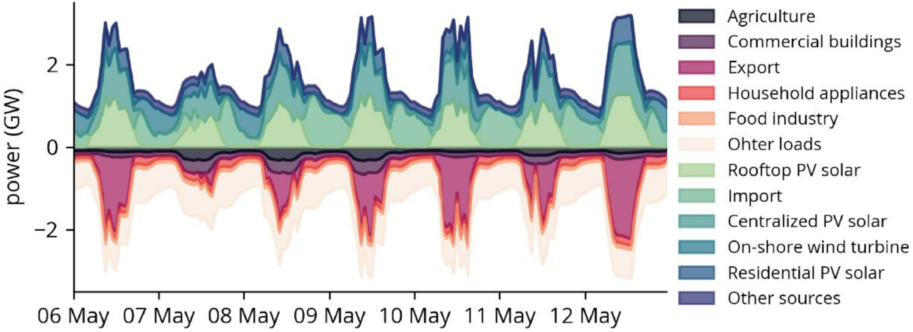
Setting up a simple model

- Single node model of Dutch electricity
- Based on grid outlook scenario
- Only renewables or battery storage
- No import/export



Setting up a simple model

- We will use PyPSA (Python for Power System Analysis)

"The aim of this project is to provide an open-source python environment for state-of-the-art energy system modelling."

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Karlsruher Institut für Technologie

THE UNIVERSITY of EDINBURGH

Setting up a simple model

Step 1: loading data

```python
from pypsa import Network
import pandas as pd


# Load timeseries data
ts = pd.read_csv("data/timeseries.csv", index_col=0, header=0)
# trim to 4 weeks
ts = ts[0:672]
# load costs
costs = pd.read_csv("data/costs.csv", index_col=0, header=0)
```

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Step 2: initialize network model

```python
# initialize network
n = Network()
# set snapshots based on timesteps
n.set_snapshots(ts.index)
# add buses
n.add("Bus", "electricity")

```

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Step 3: add components

```python
# add load
n.add(
    "Load",
    "demand",
    bus="electricity",
    p_set=ts.load,
)

# add solar and wind
for tech in ["wind", "solar"]:
    n.add(
        "Generator",
        tech,
        bus="electricity",
        p_max_pu=ts[tech],
        capital_cost=costs.at[tech, "capital_cost"],
        marginal_cost=costs.at[tech, "marginal_cost"],
        p_nom_extendable=True,
    )
```

```python
# add storage
EP_RATIO = 6
n.add(
    "StorageUnit",
    "battery storage",
    bus="electricity",
    max_hours=EP_RATIO,
    capital_cost=costs.at["battery inverter", "capital_cost"]
    + EP_RATIO * costs.at["battery storage", "capital_cost"],
    efficiency_store=costs.at["battery inverter", "efficiency"],
    efficiency_dispatch=costs.at["battery inverter", "efficiency"],
    p_nom_extendable=True,
    cyclic_state_of_charge=True,
)
```

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Step 4: solving model using HiGHS (open source solver)

```python
# Solve network
n.optimize(solver_name="highs")

```

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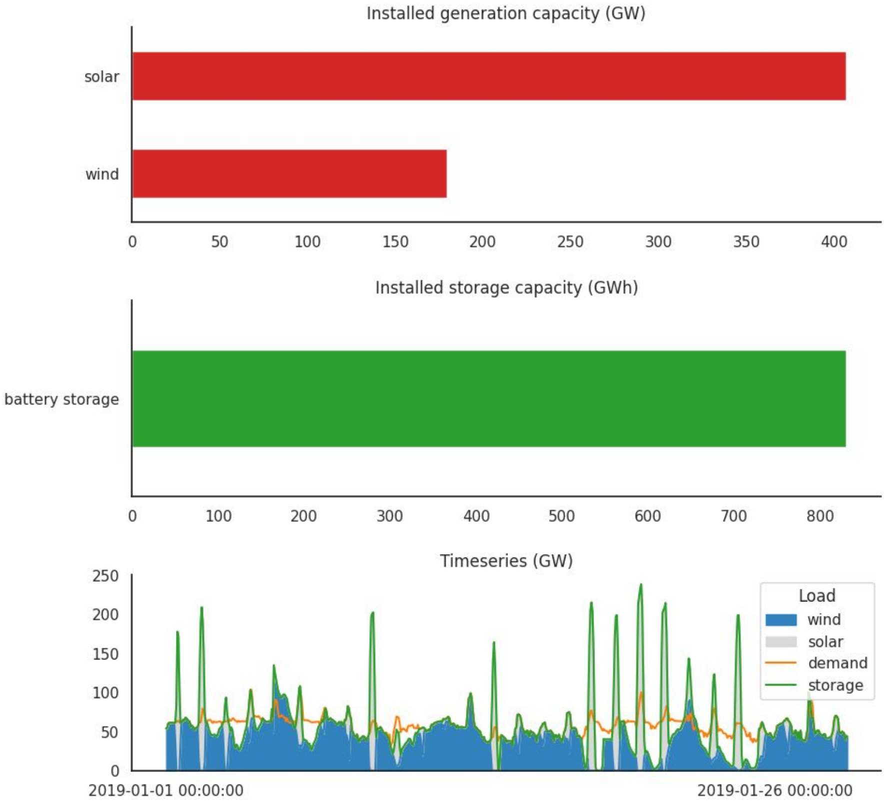
Step 5: plot results

```python
mport seaborn as sns
import matplotlib.pyplot as plt

fig, ax = plt.subplots(3, 1, figsize=(10, 10))
plt.subplots_adjust(hspace=0.4)

sns.set_theme("notebook", style="white")
n.generators.p_nom_opt.div(1e3).plot(
    ax=ax[0], kind="barh", title="Installed generation capacity (GW)", color="tab:red"
)
n.storage_units.p_nom_opt.div(1e3).mul(EP_RATIO).plot(
    ax=ax[1], kind="barh", title="Installed storage capacity (GWh)", color="tab:green"
)

# Calculate storage relative to load
storage_rel_to_load = n.loads_t.p["demand"] - n.storage_units_t.p["battery storage"]
storage_rel_to_load.index = n.generators_t.p.index
storage_rel_to_load = storage_rel_to_load.to_frame()


n.generators_t.p.plot(
    ax=ax[2], kind="area", title="Generation (MW)", legend=False, color="tab:blue"
)

n.loads_t.p.plot(ax=ax[2], kind="line", color="tab:orange")
storage_rel_to_load.plot(
    ax=ax[2], kind="line", title="Storage (MW)", legend=False, color="tab:green"
)


ax[2].set_xticks(range(0, len(ts.index), 24))


for axx in ax:
    sns.despine(ax=axx, top=True, right=True)
    axx.set_ylabel("")
    axx.set_xlabel("")

```



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Review this at your own pace and try it out

https://github.com/thesethtruth/esi-course-utwente/blob/main/lecture/lecture-case-example.py

Or a more advanced version

https://pypsa.readthedocs.io/en/latest/examples/capacity-expansion-planning-single-node.html#Simple-capacity-expansion-planning-example

Installation guide PyPSA

This will also be available as PDF on Canvas

https://github.com/thesethtruth/esi-course-utwente/blob/main/installation-guide.md

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