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Energy System Modelling for Transition to a net-Zero 2050 for EU via REPowerEU

Performante Modellierung des Wettbewerbs von Flexibilitäten am Strommarkt

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Motivation

Flexibility modelling with AMIRIS

Transformation to **renewable-dominated** energy system

> Rising shares of fluctuating renewable energies
> Merit-order effect: falling market values of RES
> Refinancing uncertain

More **flexibility options** are installed

> New flexibility technologies emerge
> Increasing competition: falling margins
> Refinancing uncertain

Aim

- Understand **market effects** of renewables and flexibilities
- Consider **actors' behaviour**, uncertainty and market distortions caused by regulatory framework
- Study **policy instruments** to incite system-friendly investment and operational decisions

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AMIRIS: Overview

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AMIRIS

Agent-Based Market Model for the Investigation of Renewable and Integrated Energy Systems

- **Agent-based** model for power markets
- Models **business-oriented** dispatch decisions under different regulatory framework conditions
- Focus on **renewable** energy sources and **flexibility** options
- Developed **open source** without copyleft

https://wonderl.ink/@amiris

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AMIRIS

Agent-Based Market Model for the Investigation of Renewable and Integrated Energy Systems

- Simulates **trading** of supply and demand
- Considers **uncertainty** and market distortions
- Resolution: hourly (temporal) – market zones (spatial)
- Runs yearly simulations on laptops in less than a minute

https://wonderl.ink/@amiris

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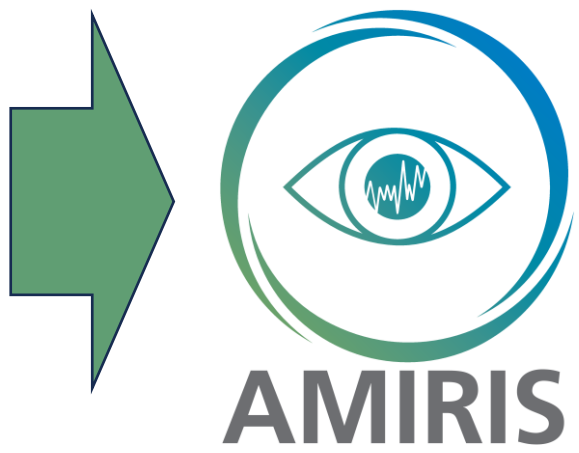
Input & Output

Input

- Power plant park
  - Efficiencies
  - Outages
  - Feed-in potential
- Demand
- Fuel prices
- CO_2 prices



Output

- Electricity prices
- Power plant dispatch
- Market values
- CO_2 emissions
- System costs
- Costs for support instruments

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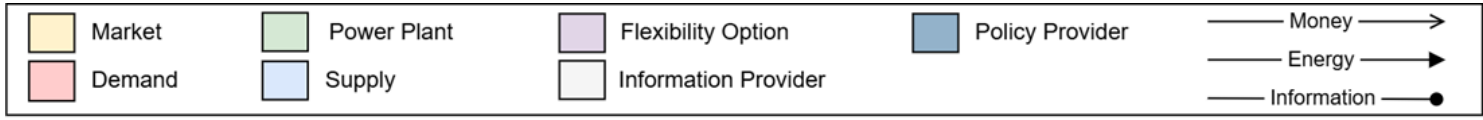
AMIRIS

Agent types



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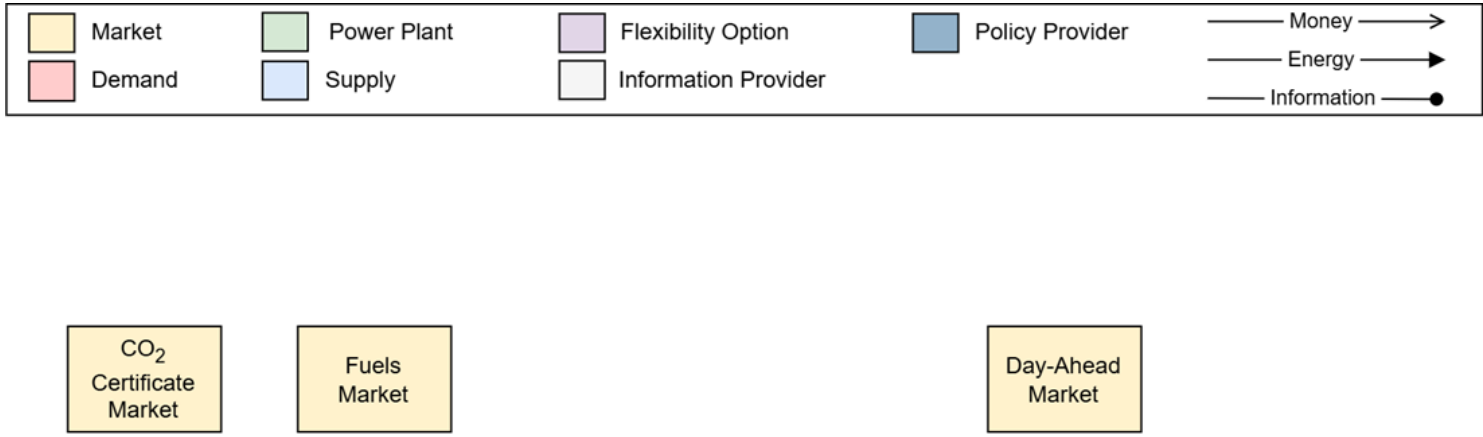
AMIRIS

Agent types

Markets

- Determine prices



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AMIRIS

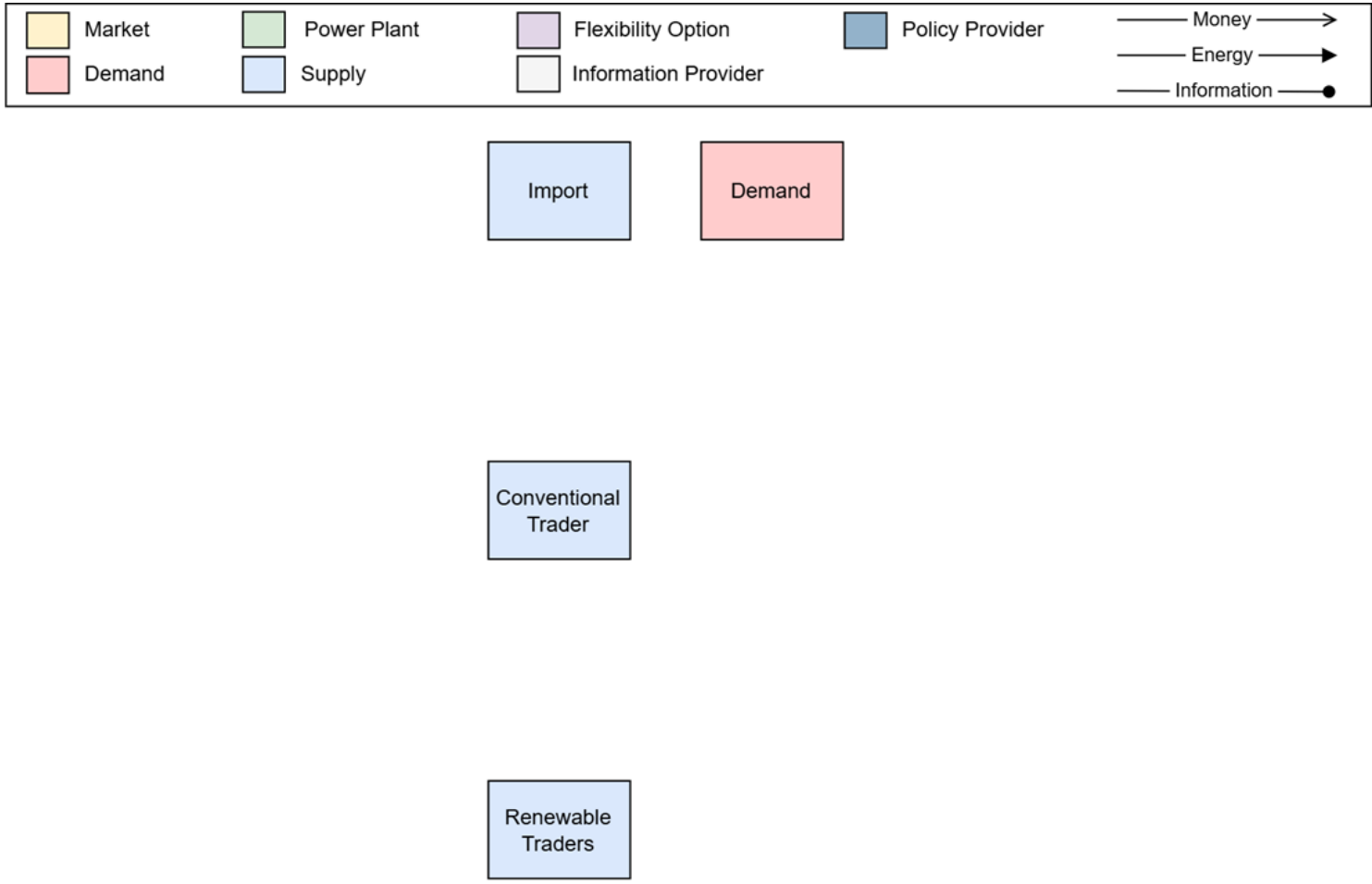
Agent types

Markets

- Determine prices

Traders

- Fulfil marketing strategies



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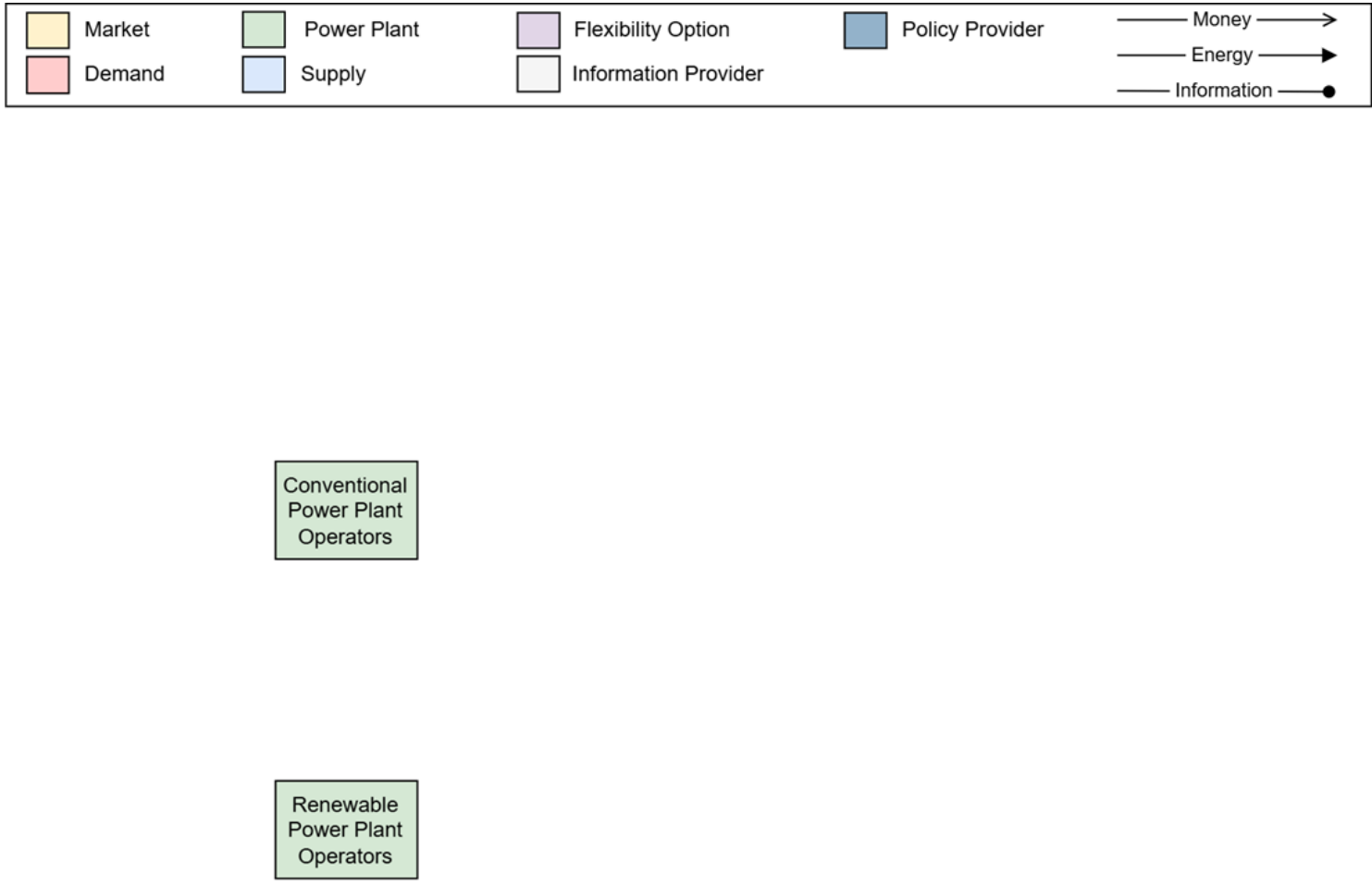
AMIRIS

Agent types

Markets
- Determine prices

Traders
- Fulfil marketing strategies

Plant operators
- Control power plants



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AMIRIS

Agent types

Markets
- Determine prices

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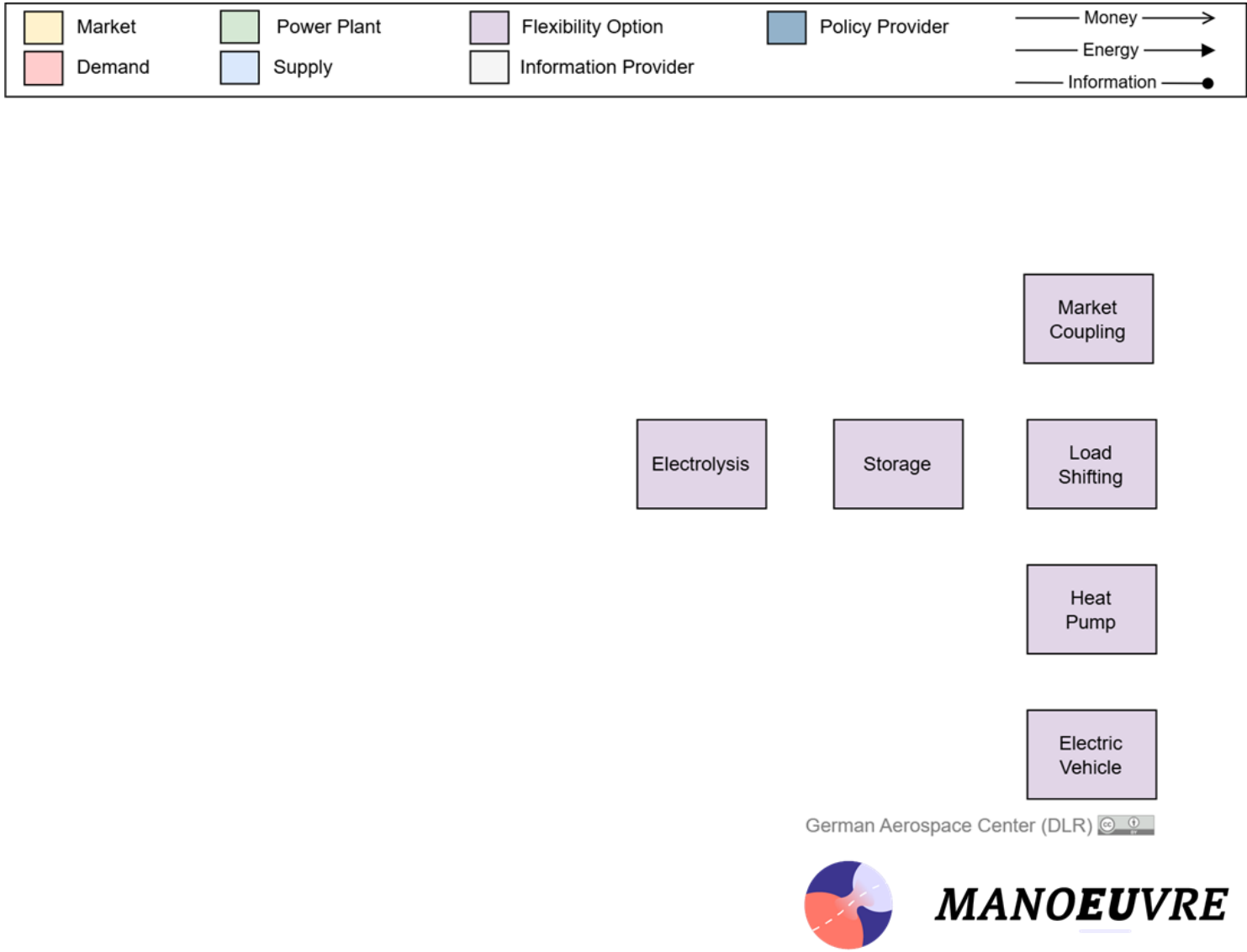
Plant operators
- Control power plants

Flexibility providers
- Optimise dispatch



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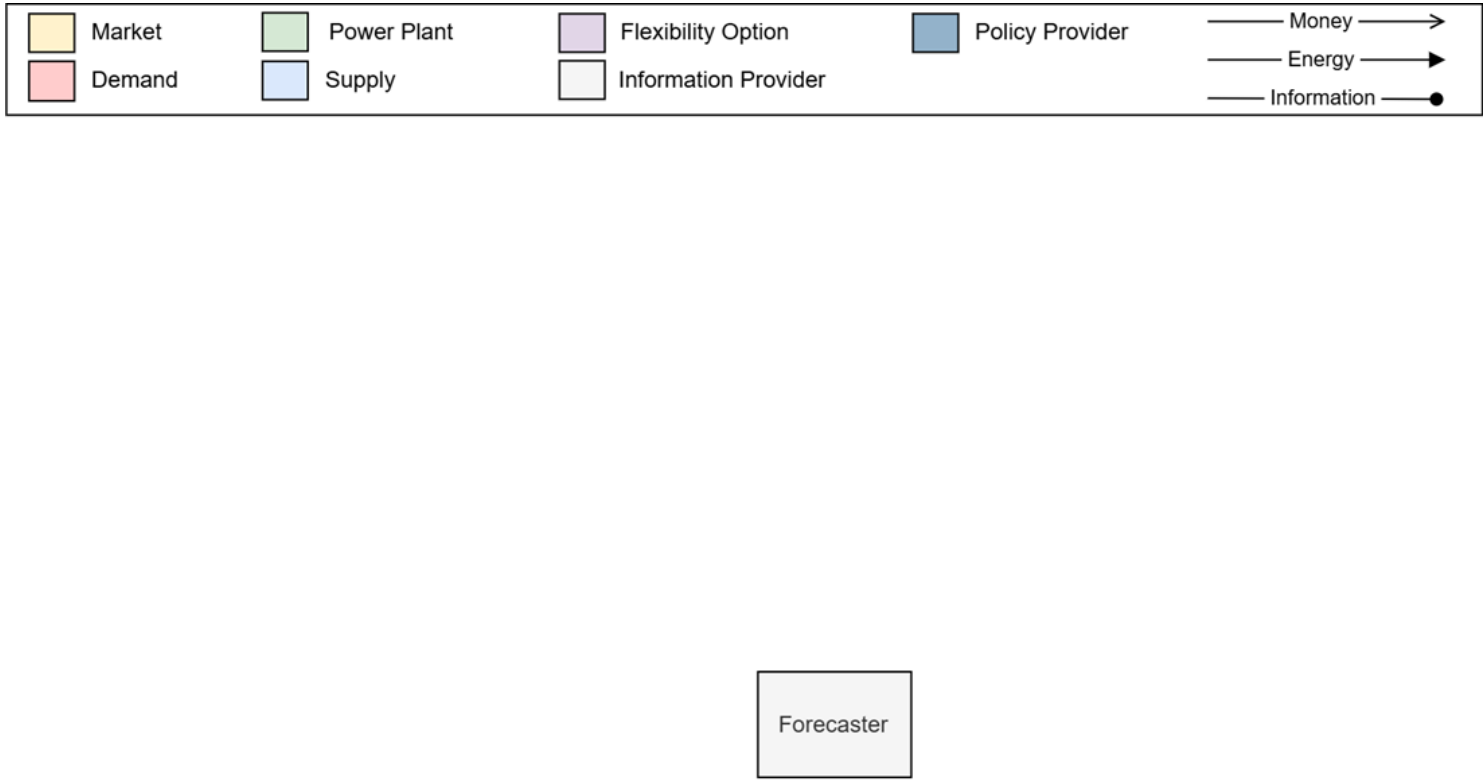
Flexibility providers
- Optimise dispatch

Information provider
- Create forecasts



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Information provider
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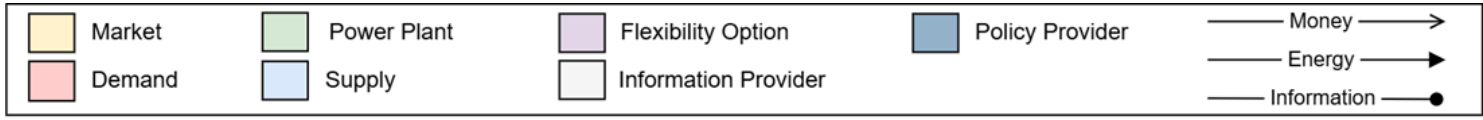
Policy
- Provide support



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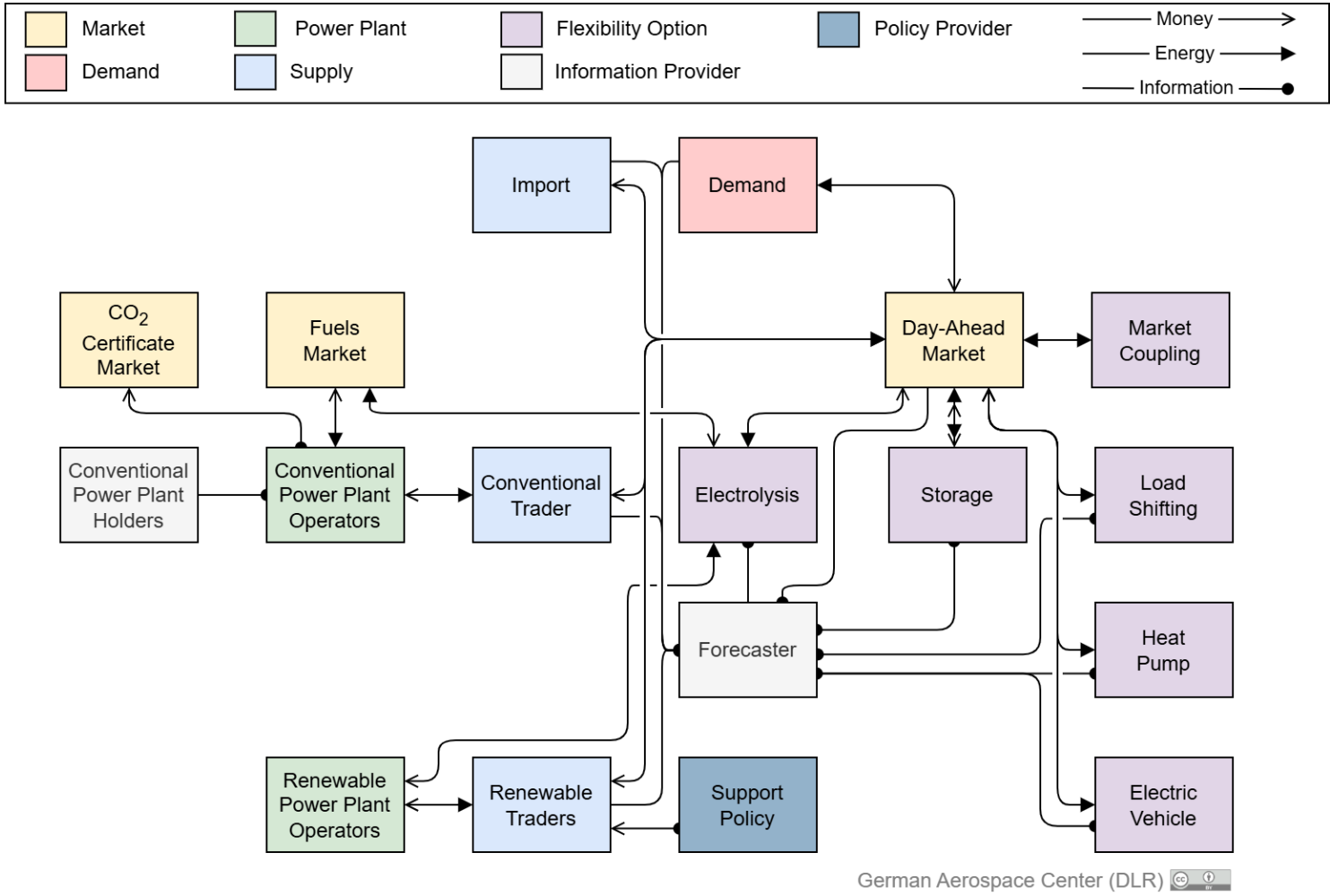

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Modelling Flexibility

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Modelling Flexibility

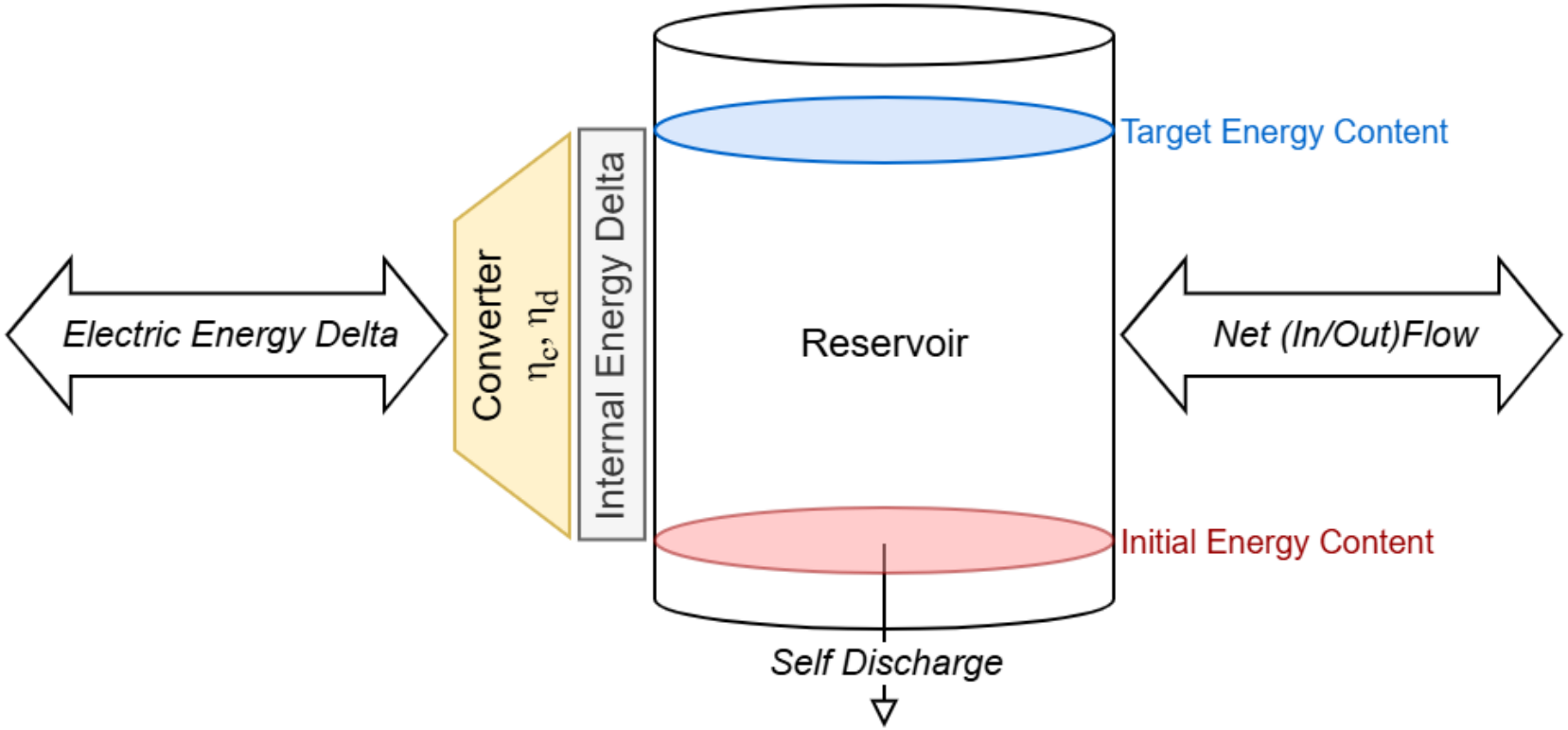
The Flexibility Device

Reservoir
- Storage capacity in MWh

Converter
- (Dis-) charging power in MW
- (Dis-) charging efficiency

Transitions
- Initial → target energy content
- Internal energy delta → external electric energy delta
- Self discharge
- Inflows / outflows

Modelling Capabilities
- Pumped hydro (+inflow)
- Hydro reservoir
- Battery storage



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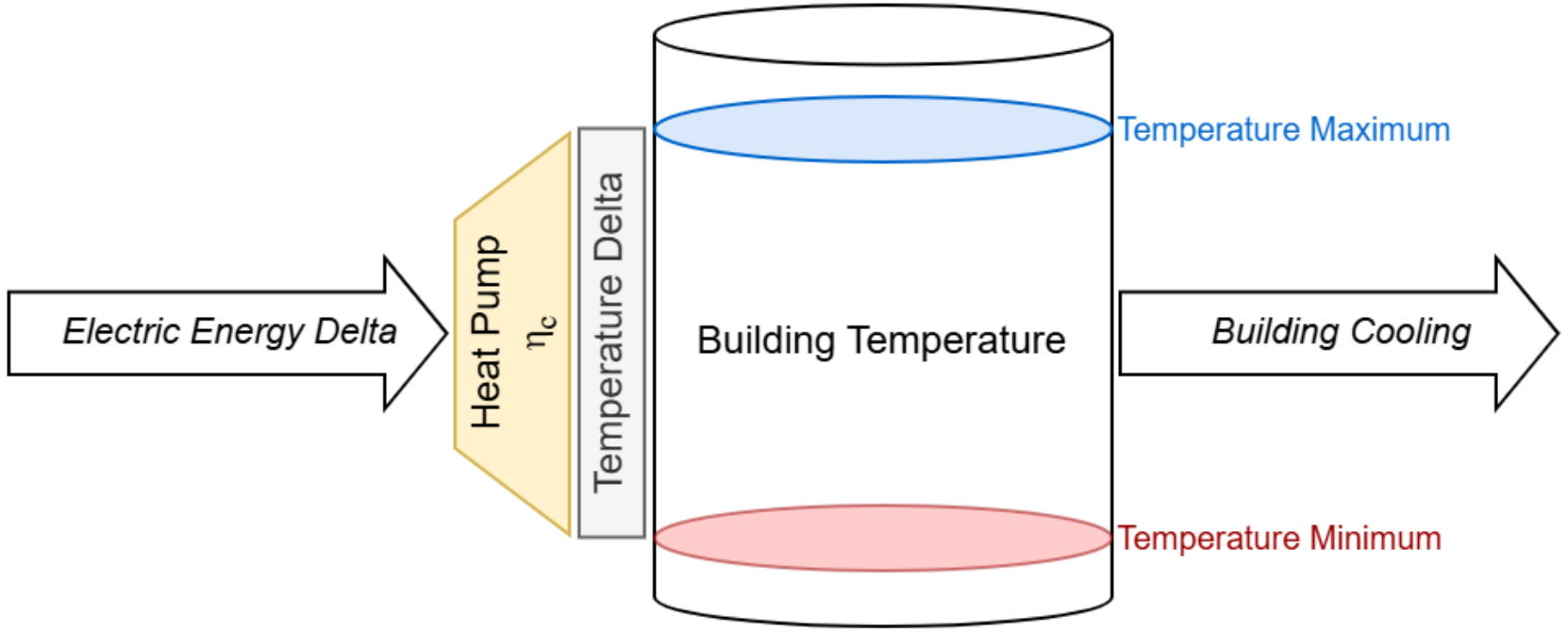
Modelling Flexibility

Flexible Heat Pumps

Reservoir
- Upper and lower temperature bounds

Converter
- Heating power
- Temperature-dependent efficiency

Transitions
- Outflows: Building's temperature loss



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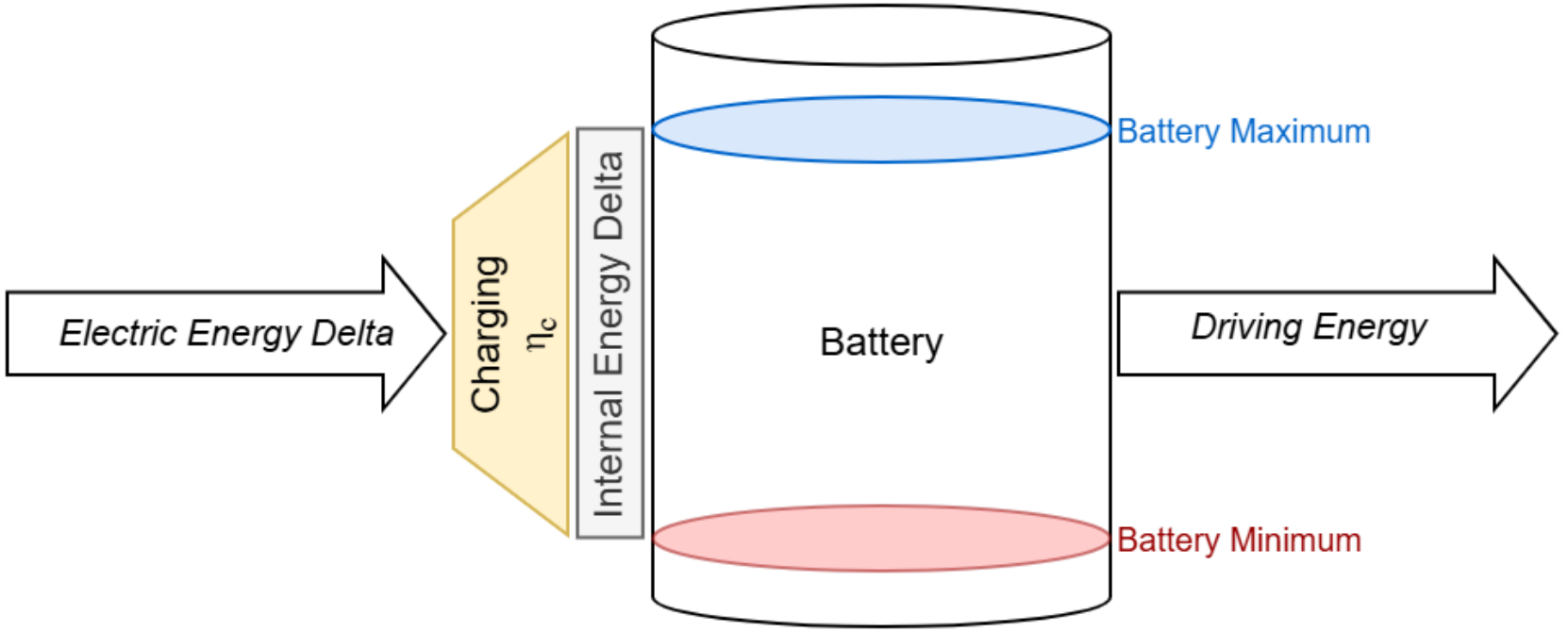
Modelling Flexibility

Flexible EV Charging - Unidirectional

Reservoir
- Upper and lower battery availability

Converter
- Connection-dependent charging power

Transitions
- Outflows: Energy use of driving



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Modelling Flexibility

Flexible EV Charging - Bidirectional

Reservoir

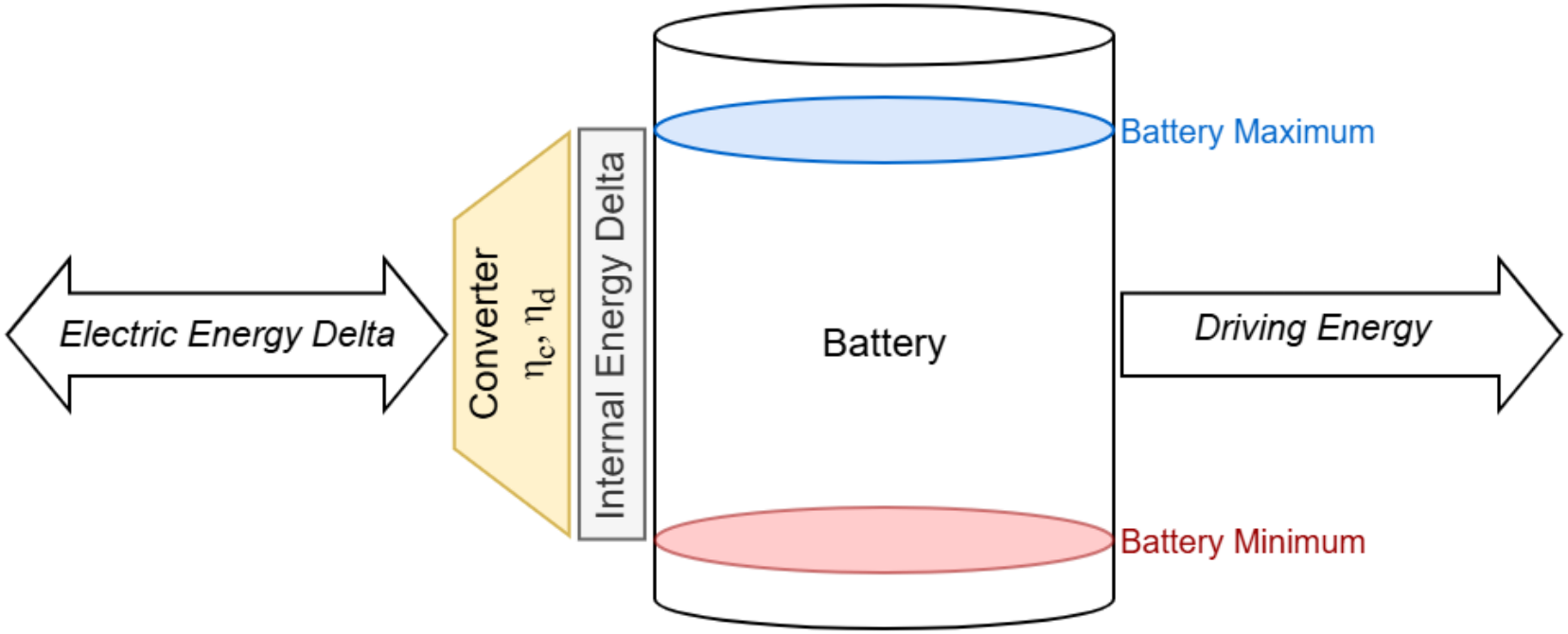
- Upper and lower battery availability

Converter

- Connection-dependent charging & *discharging* power

Transitions

- Outflows: Energy use of driving



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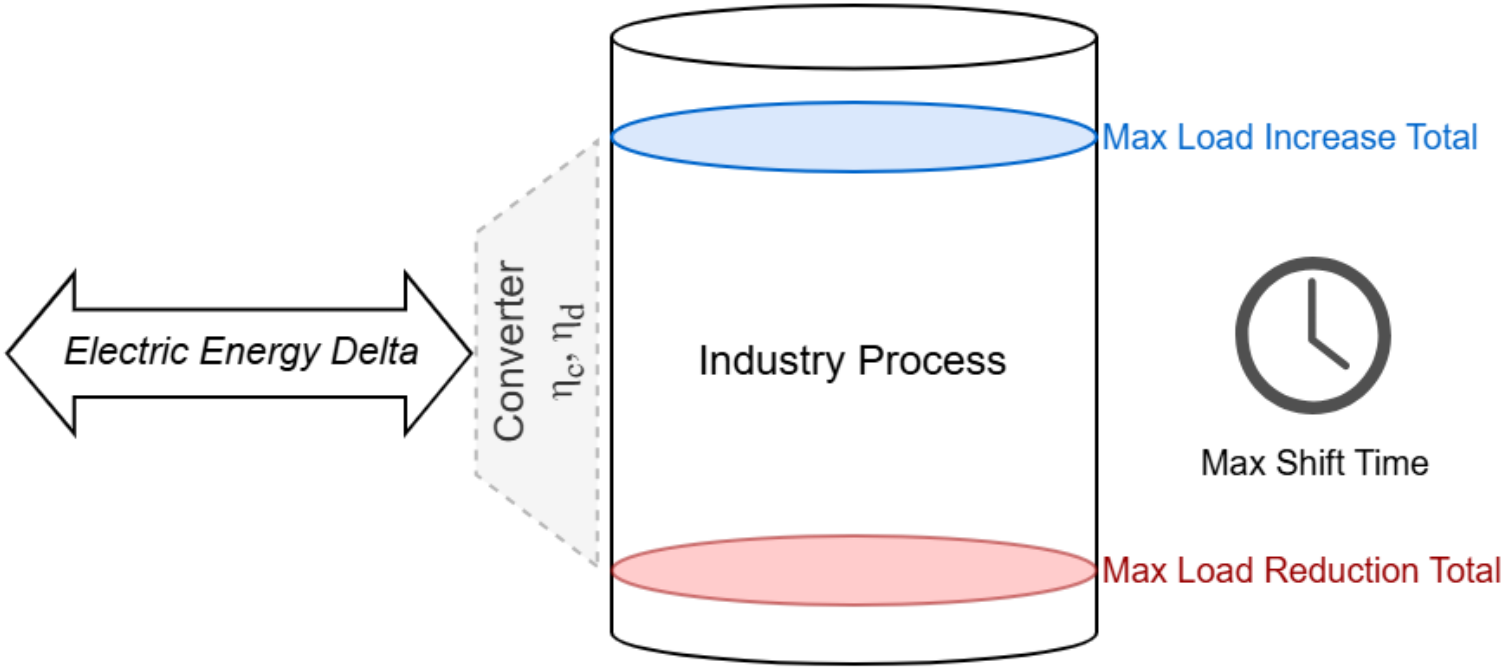
Modelling Flexibility

Load shifting

Reservoir
- Maximum time out of balance (shift time)

Converter
- Variable cost for load shifting

Transitions
- No self-discharge / flows



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Modelling Competing Flexibility

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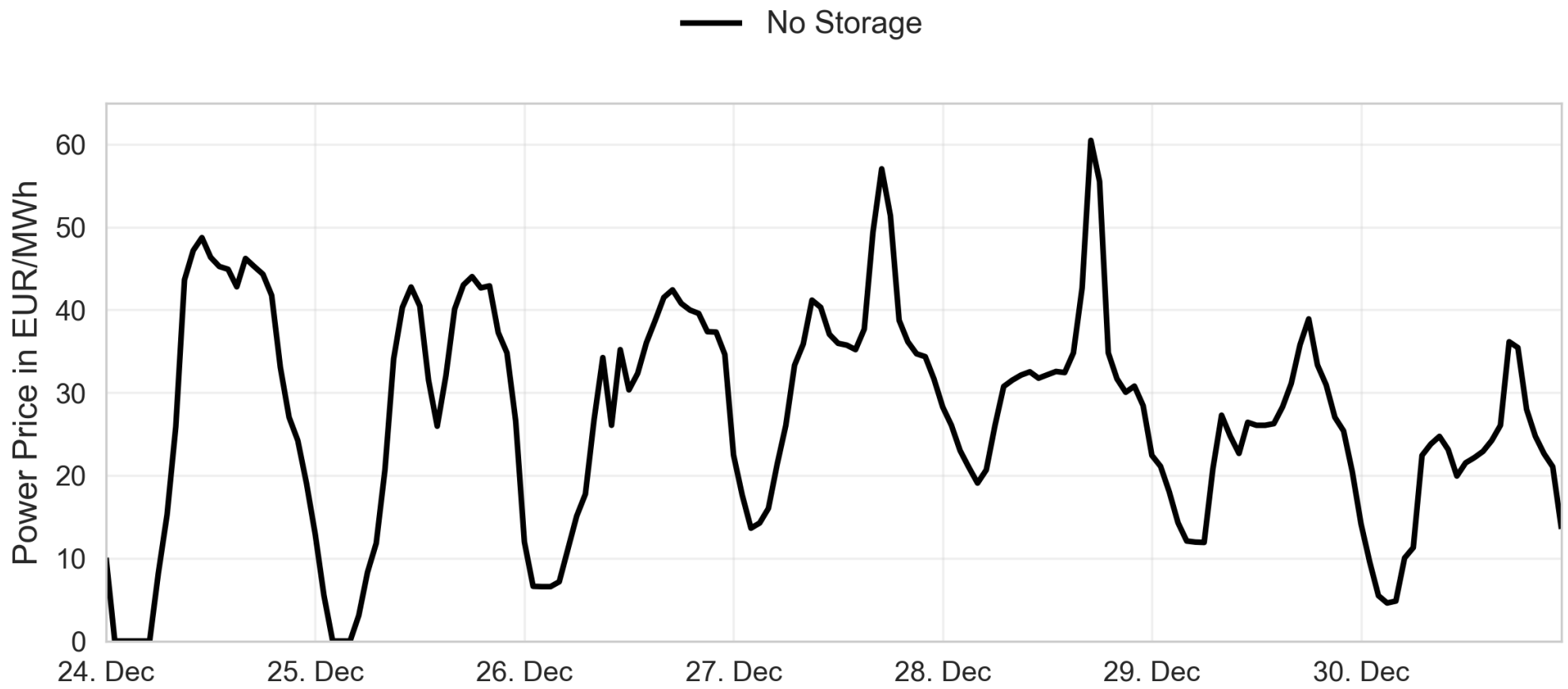
Modelling Competing Flexibility

The Task

When to charge or to discharge…

→ Use electricity price *forecast* → Optimise dispatch with *dynamic programming*



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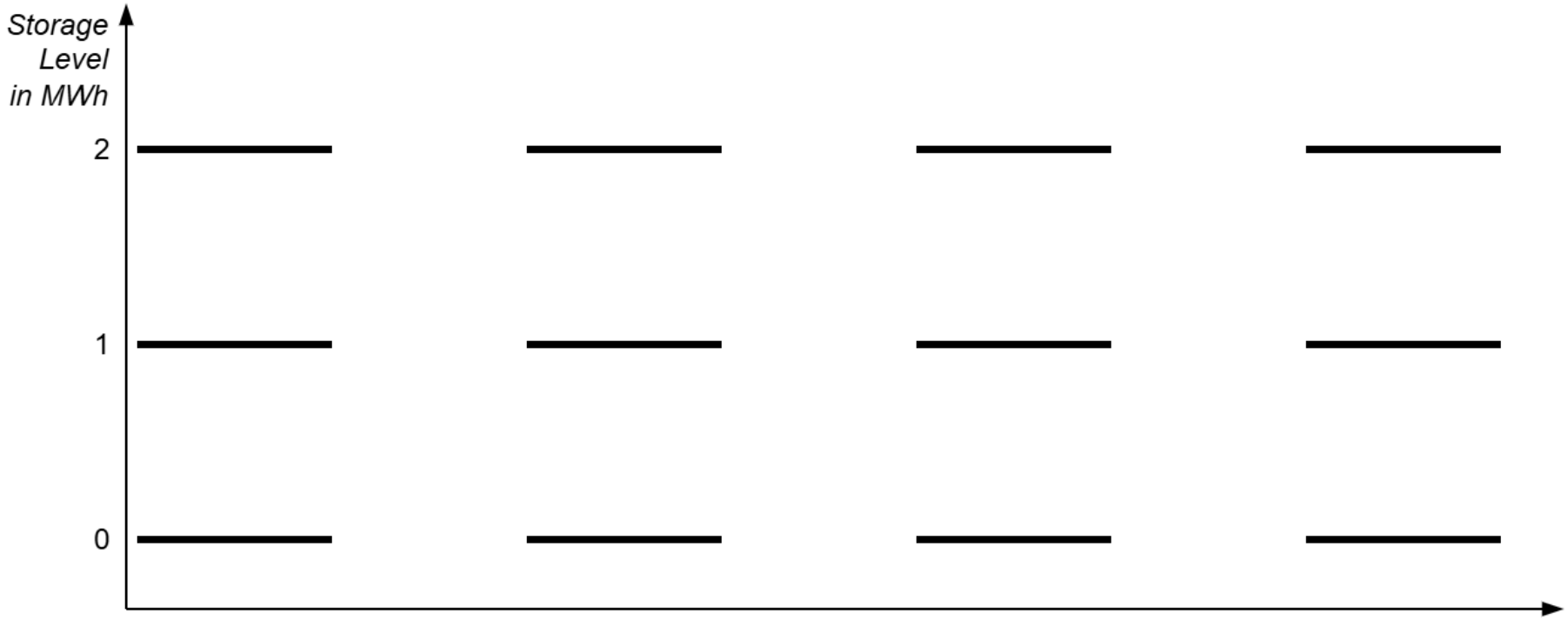
Modelling Competing Flexibility

Dynamic Programming

Discretise storage content

- e.g. 10 MWh steps



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Modelling Competing Flexibility

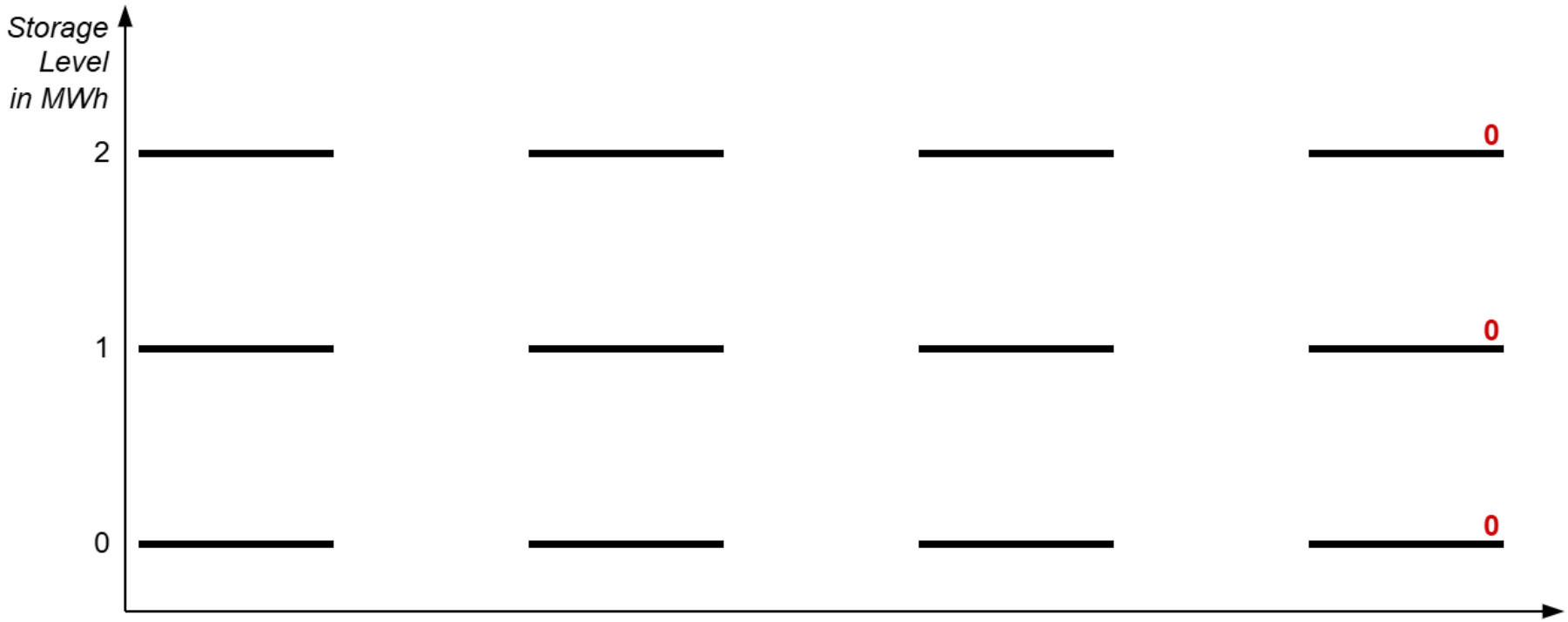
Dynamic Programming

Discretise storage content

- e.g. 10 MWh steps

Assign final value

- e.g. zero, or water value



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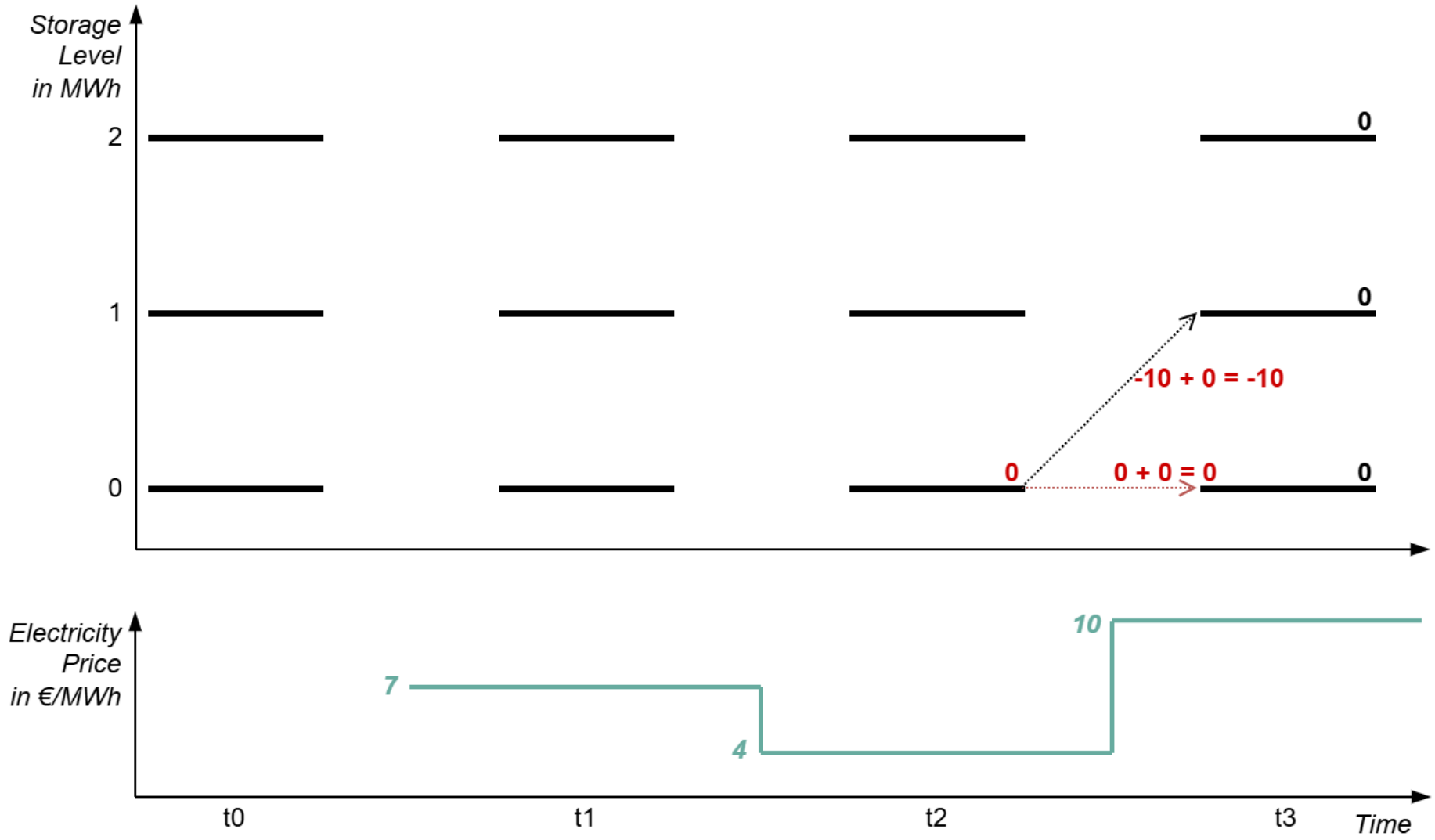
Modelling Competing Flexibility

Dynamic Programming

Discretise storage content
- e.g. 10 MWh steps

Assign final value
- e.g. zero, or water value

Evaluate transitions
- Pick optimisation target
- Backwards in time
- Assess all allowed transitions
- Choose best transition



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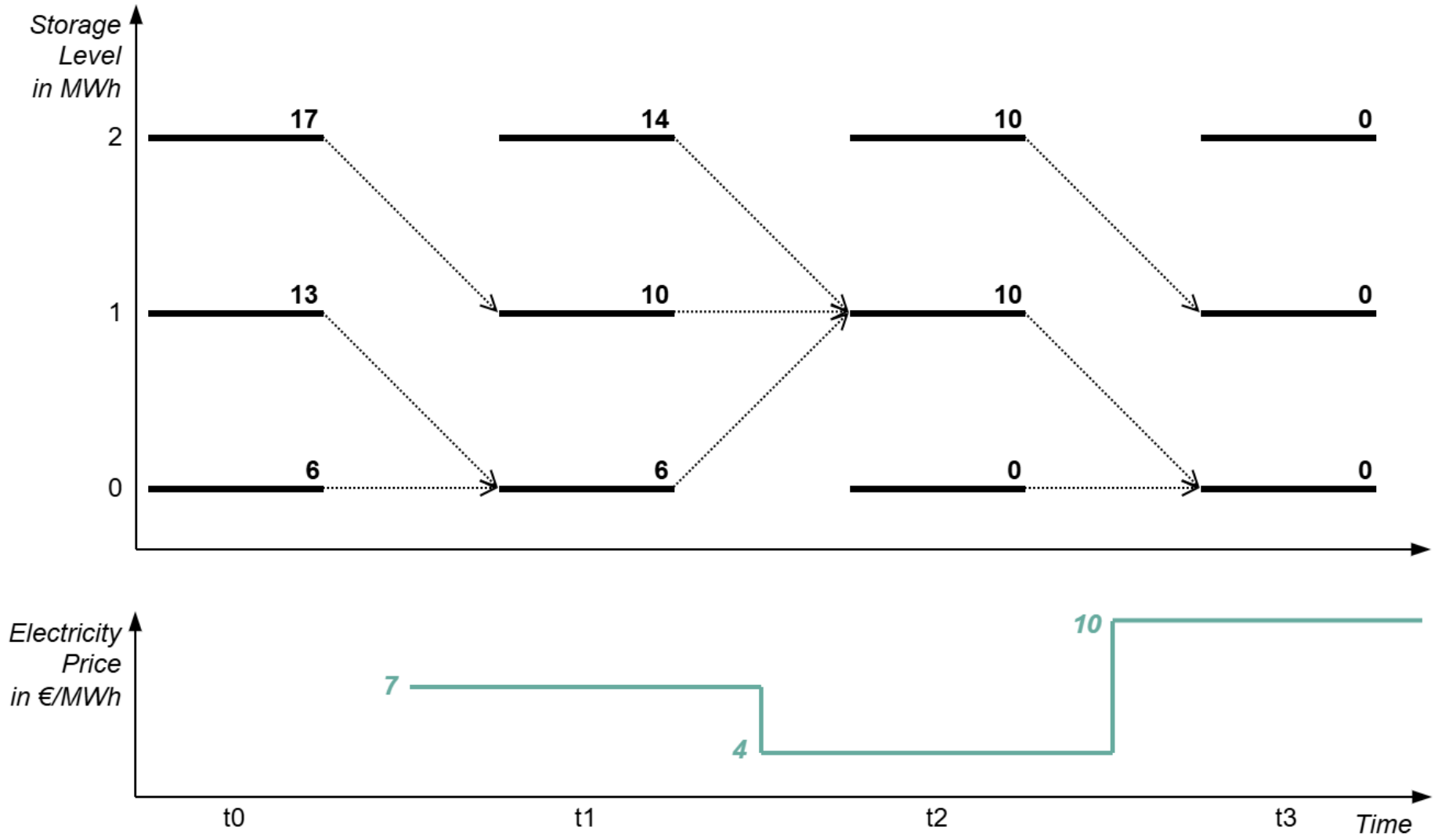

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Evaluate transitions
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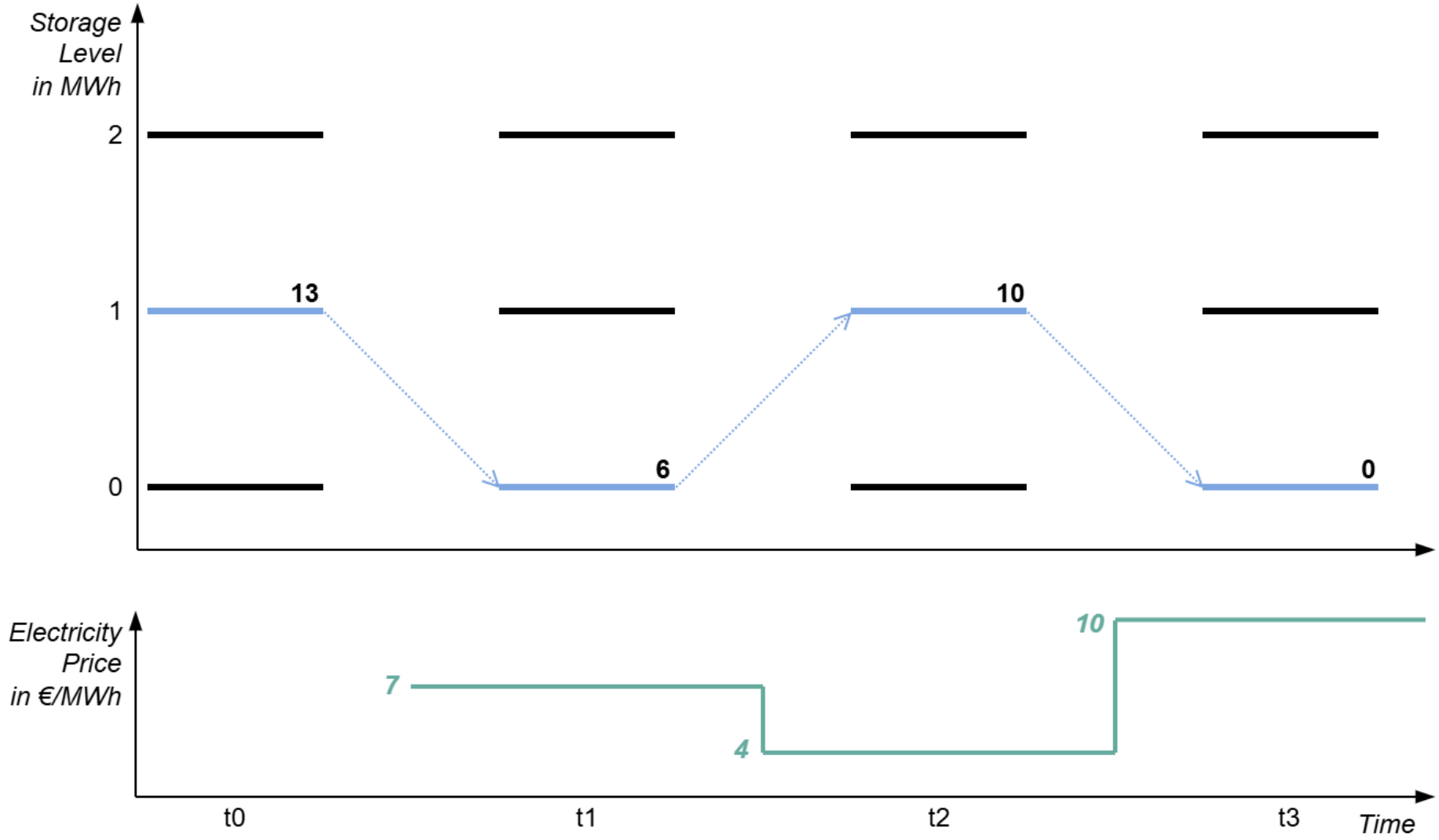
Plan dispatch
- Begin at current state
- Follow best transitions



Modelling Competing Flexibility

Dynamic Programming

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Assign final value
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Evaluate transitions
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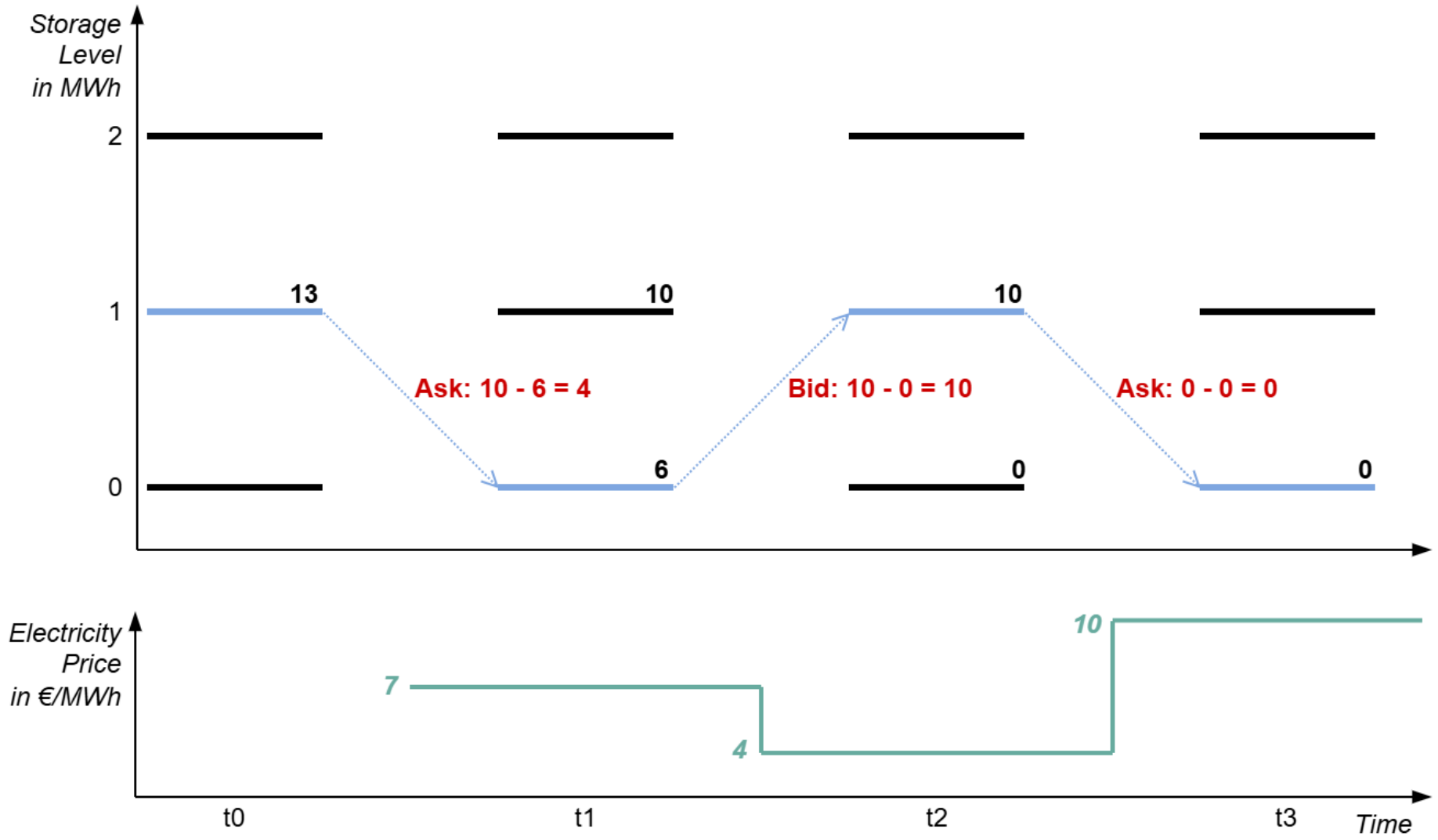
Plan dispatch
- Begin at current state
- Follow best transitions

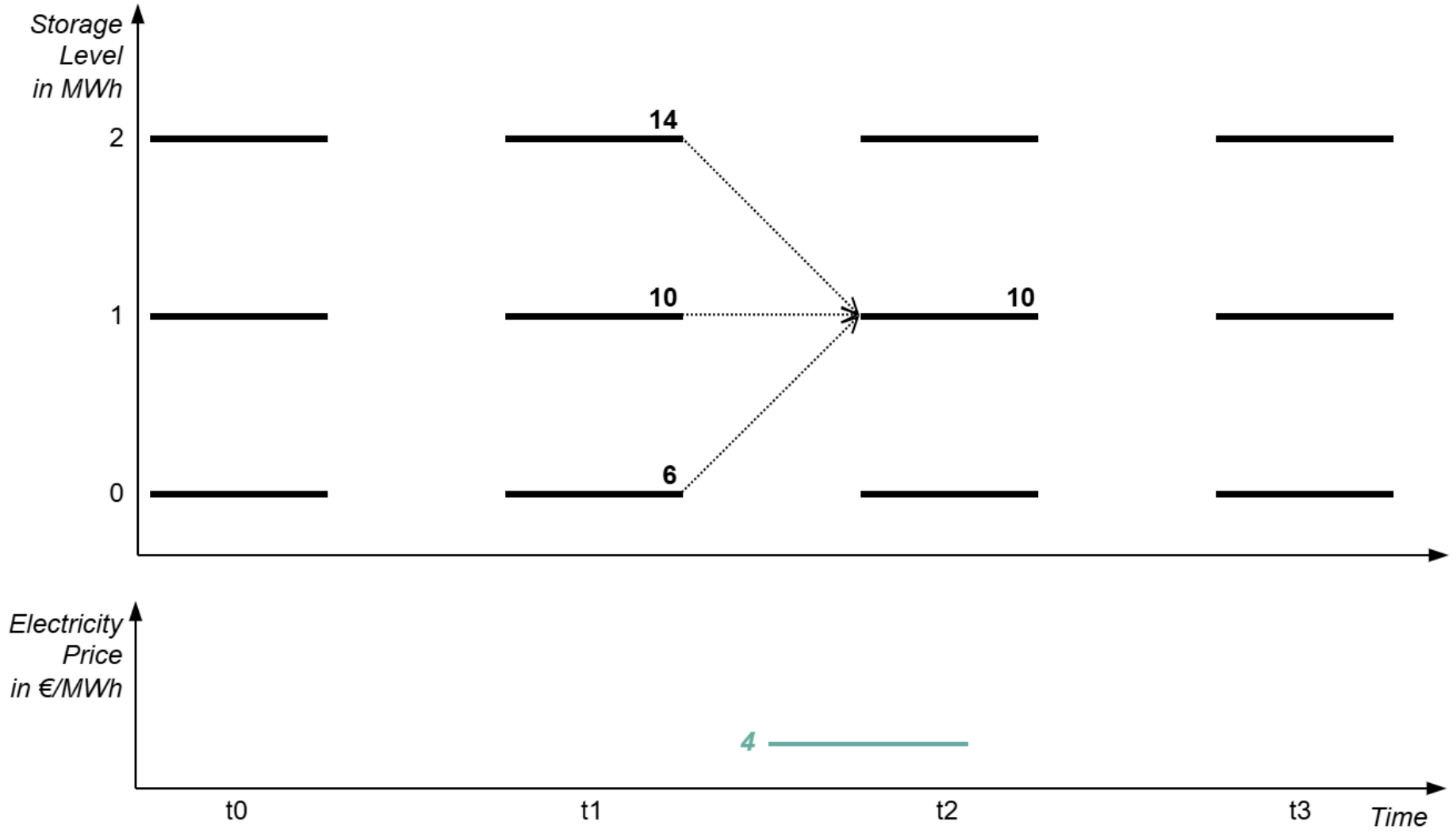
Bidding strategy
- Consider expected value



Modelling Competing Flexibility

Price impacts

Static price assumption



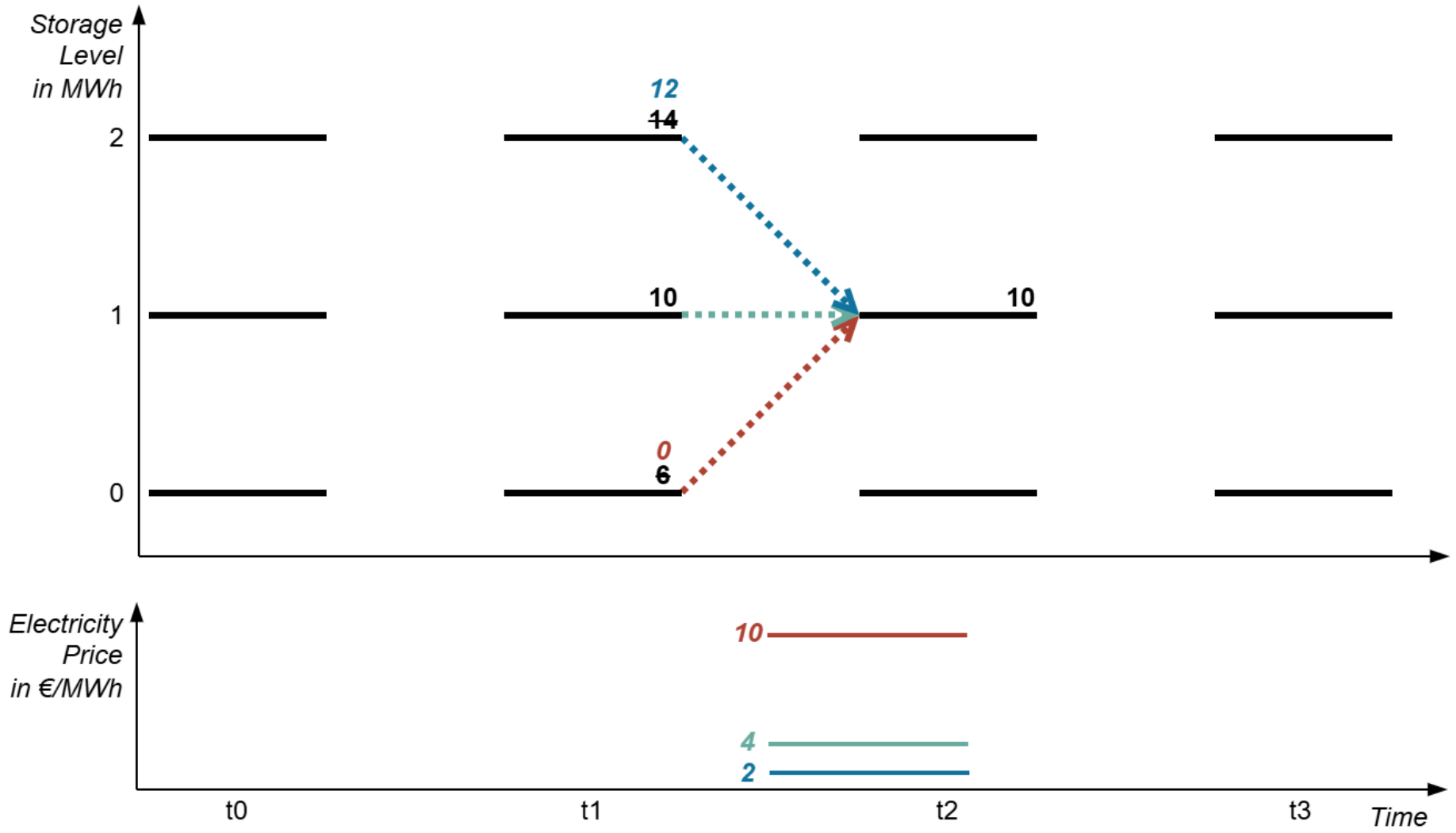
Modelling Competing Flexibility

Price impacts

Static price assumption

- Is wrong

Prices depend on dispatch



Modelling Competing Flexibility

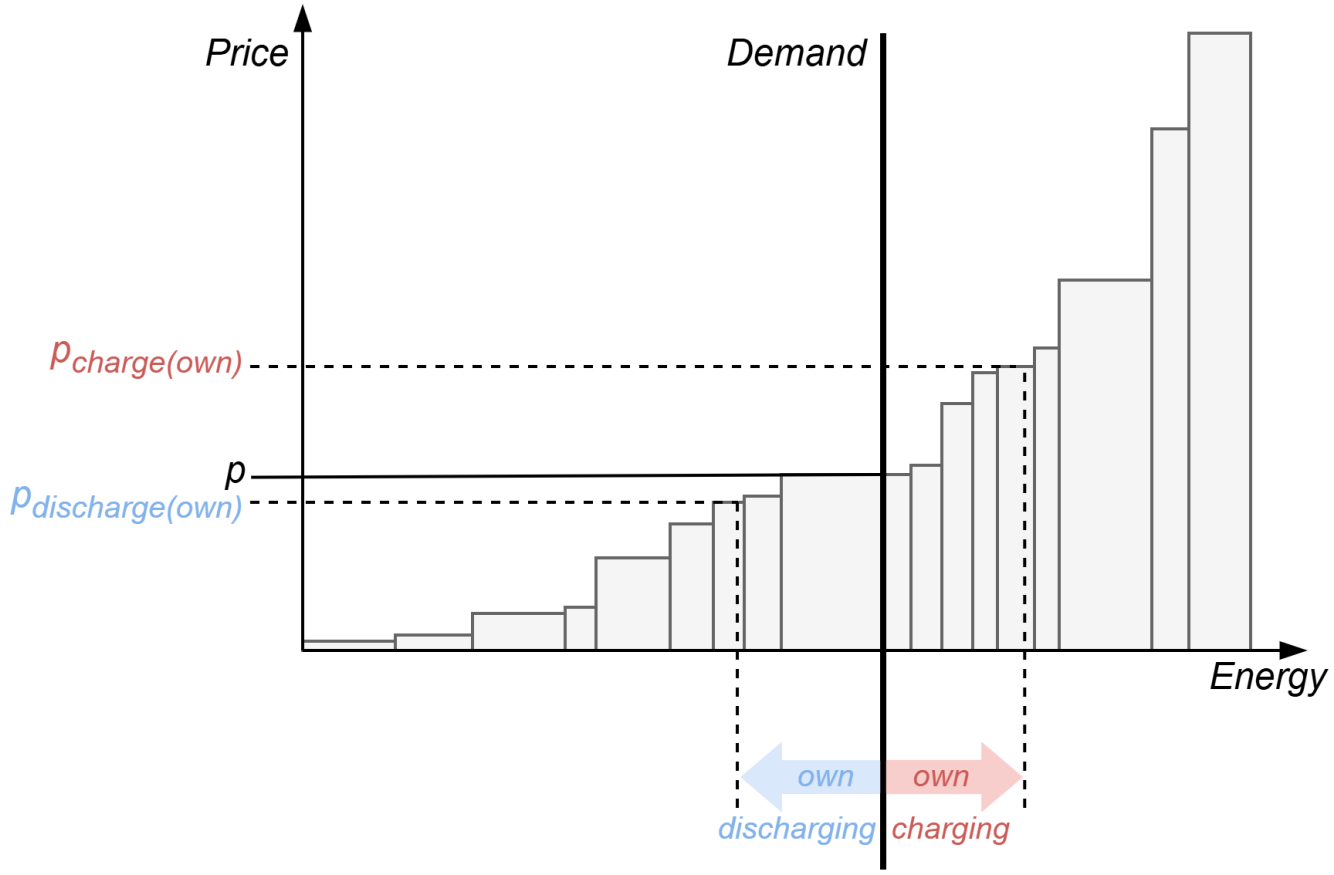
Price impacts

Static price assumption

- Is wrong

Prices depend on dispatch

→ Merit order forecast



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Modelling Competing Flexibility

Forecast: Inflexible Units

Inflexible units

- Provide their bid forecasts

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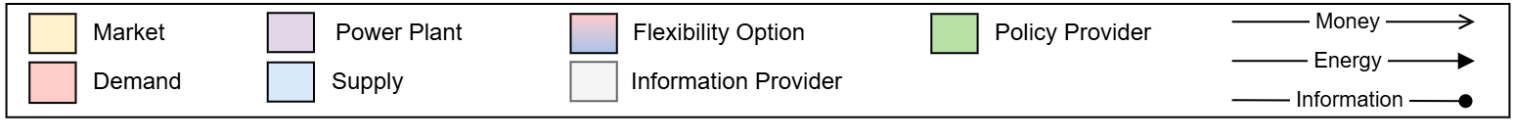
Modelling Competing Flexibility

Forecast: Inflexible Units

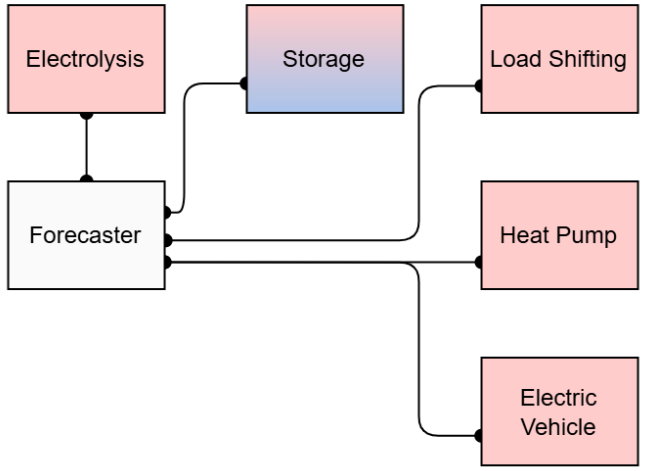


Inflexible units

- Provide their bid forecasts

Forecaster

- Derives merit order
- Sends effective prices @ dispatched MWh



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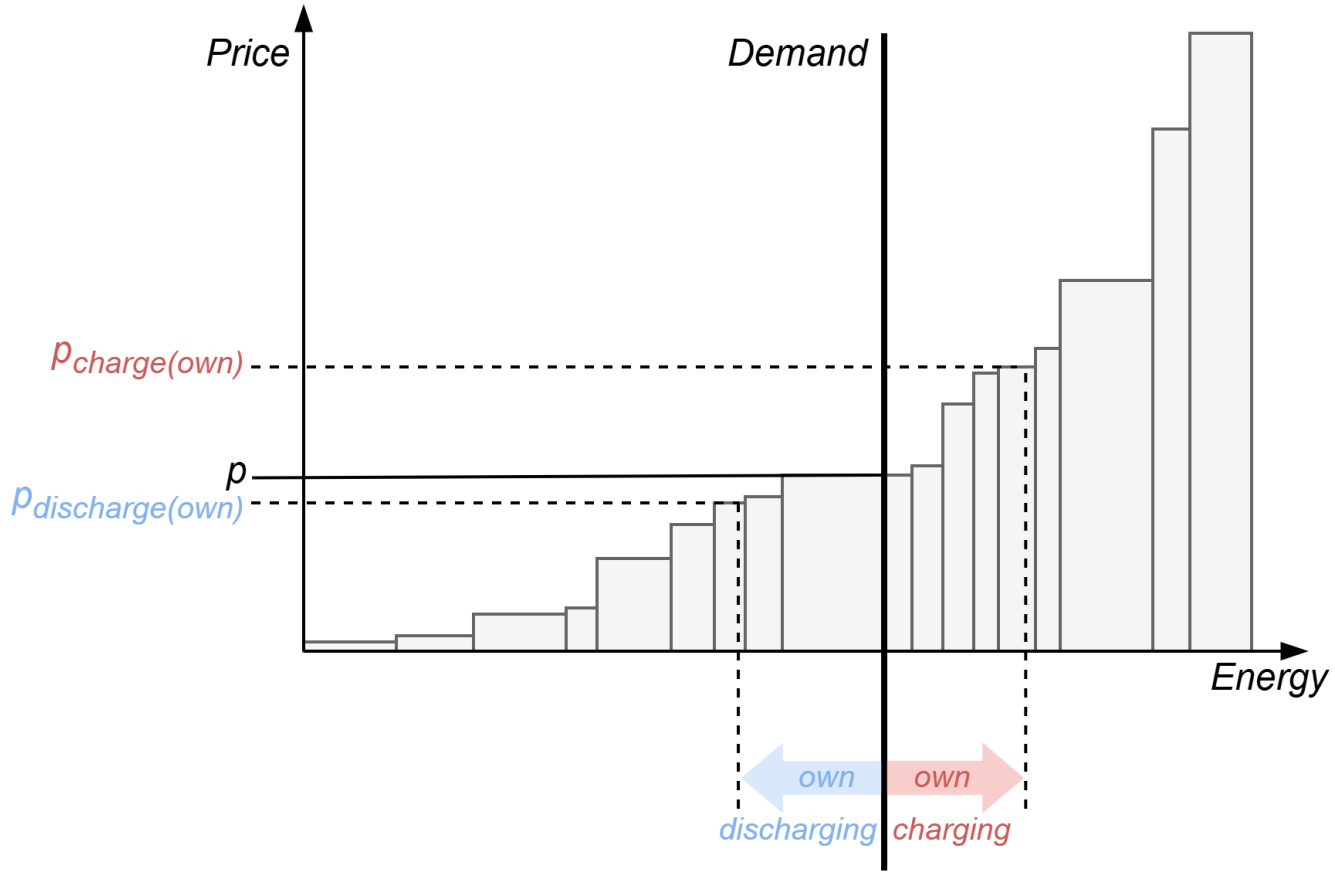
Modelling Competing Flexibility

Forecast: Inflexible Units

Inflexible units
- Provide their bid forecasts

Forecaster
- Derives merit order
- Sends effective prices @ dispatched MWh

Flexibilities
- Consider price changes in their dispatch optimisation



But how consider competition?

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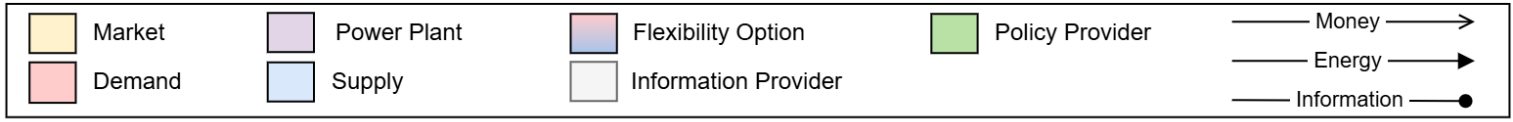
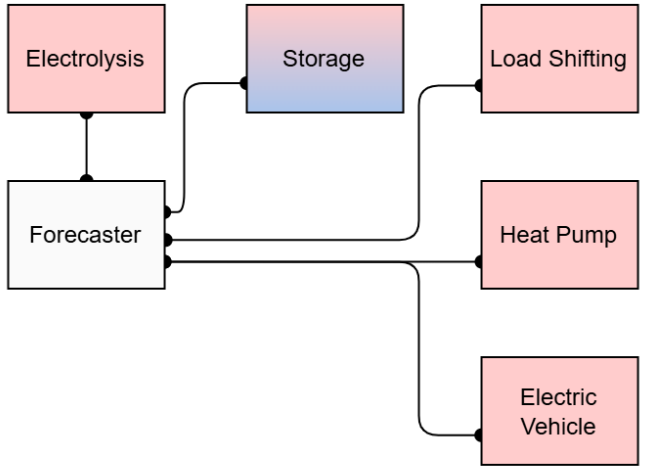
Modelling Competing Flexibility

Forecast: Flexibility Units



Flexibilities

- Provide their historic dispatch



Modelling Competing Flexibility

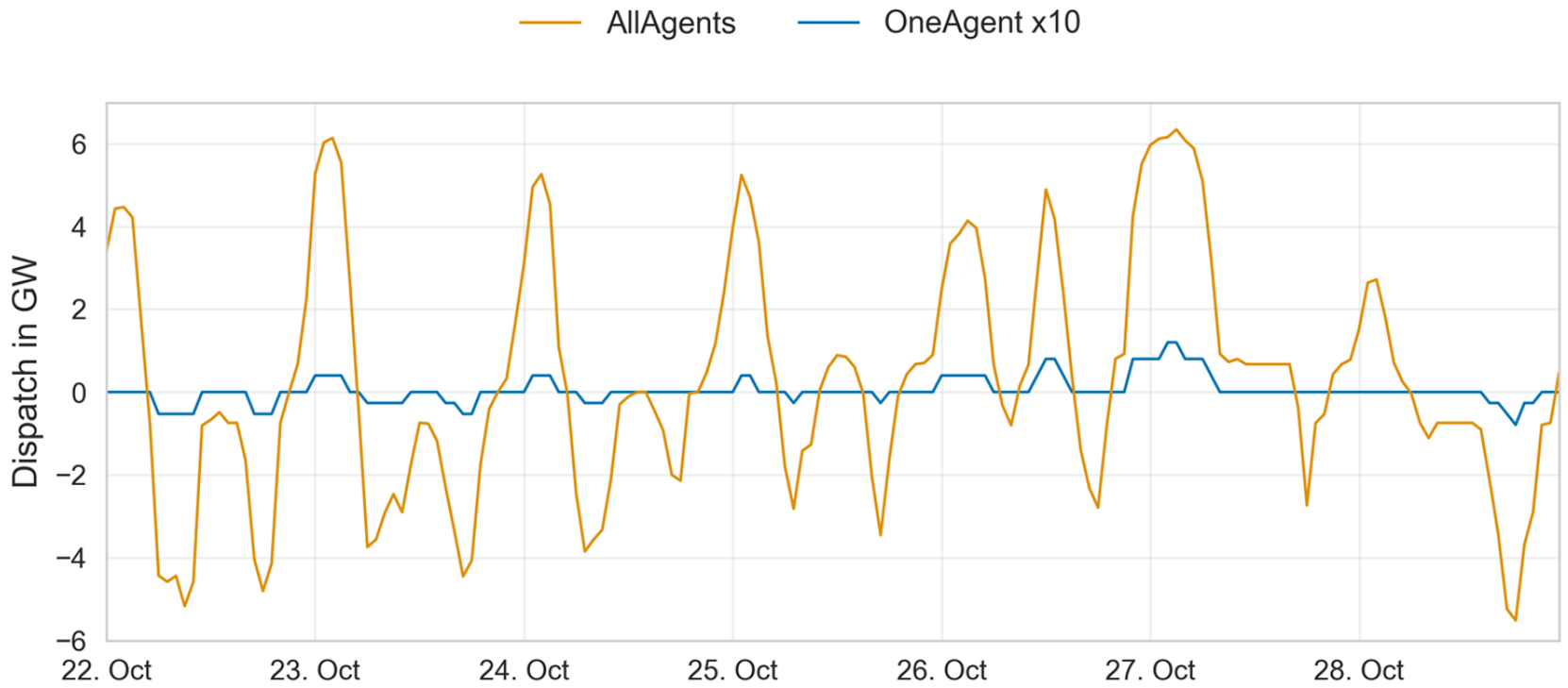
Forecast: Flexibility Units

Flexibilities

- Provide their historic dispatch

Forecaster

- Compares each unit's dispatch with total dispatch



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Modelling Competing Flexibility

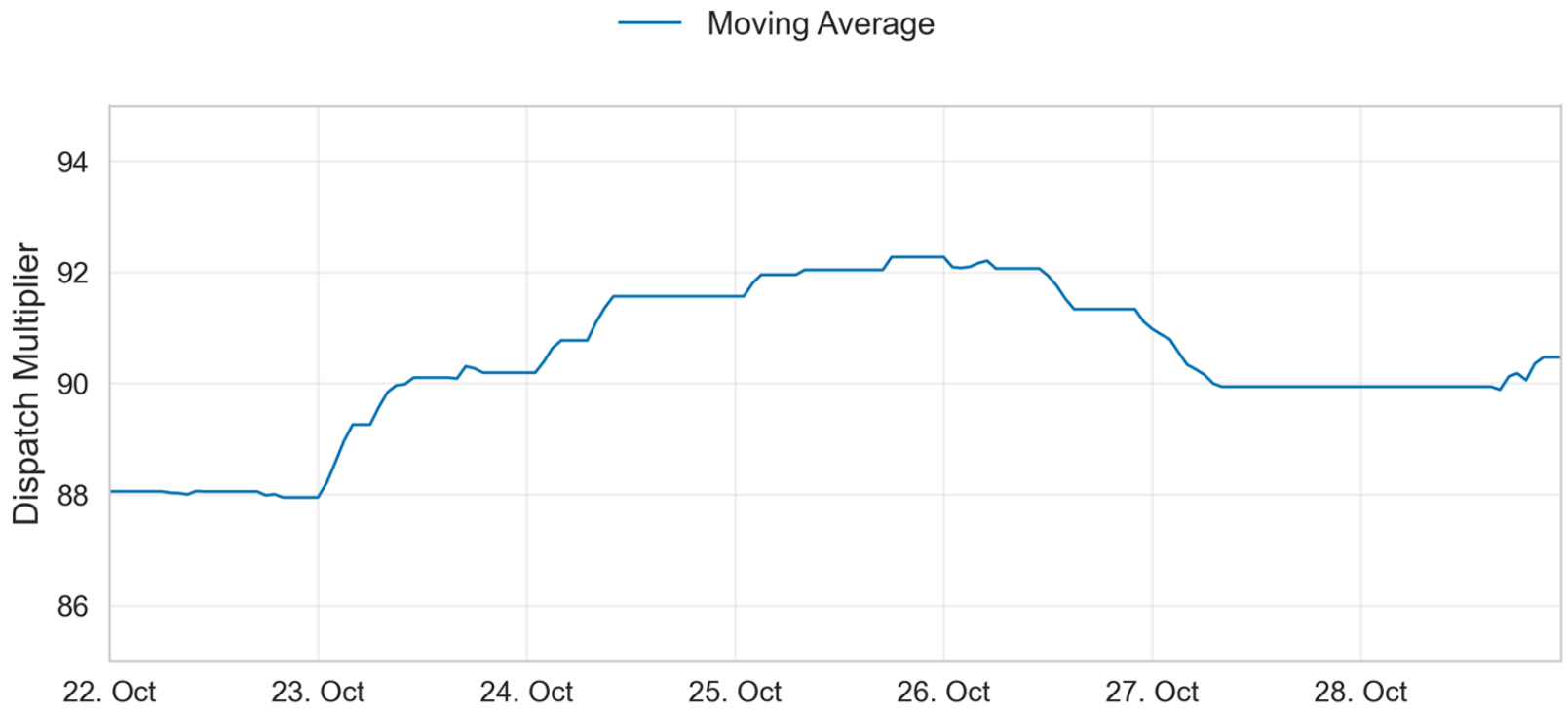
Forecast: Flexibility Units

Flexibilities

- Provide their historic dispatch

Forecaster

- Compares each unit's dispatch with total dispatch
- Derives an average "dispatch multiplier"



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Modelling Competing Flexibility

Forecast: Flexibility Units

Flexibilities

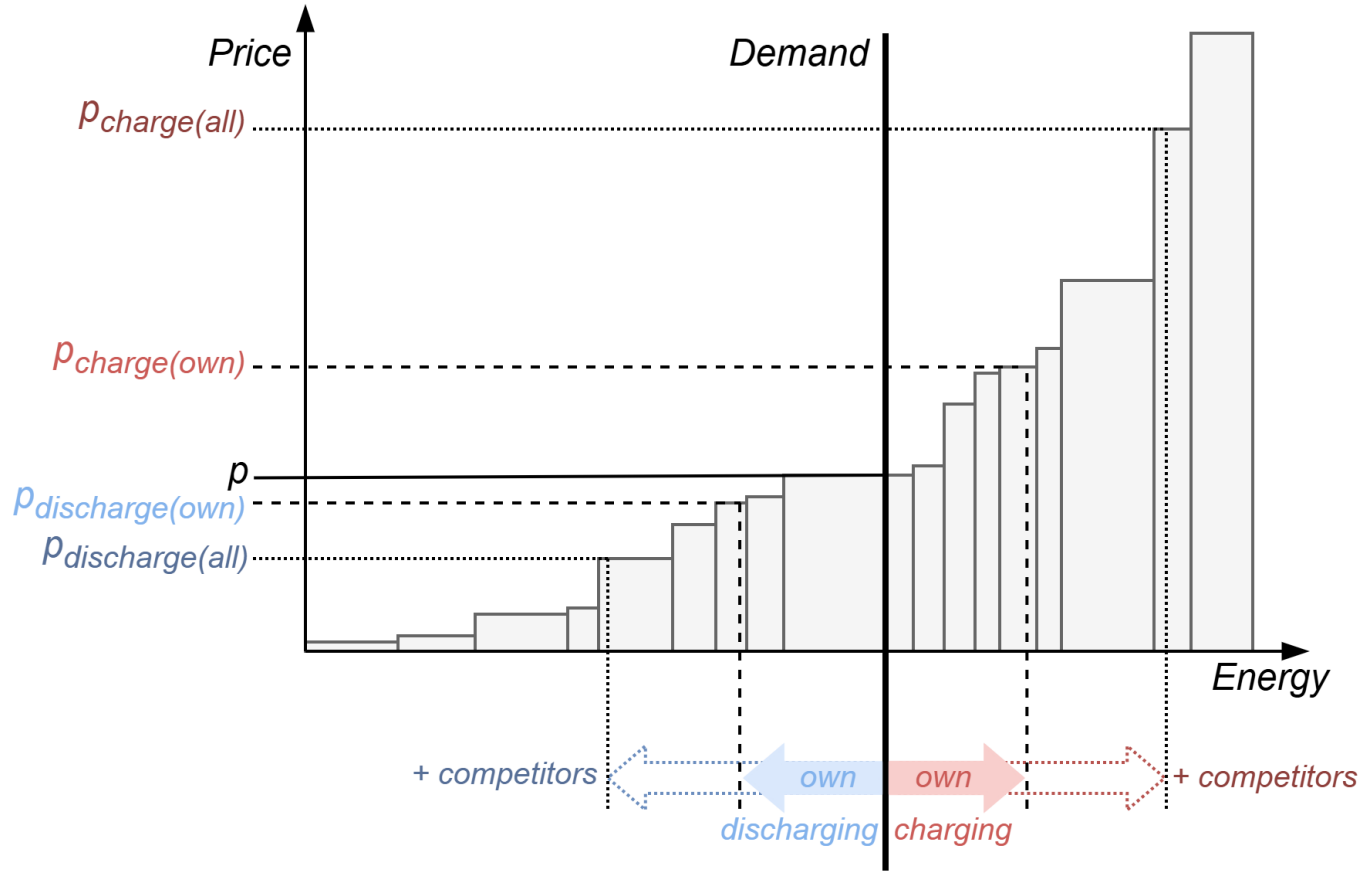
- Provide their historic dispatch

Forecaster

- Compares each unit's dispatch with total dispatch
- Derives an average "dispatch multiplier"
- Sends effective prices @ dispatched MWh

Flexibilities

- Consider price changes in their dispatch optimisation using the multiplier



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Hands-on: Model Setup

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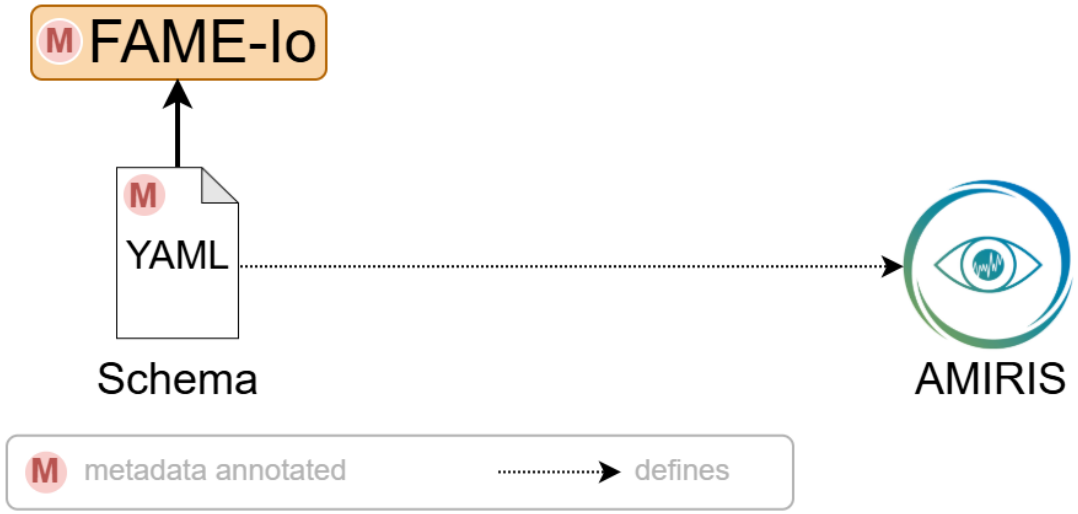
AMIRIS: based on FAME

The open Framework for distributed Agent-based Modelling of Energy systems

Input Preparation | **Execution** | **Output Processing**



FAME-Core: https://joss.theoj.org/papers/10.21105/joss.05087
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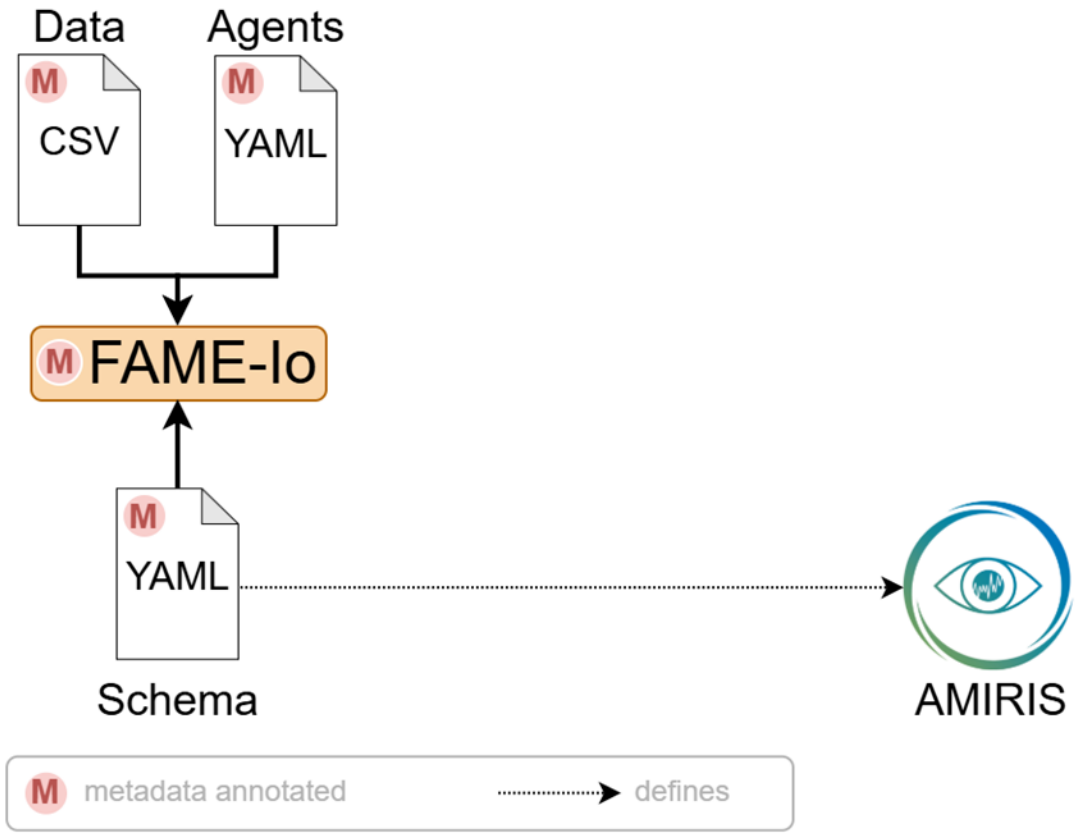

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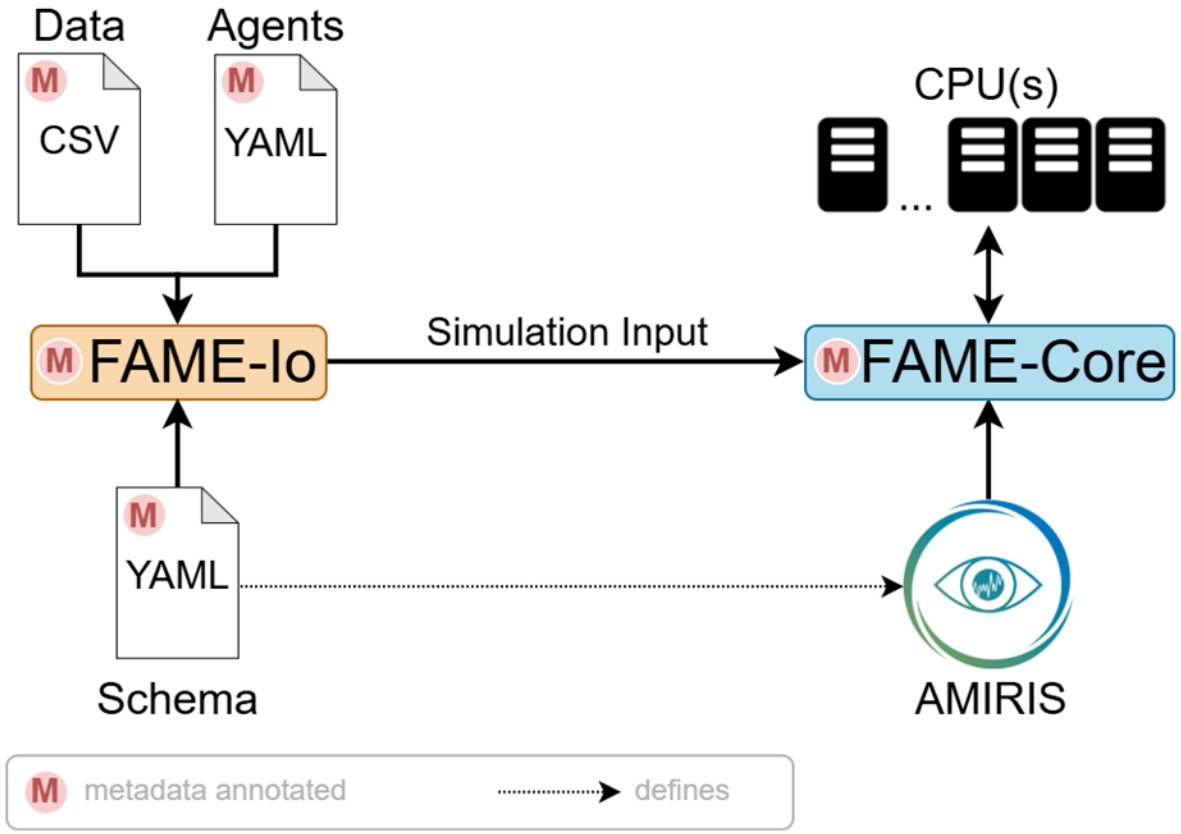

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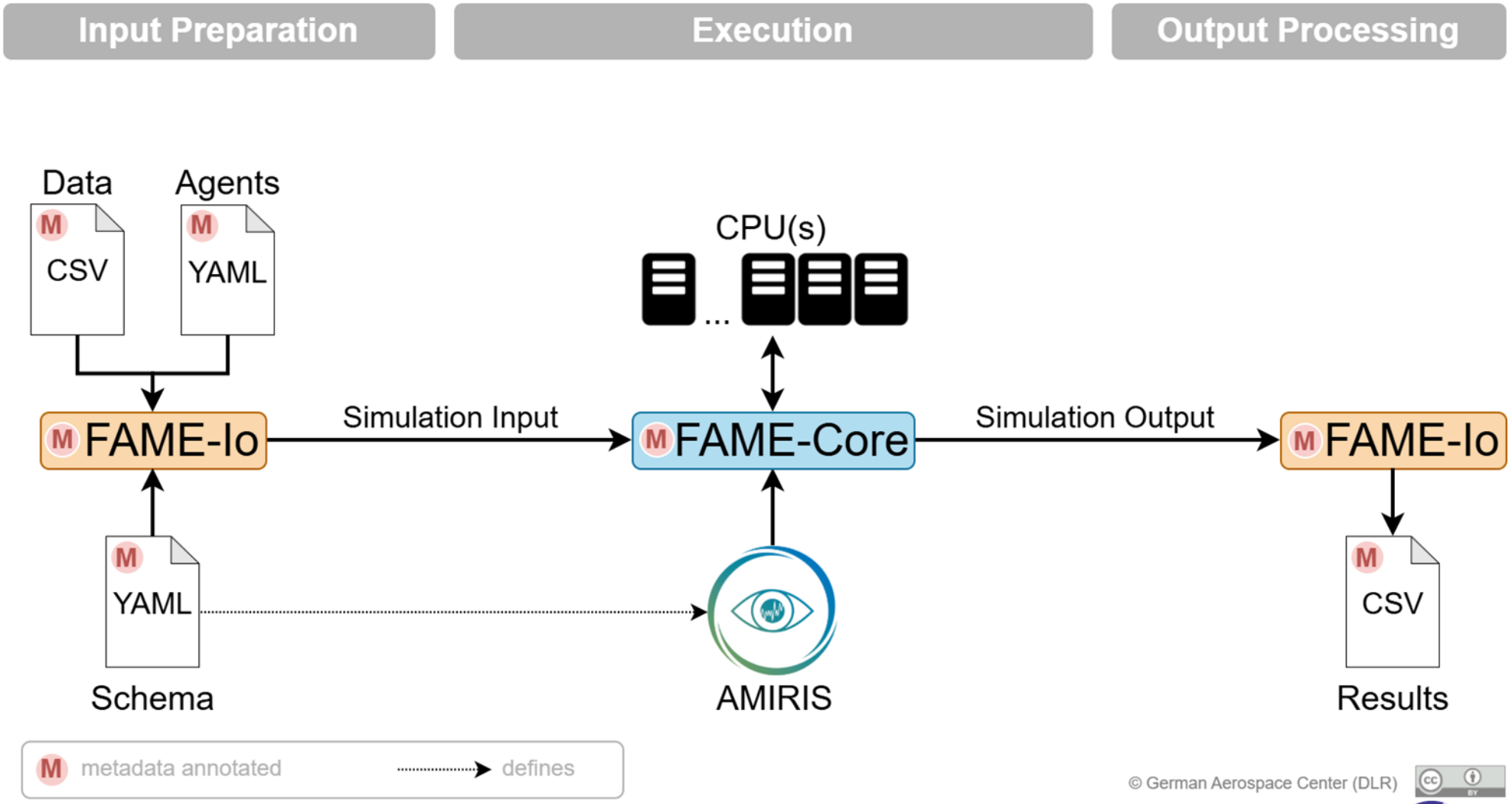

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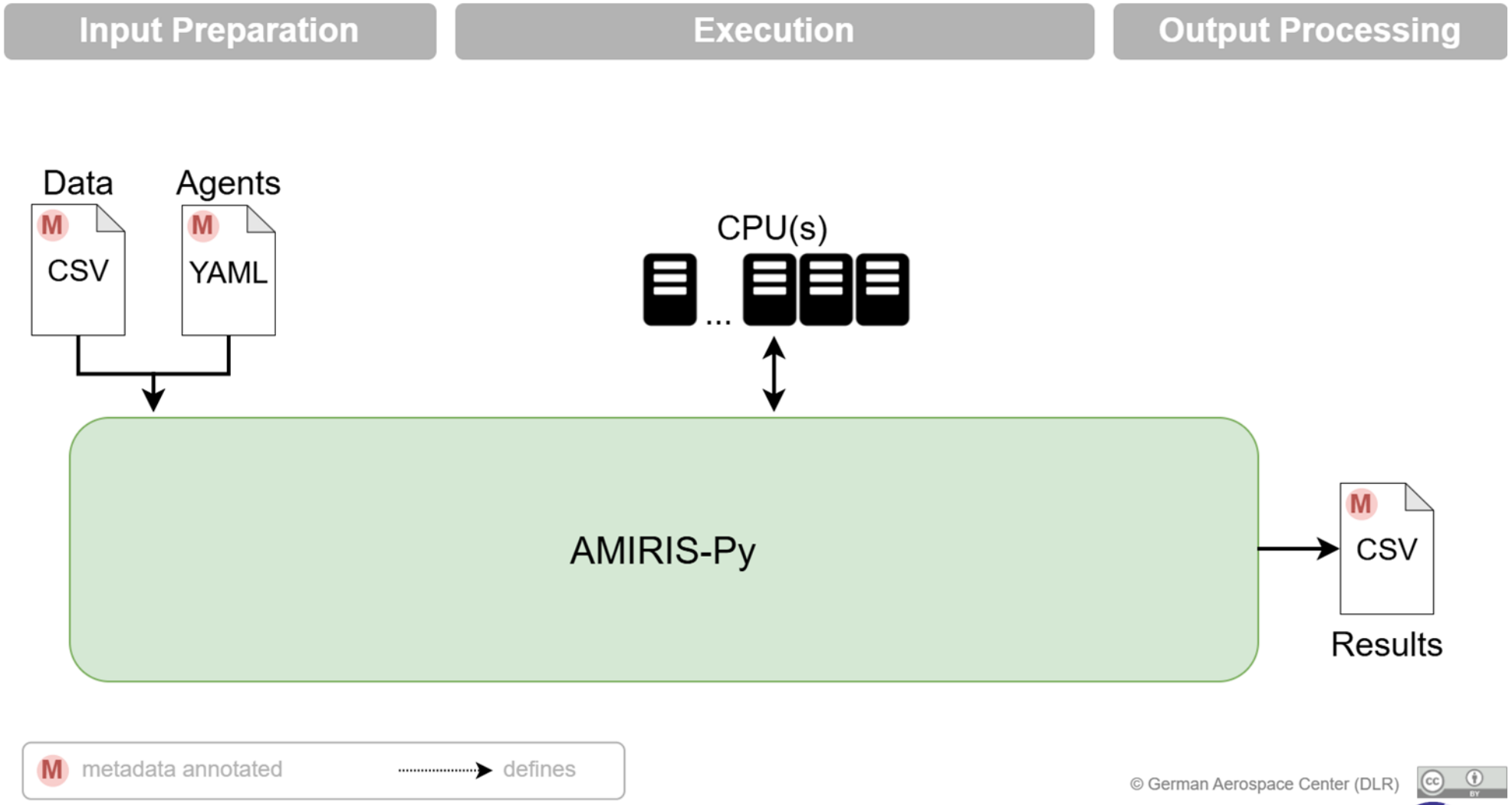

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FAME-Io: https://joss.theoj.org/papers/10.21105/joss.04958

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Setup

Requirements

- Java JDK 11 or greater

```
(base) PS C:\> java --version
openjdk 11.0.29 2025-10-21
OpenJDK Runtime Environment Temurin-11.0.29+7 (build 11.0.29+7)
OpenJDK 64-Bit Server VM Temurin-11.0.29+7 (build 11.0.29+7, mixed mode)
```

  - Obtain from, e.g., https://adoptium.net/

- Python 3.10 or greater

```
(base) PS C:\> python --version
Python 3.10.14
```

  - Obtain from, e.g., https://github.com/conda-forge/miniforge#mambaforge

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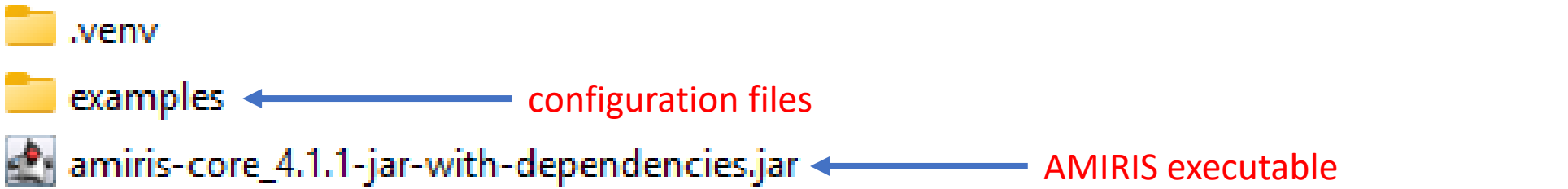
Setup

AMIRIS-Py

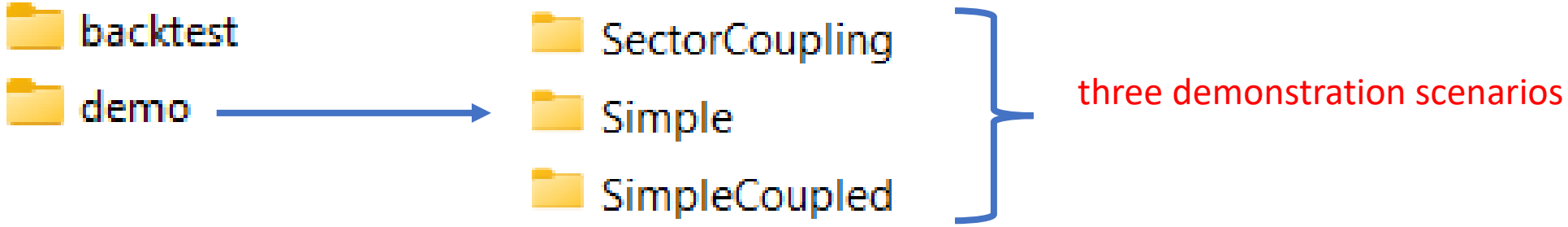
- Create folder
```
(base)> mkdir amiris; cd amiris
```
- Create environment
```
(base)> uv venv --python 3.11
```
- Install *amirispy*
```
(base)> uv pip install amirispy
```
- Activate environment
```
(base)> .venv/Scripts/activate
```
- Download AMIRIS
```
(amiris)> amiris download
```

Setup

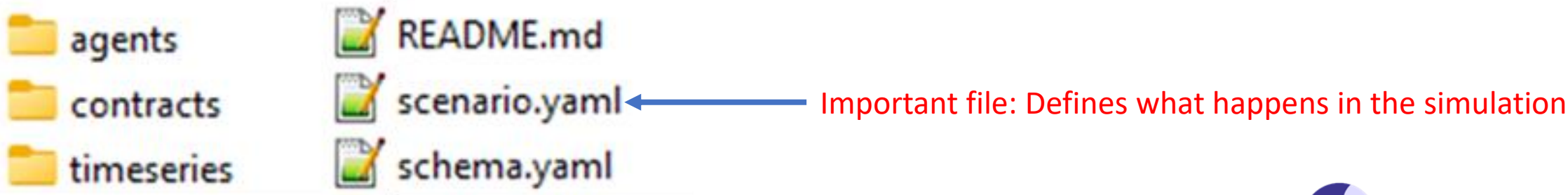
Files



examples/



examples/demo/Simple/



MANOEUVRE

Setup

Run AMIRIS

```
(amiris) PS C:\amiris> amiris run
usage: amiris run [-h] --scenario SCENARIO [--jar JAR] [--output OUTPUT]
                  [--output-options OUTPUT_OPTIONS] [--no-checks]
```

Required argument

- -s Scenario file

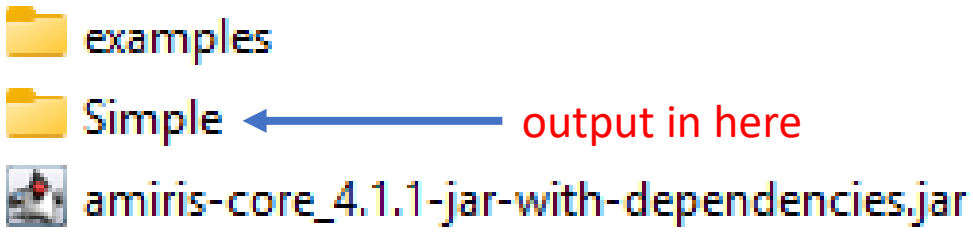
Use tab-completion for scenario

```
(amiris) PS C:\amiris> amiris run –s .\examples\demo\Simple\scenario.yaml –o Simple
```

output folder

Console output

```
2026-03-27 13:47:21:: Simulation completed after executing 291 ticks in 0.16 seconds.
13:47:21 – PRINT – Successfully executed AMIRIS. See your results in ‘Simple'
```



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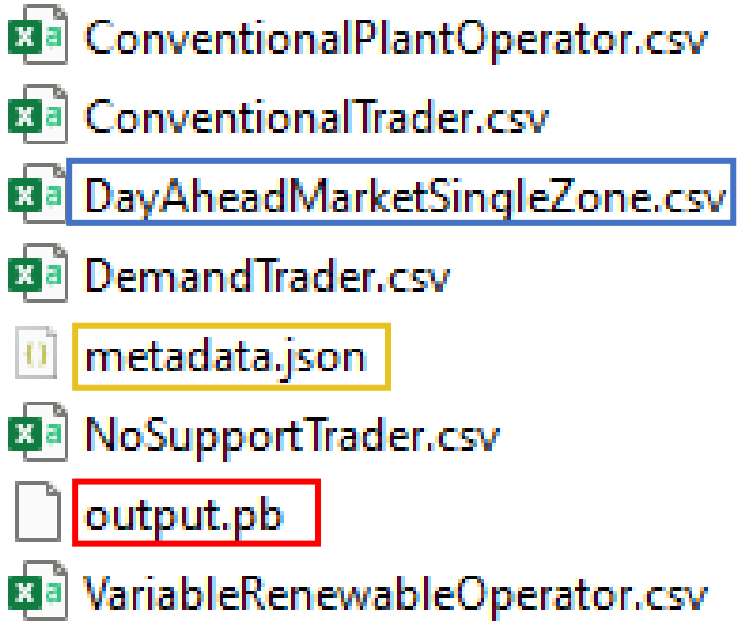
Setup

Results



AgentId	TimeStep	AwardedEnergyInMWH	ElectricityPriceInEURperMWH
1	01.01.2021 00:00	12431	267.4721054
1	01.01.2021 01:00	11416	262.9066734
1	01.01.2021 02:00	11163	260.8119727
1	01.01.2021 03:00	11036	257.4786831
1	01.01.2021 04:00	11192	256.4702082
1	01.01.2021 05:00	12177	256.2193284
1	01.01.2021 06:00	12685	256.2193284
1	01.01.2021 07:00	15222	259.7771467
1	01.01.2021 08:00	16491	260.2935264
1	01.01.2021 09:00	17125	257.9859146
1	01.01.2021 10:00	17378	255.7190453
1	01.01.2021 11:00	16997	255.4696391
1	01.01.2021 12:00	16237	257.2258181
1	01.01.2021 13:00	15476	256.4702082

Result binary: input, output, metadata

metada.json: fields described by Open Energy Ontology
https://openenergyplatform.org/ontology/

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Parameterisation

Scenario: Main config file to bundle all simulation properties

Open: examples/backtest/Germany2018/scenario.yaml

scenario.yaml

Schema	*definition of valid agent and contract structures*
GeneralProperties	*simulation start/end time, random seed*
StringSets	*names used by multiple agents, e.g. fuels*
Agents	*which agents have what parameters*
Contracts	*how and when agents interact*
Metadata	*describe the scenario*

*Content of scenario.yaml distributed across separate files, for schema, agents, and contracts and joined with **!include**, see https://gitlab.com/fame-framework/fame-io#split-and-join-multiple-yaml-files*

Agents: !include ["agents/*.yaml", "Agents"]

Join contents in section “Agents” of each file ending with “.yaml” in folder “agents” and assign to field **Agents**.

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Simulation 1: Single Storage

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Single Storage

Germany 2018

```
(amiris) PS C:\amiris> amiris run -s .\examples\backtest\Germany2018\scenario.yaml
                                -o 2018
```

Console output

```
2026-04-23 14:05:21:: Simulation completed after executing 184,027 ticks
in 14.56 seconds.
14:05:27 – PRINT – Successfully executed AMIRIS. See your results in '2018'
```

Open: 2018/ GenericFlexibilityTrader.csv

Agent Id	TimeStep	ReceivedMoney InEUR	StoredEnergy InMWH	VariableCosts InEUR	DispatchMultiplier	OfferedEnergy InMWH	AwardedEnergy InMWH
7	01.01.2018 00:00	0	40	0	1	854.4	-854.4
7	01.01.2018 01:00	0	40	0	1	0	0

Profit: 79.5 M€ **Dispatched energy**: 7.3 TWh **Average Price**: 46.22 €/MWh

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Single Storage

Germany 2018

`./examples/backtest/Germany2018/agents/Storage.yaml`

```yaml
- Type: GenericFlexibilityTrader # Pumped Hydro
  Id: 7
  Attributes:
    Device:
      GrossChargingPowerInMW: 8988.8
      NetDischargingPowerInMW: 7120.
      ChargingEfficiency: 0.89
      DischargingEfficiency: 0.89
      EnergyContentUpperLimitInMWH: 40000.
      InitialEnergyContentInMWH: 1000.
    Assessment:
      Type: MIN_SYSTEM_COST
    StateDiscretisation:
      Type: STATE_OF_CHARGE
      PlanningHorizonInHours: 168
      EnergyResolutionInMWH: 160
    Bidding:
      Type: ENSURE_DISPATCH
      SchedulingHorizonInHours: 24
```

change assessment function to **MAX_PROFIT**

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Single Storage

Profit Maximisation

```
(amiris) PS C:\amiris> amiris run -s .\examples\backtest\Germany2018\scenario.yaml
                                  -o MaxProfit
```

Console output

```
2026-04-23 14:25:21:: Simulation completed after executing 184,027 ticks
in 13.74 seconds.
14:25:27 – PRINT – Successfully executed AMIRIS. See your results in 'MaxProfit'
```

Open: MaxProfit/GenericFlexibilityTrader.csv

Open: MaxProfit/DayAheadMarketSingleZone.csv

Profit: 112.6 M€ **Dispatched energy**: 4.8 TWh **Average Price**: 46.30 €/MWh

MAX_PROFIT	MIN_SYSTEM_COST
Collusion	Competition
Higher system cost	Less profit
Less dispatch	More dispatch

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Simulation 2: Competing Storage Units

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Competing Storage Units

Germany 2019

`./examples/backtest/Germany2019/agents/Storage.yaml`

```
Agents:
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
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- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
- Type: GenericFlexibilityTrader
```

18 pumped-hydro storage units, differing by

- Efficiency
- Converter power
- Reservoir size

Details

Schimeczek et al. (2026). 10.1016/j.est.2025.120054

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Competing Storage Units

Germany 2019

```
(amiris) PS C:\amiris> amiris run -s .\examples\backtest\Germany2019\scenario.yaml
                                -o 2019
```

Console output

```
2026-04-23 17:37:07:: Simulation completed after executing 184,027 ticks
in 39.16 seconds.
17:37:14 – PRINT – Successfully executed AMIRIS. See your results in ‘2019'
```

Open: 2019/GenericFlexibilityTrader.csv

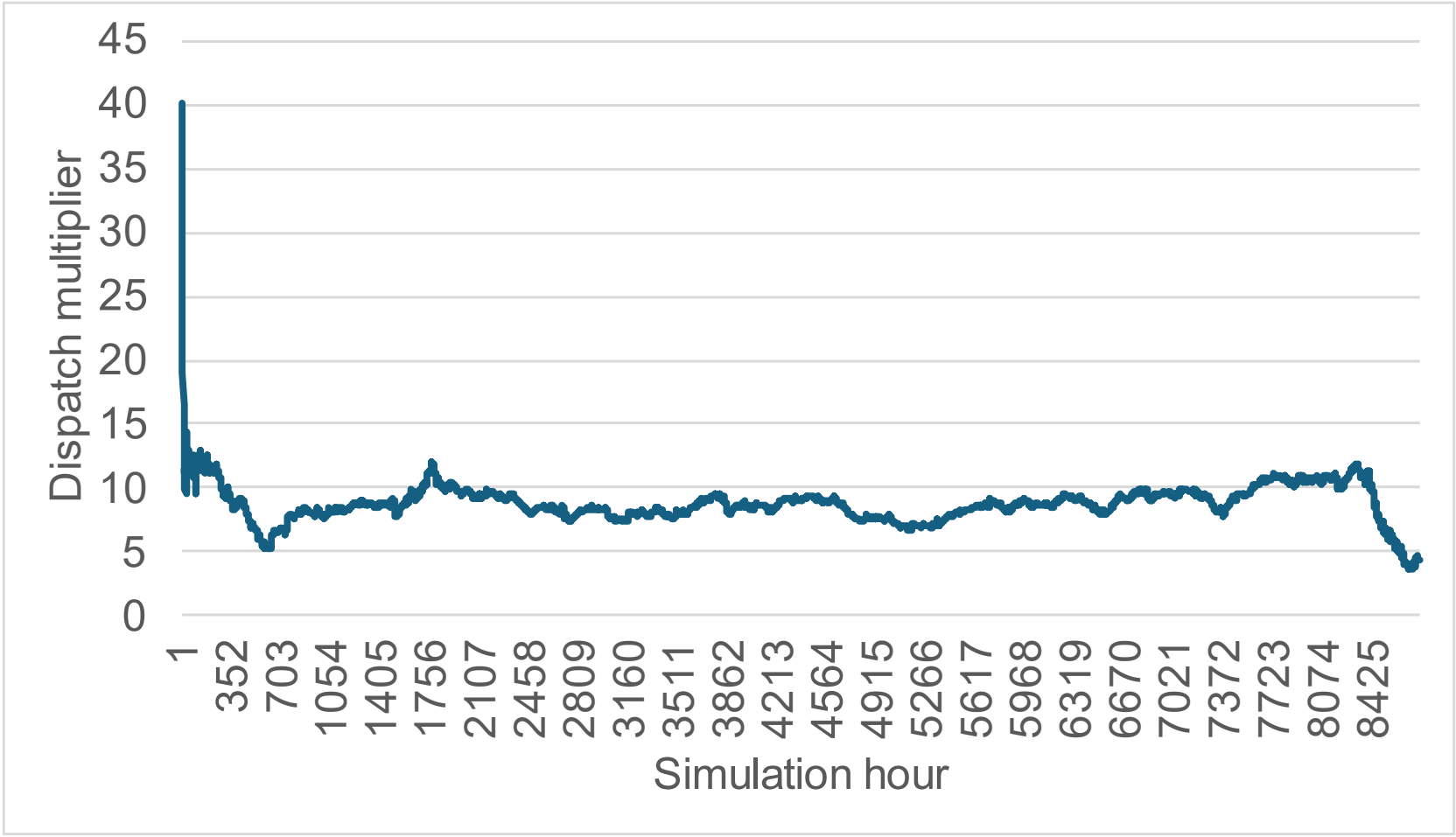
Competing Storage Units

Dispatch Multipliers

Agent 700
Small converter
→ High multiplier

Small reservoir
→ Even higher multiplier

Agent 717
Even smaller converter
but huge reservoir
→ Significantly lower multiplier



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Competing Storage Units

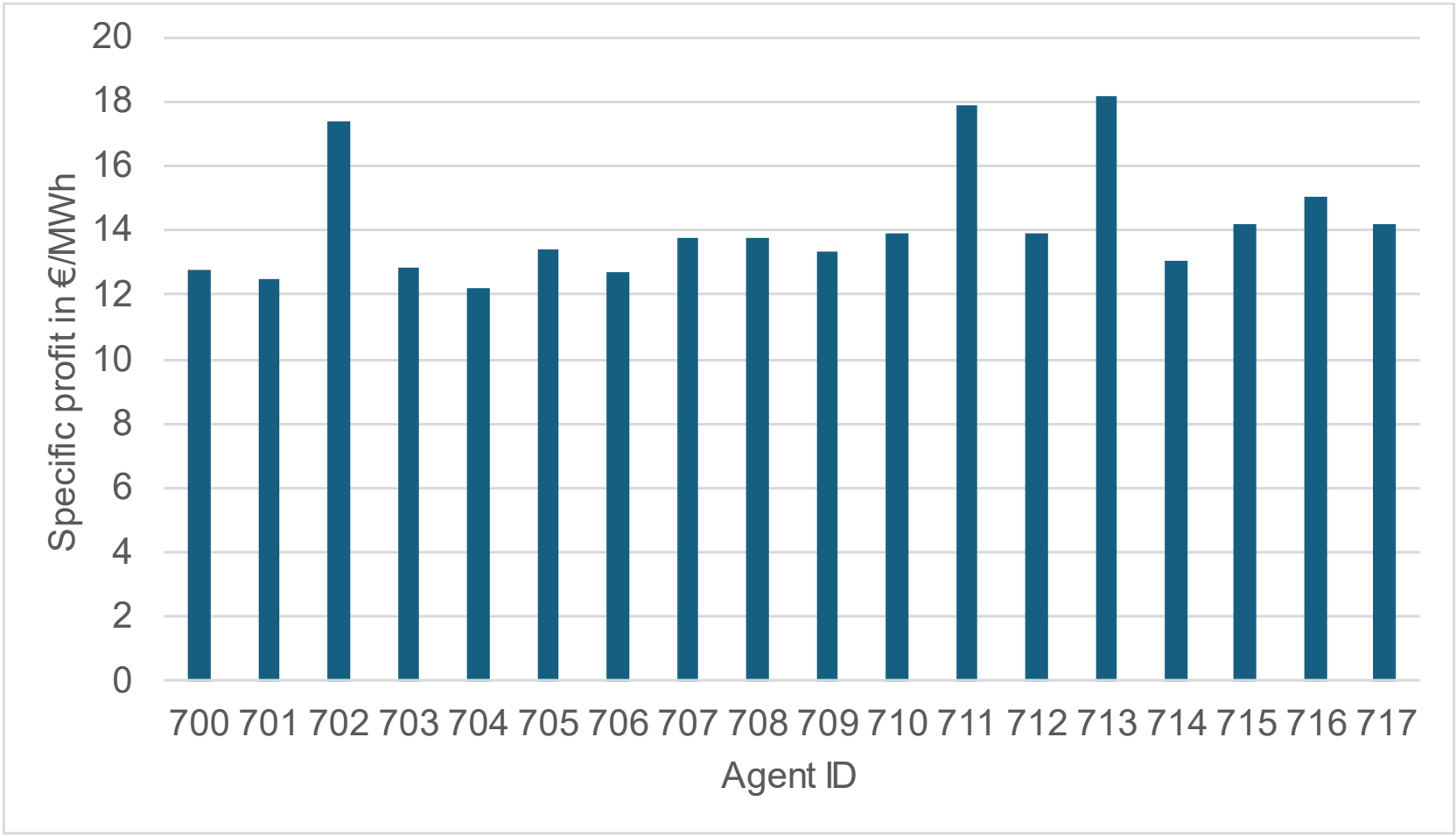
Storage Performance

Energy Share

- Depends on converter power, reservoir size and round-trip efficiency

Profit per MWh

- Higher margins for units with high round-trip efficiency



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Simulation 3: Cross-sector Competition

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Cross-sector Competition

`./examples/demo/SectorCoupling/agents/Storage.yaml`

```yaml
Agents:
  - Type: GenericFlexibilityTrader # Pumped Hydro
  - Type: GenericFlexibilityTrader # Heat Pump
  - Type: GenericFlexibilityTrader # EV unidirectional
  - Type: GenericFlexibilityTrader # EV bidirectional
  - Type: GenericFlexibilityTrader # Load Shifting
```

- 1 large pumped-hydro storage unit
- 1 small heat pump
- 1 small EV unidirectional
- 1 small bidirectional
- 1 small load shifting

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Cross-sector Competition

```
(amiris) PS C:\amiris> amiris run -s .\examples\demo\SectorCoupling\scenario.yaml
                                  -o SectorCoupling
```

Console output

```
2026-04-23 14:59:20:: Simulation completed after executing 184,027 ticks
in 20.82 seconds.
14:59:25 – PRINT – Successfully executed AMIRIS. See your results in ‘SectorCoupling'
```

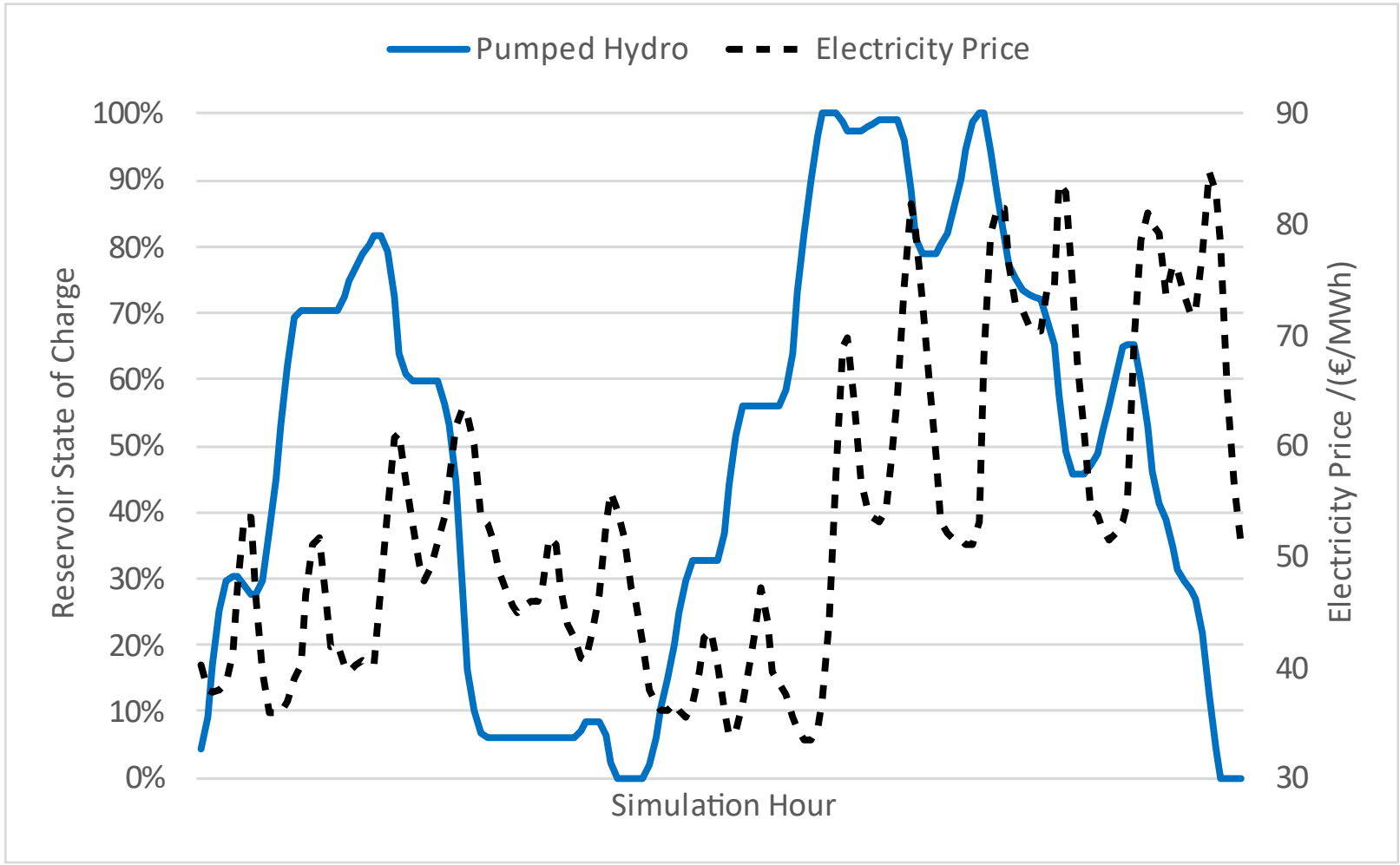
Open: SectorCoupling/GenericFlexibilityTrader.csv

Cross-sector Competition

Evaluation

Pumped Hydro

- Low round-trip efficiency
  → few cycles
  → ignores small price changes



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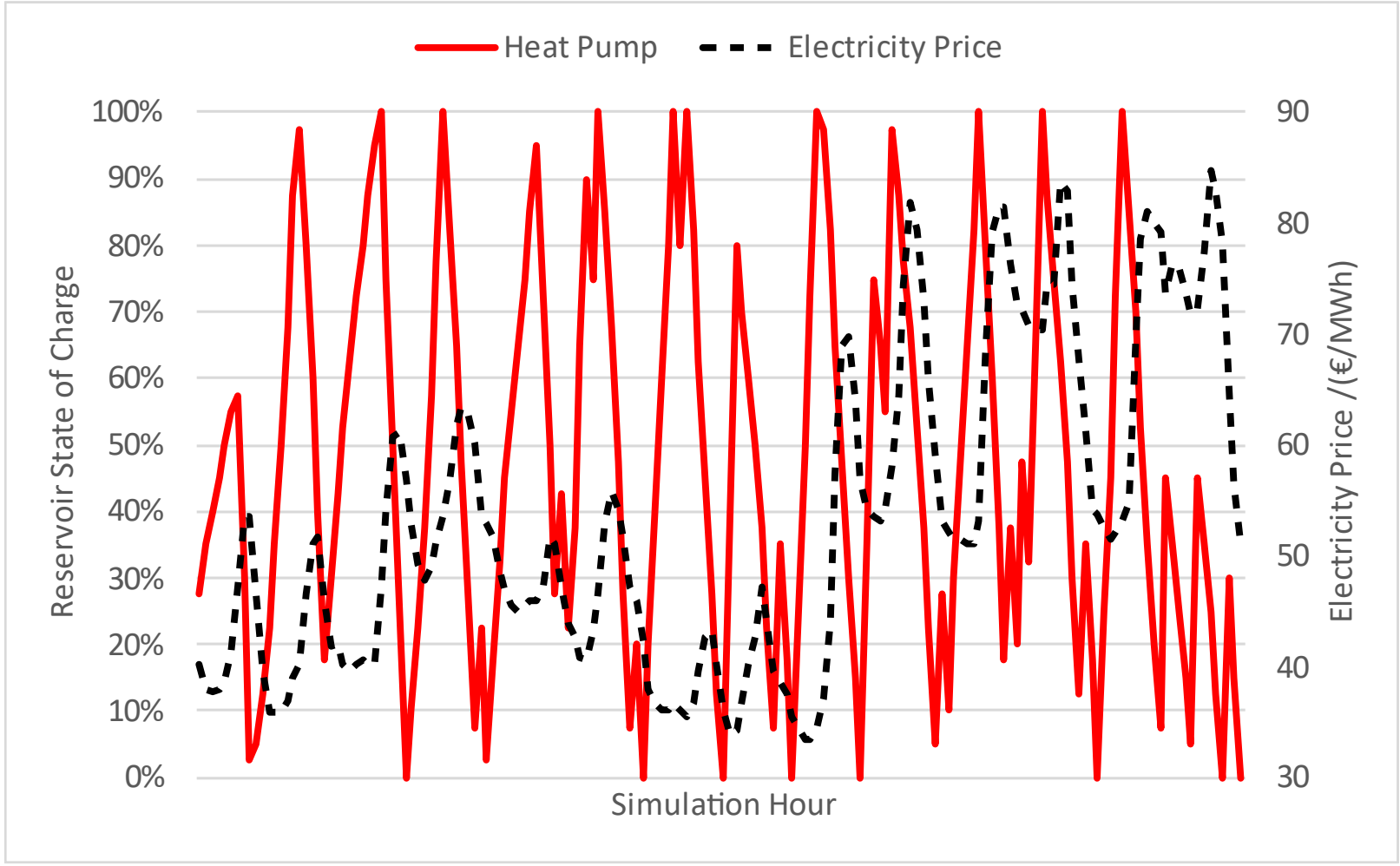
Cross-sector Competition

Evaluation

Heat Pump

- Low outside temperatures
  → fast cooling
  → many cycles
  → forced activity at high prices



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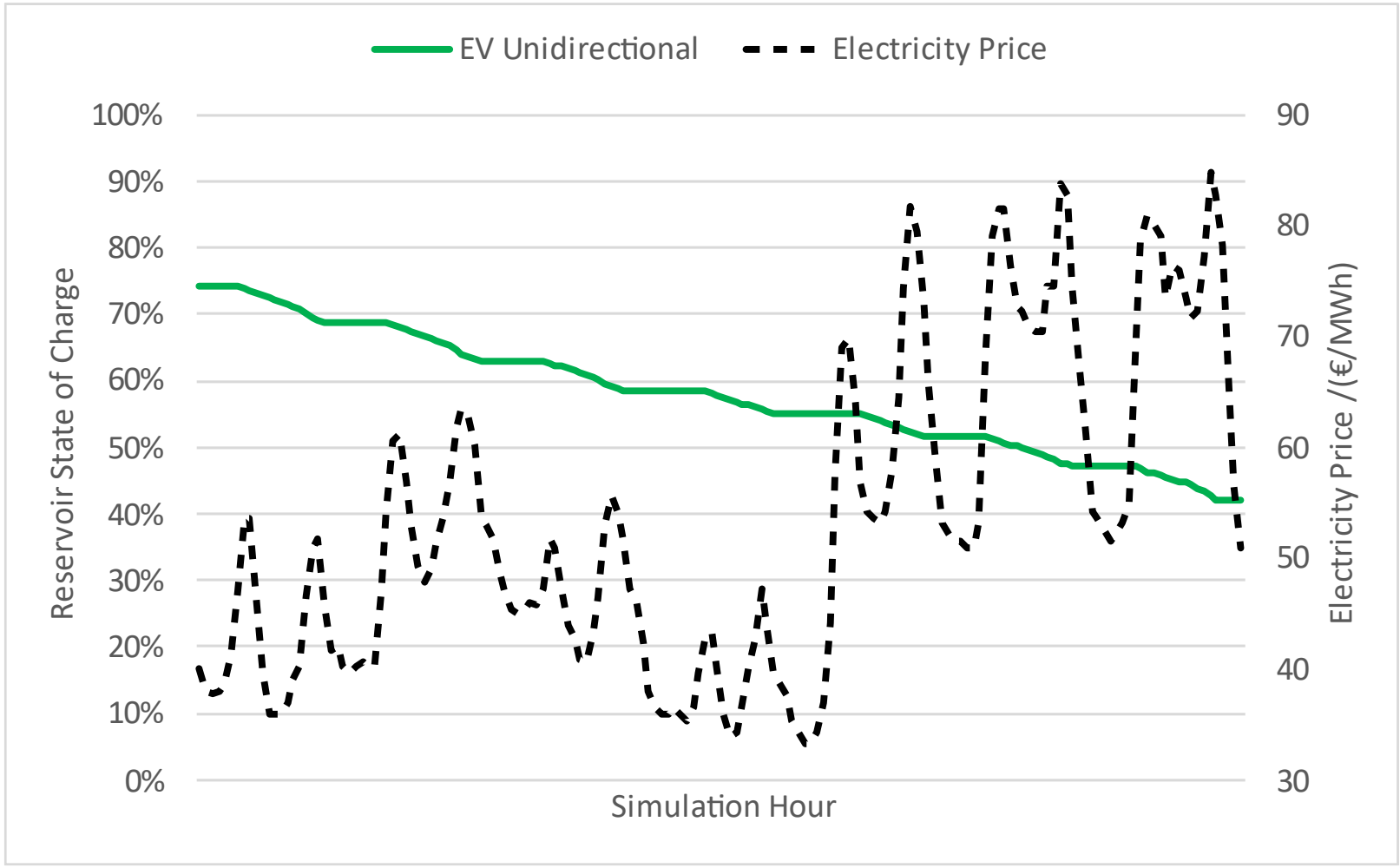
Cross-sector Competition

Evaluation

EV Unidirectional Charging

- Low drain from driving energy
  → slow loss of energy
  → charges only at very low prices



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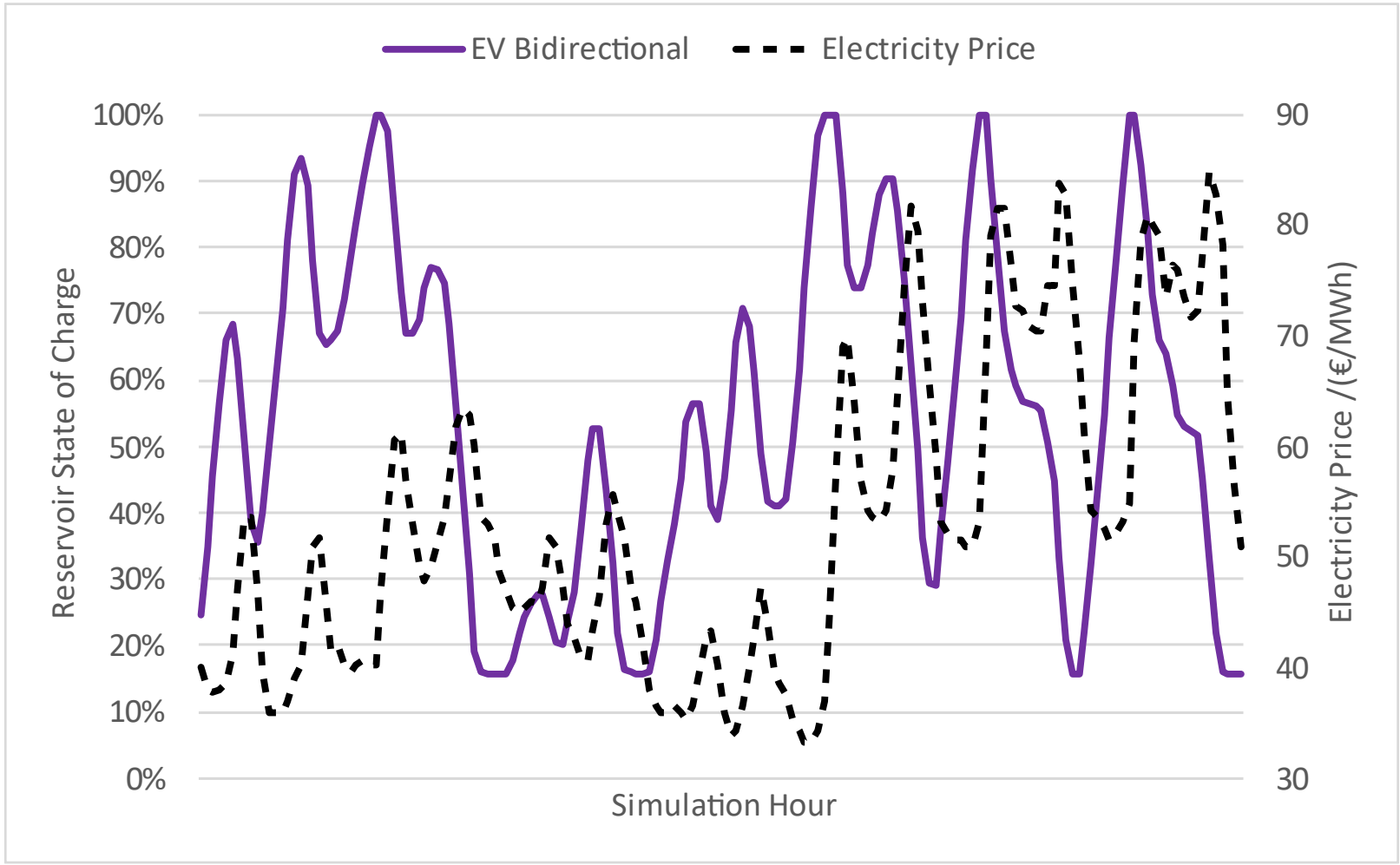
Cross-sector Competition

Evaluation

EV Bidirectional Charging

- High round-trip efficiency
  → many cycles
  → exploits small opportunities



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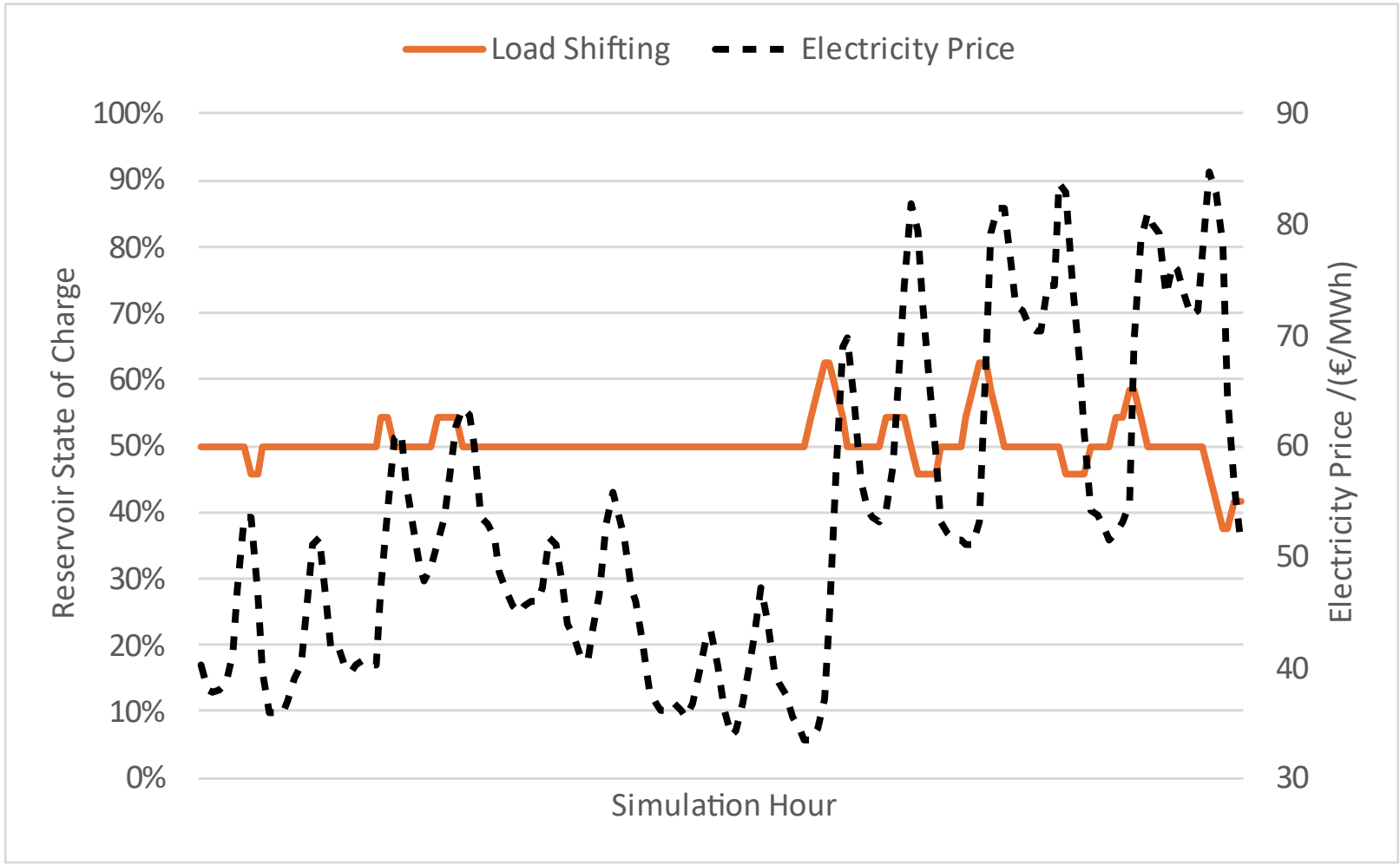
Cross-sector Competition

Evaluation

Load Shifting

- High variable shifting cost
  → few cycles
  → only at largest price differences



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Final Remarks

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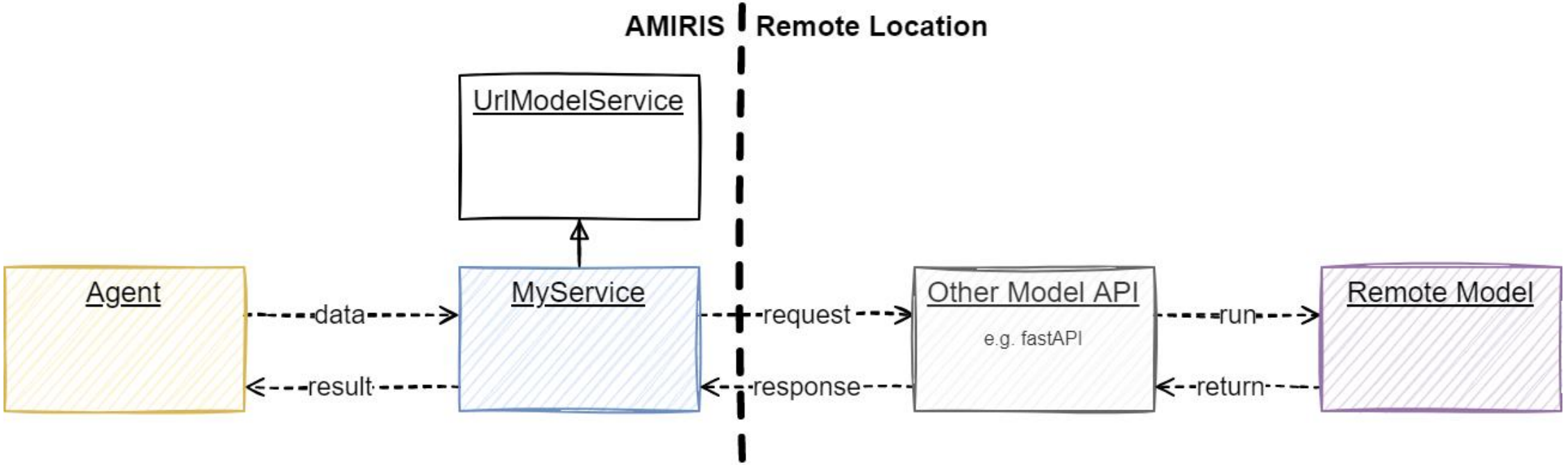
AMIRIS: Model Coupling

Support tools



Benefits

- Easy setup
- Couple with virtually any model
- Allows *interactive* coupling

Examples

- Load shifting optimisation
- Market clearing model
- Heat pump operation
- Neural Network Decision Modules

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AMIRIS

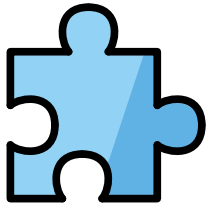
Following FAIR4RS Principles

Findable

- Website
- DOI
- Wikipedia
- COMSES
- HECI
- OEP
- openmod

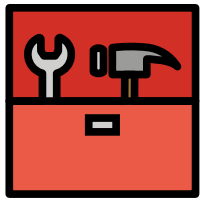
Accessible

- GitLab
- PyPI
- Zenodo



Interoperable

- API
- Workflow tools
- CSV
- YAML
- OEMetadata



(Re-)usable

- Apache 2.0
- REUSE
- Wiki
- Javadoc
- Win/Mac/Linux
- Scalable (H)PC

Key Indicators

Users

- 35 confirmed external user
- 15 external contributions

PhD (candidates)

- 8 internal
- 7 external

Visibility

- 34k views on Wikipedia
- 28k views on openmod

Software

- 51 releases
- 49k downloads

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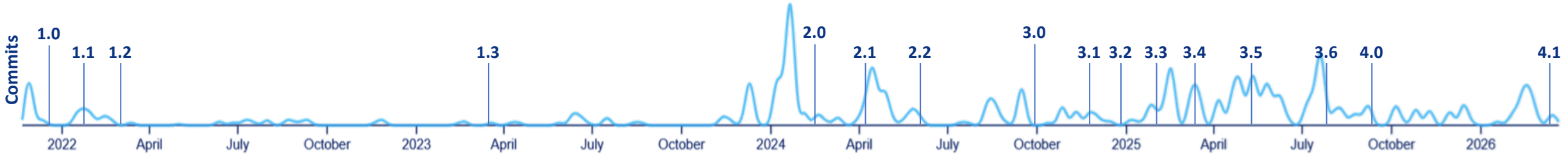
AMIRIS

Activity & Community Support



1237 commits | Last commit ≈ 5 days ago | 19 stars | 11 forks

Post any question about AMIRIS at the openMod Forum.

Send us an email.

Discuss AMIRIS issues at our Open Forum, every Friday 10 o'clock CET.

Raise issues and feel free to contribute.

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Imprint

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