University of Stuttgart
Institute of Parallel and Distributed Systems

The edge-cloud and the “smart building”- “smart grid” continuum

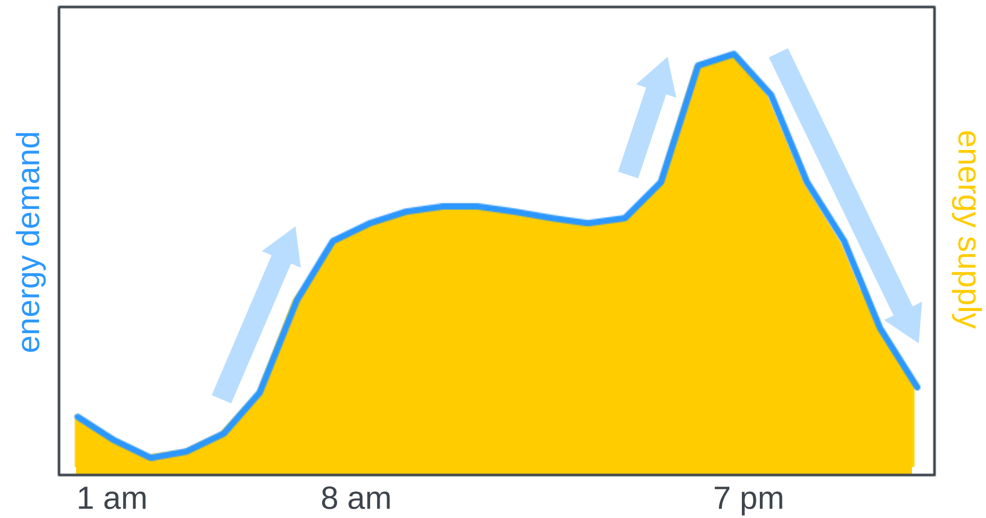
Integrating smart buildings into the smart grid at the energy edge

-- Melanie Heck

BLUE BIRD
building-integrated user-empowered flexibility trading

This project has received funding from the European Union’s Horizon research and innovation programme under grant agreement No 101192452

Once upon a time…



The dilemma of grid operators

Big suppliers and private households
want to feed electricity from renewable energy sources into the power grid

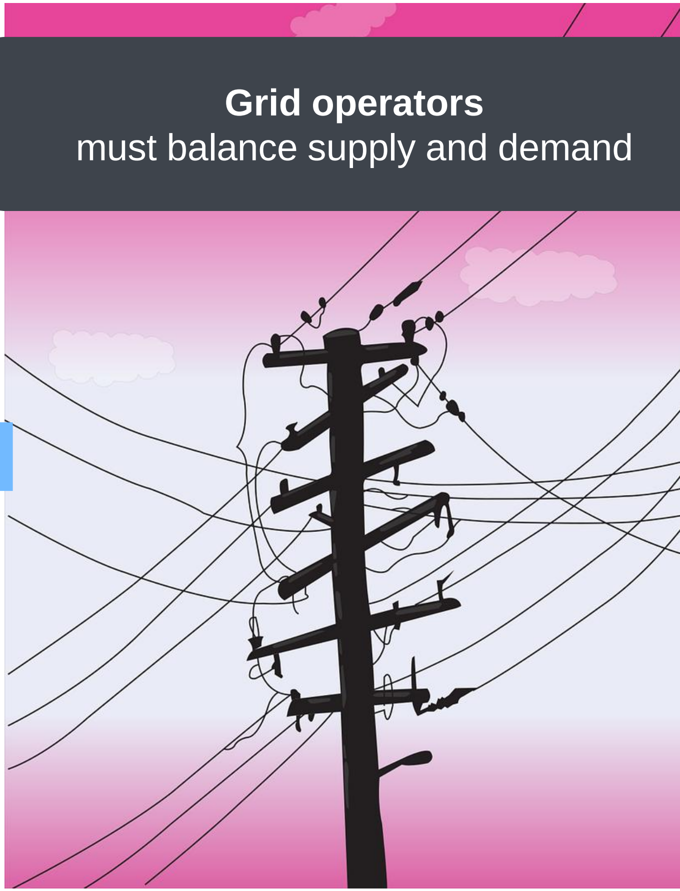
variable

distributed

less predictable

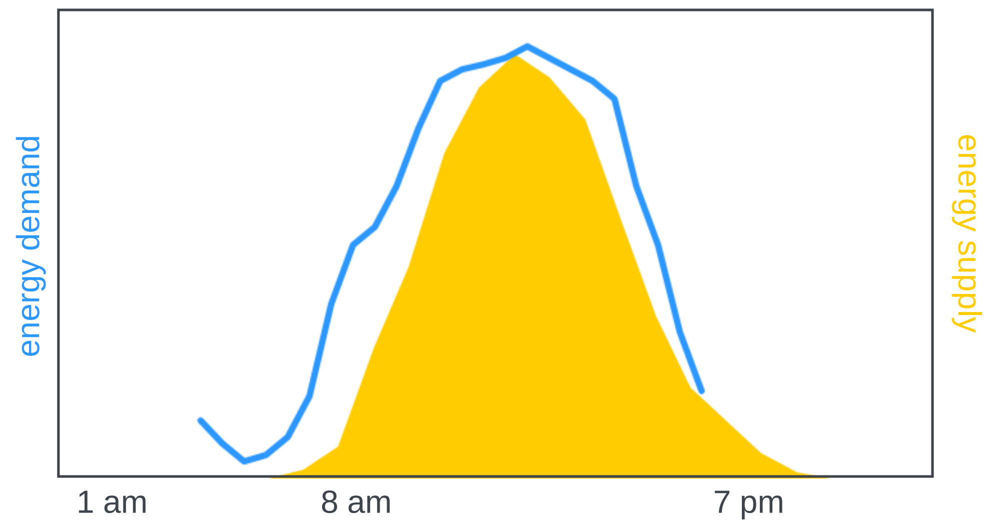
demand
must be more flexible

supply
uncontrollable



Grid operators
must balance supply and demand

New times, new measures



Demand response schemes

Incentivize consumers to align their demand with energy availability

Implicit Demand Response (price based)

- **Dynamic energy prices** reflect the availability of energy supply
- Low prices incentivize to consume energy when availability is high
  - **Real-time pricing**: Hourly price fluctuations
  - **Extreme day** / critical peak pricing: Higher prices on days / critical events with extraordinary demand
  - **Peak pricing**: Different prices for peak vs. off-peak hours

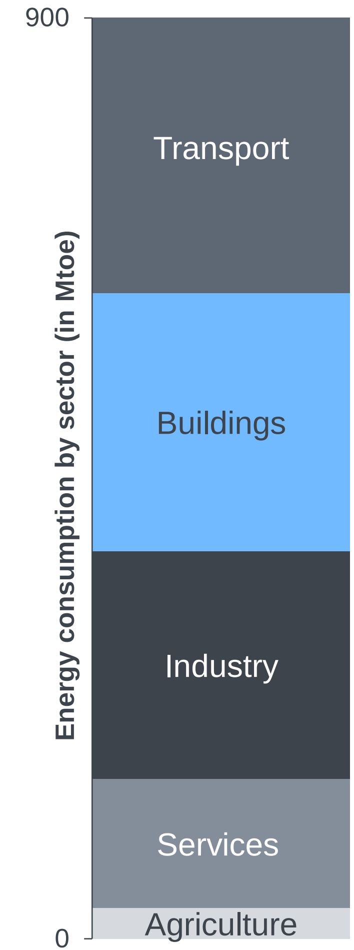
Explicit Demand Response (incentive based)

- Result of demand response actions is **sold upfront** at the electricity market through **contracts**
- When the grid operator needs flexibility, the building must deliver it (activation)
  - **Ancillary services**: Provide power to the grid if supply is low
  - **Curtailment programs**: Decrease energy consumption when a demand response event occurs
  - **Demand bidding**: Consumers offer to reduce their load at a certain price
- Contract violation results in a penalty

What are sources of energy demand flexibility?

Buildings can act as flexibility assets

- Buildings account for almost 30% of the total energy consumption
  - Almost 75% are energy inefficient [European Commission, 2024]



[Enerdata, 2022]

Sources:
Enerdata (2022). https://www.odyssee-mure.eu/publications/efficiency-by-sector/overview/final-energy-consumption-by-sector.html
European Commission (2024). https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

What are sources of energy demand flexibility?
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Technical flexibility

- **Temporal shift** through controllable loads and energy storage
- **Multiple energy carriers** (e.g., local renewables and external grid)

- Accept temperatures below (in winter) or above (in summer) personal comfort range
- Charge EV to 80% instead of 100%

Social flexibility

- **Problem**: Individual households don’t have the volume to participate in explicit demand response

BlueBird

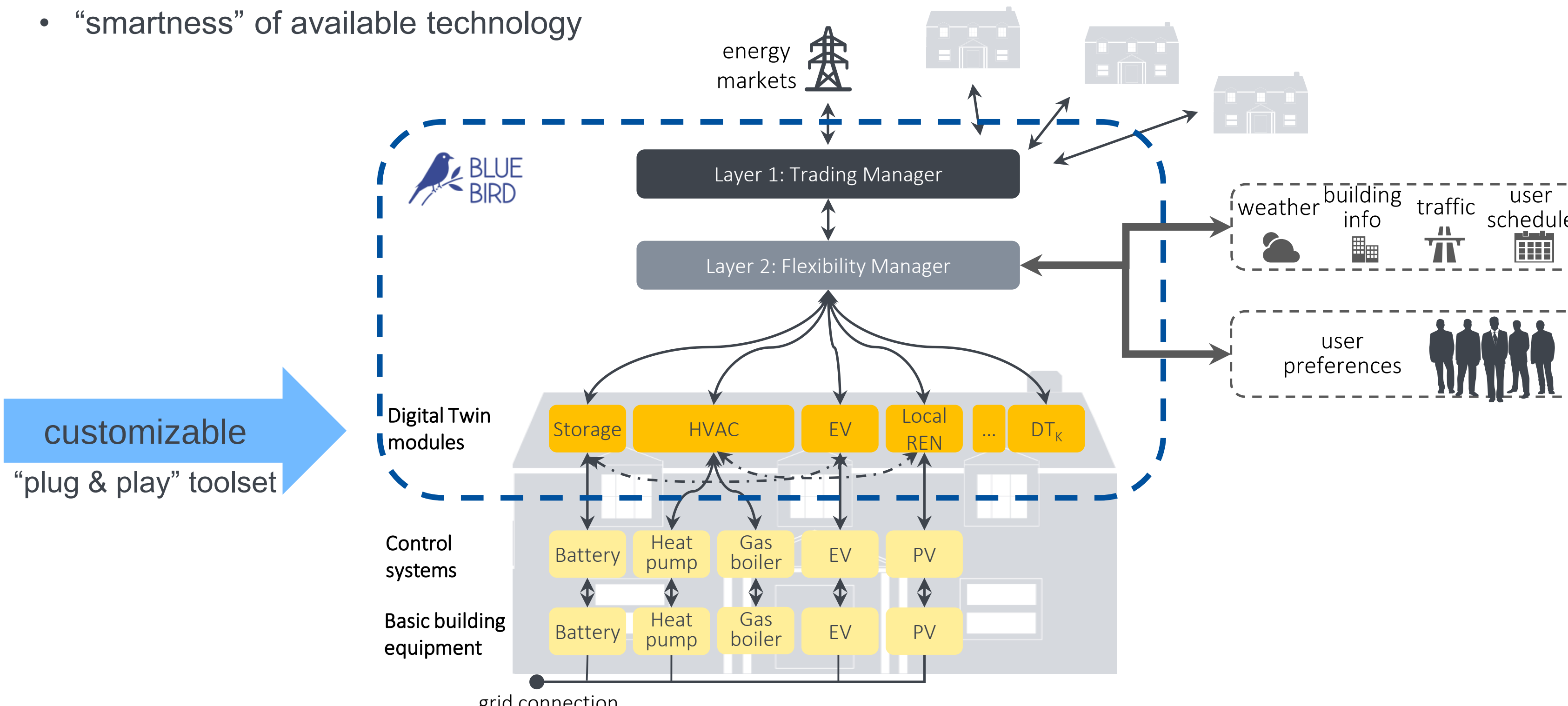
Building Integrated User Empowered Flexibility Trading

- Project funded under **HORIZON EUROPE Innovation Action under Climate, Energy and Mobility**
- 15 partners from research institutions, industry, public authorities, and NGOs across six European countries

BlueBird

Pool energy flexibility of multiple buildings and turn them into flexibility assets

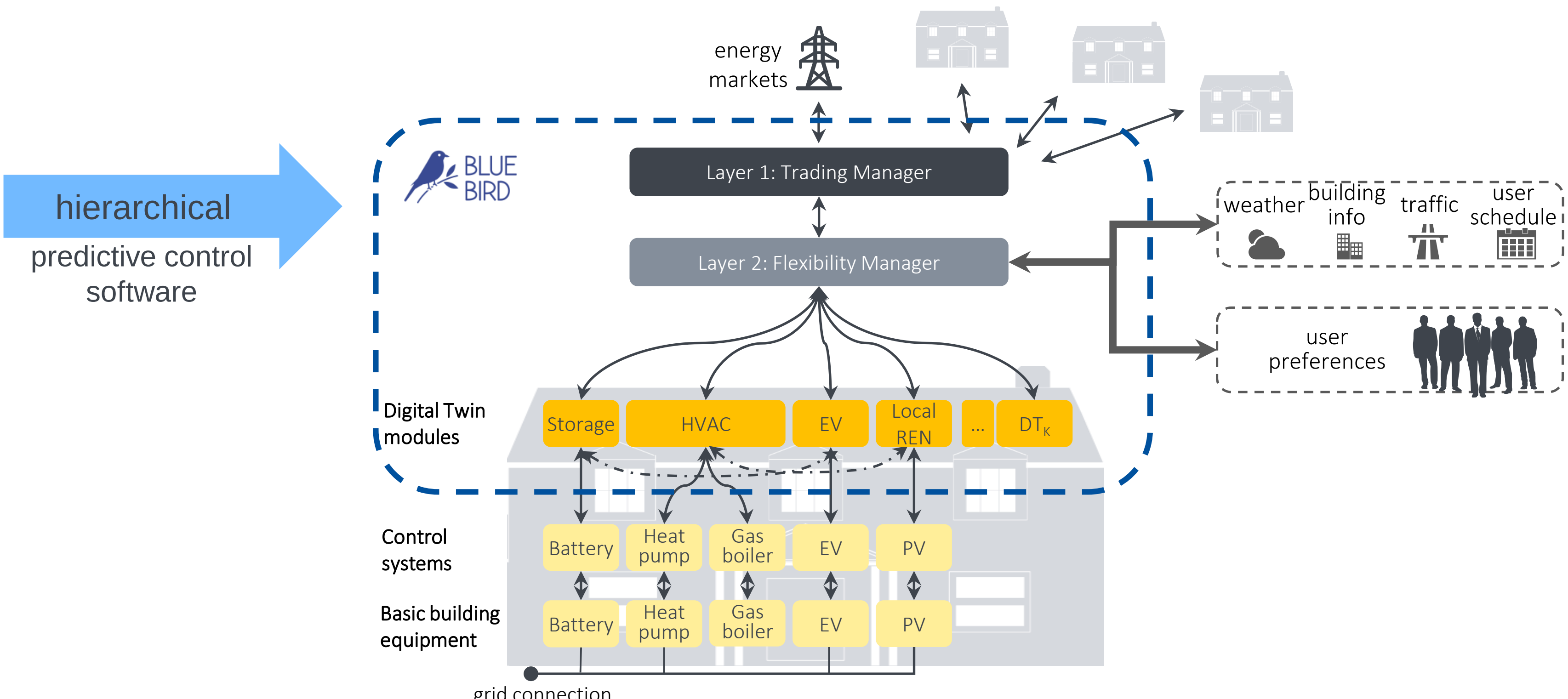
- Flexibility of a building depends on:
  - local regulations and demand response programs
  - “smartness” of available technology



BlueBird

Pool energy flexibility of multiple buildings and turn them into flexibility assets

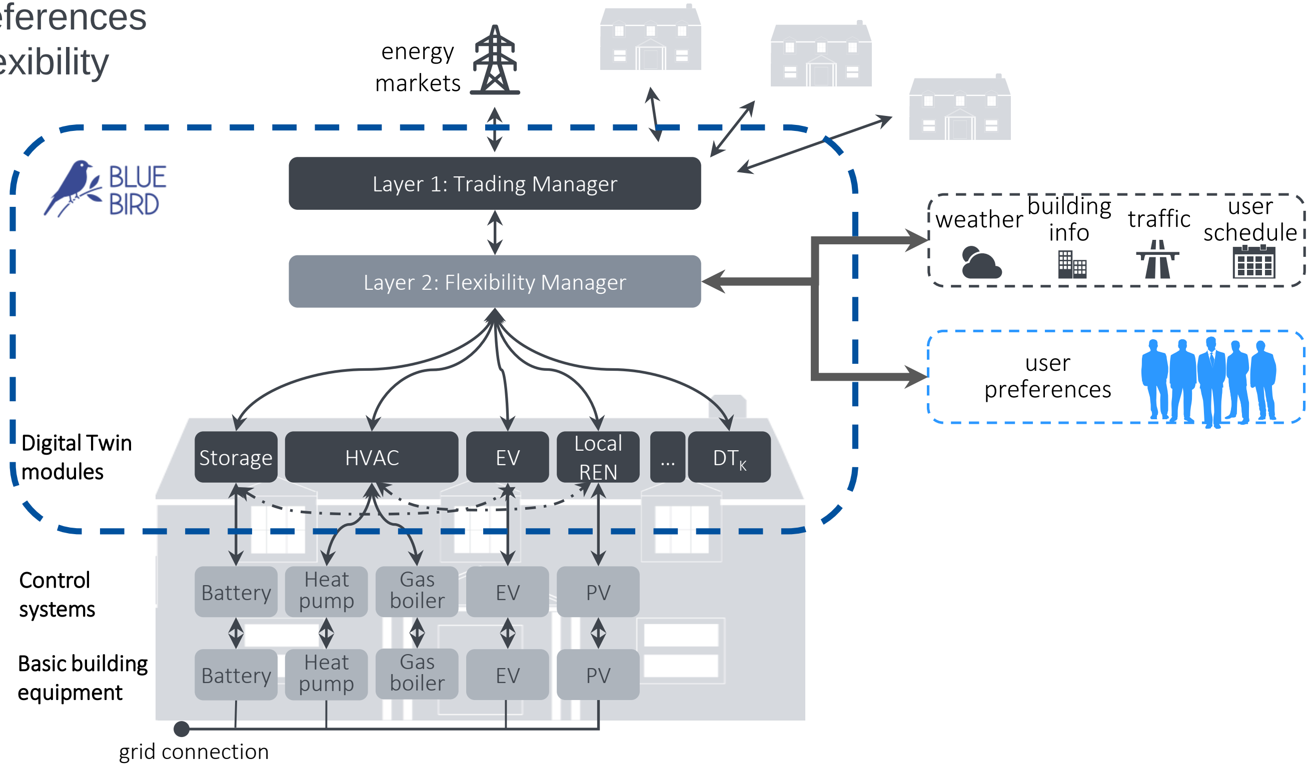
- Exploits synergies between all connected systems (HVAC, storage, local renewable energy (REN) generation, heat pump, gas, etc.)



BlueBird

Pool energy flexibility of multiple buildings and turn them into flexibility assets

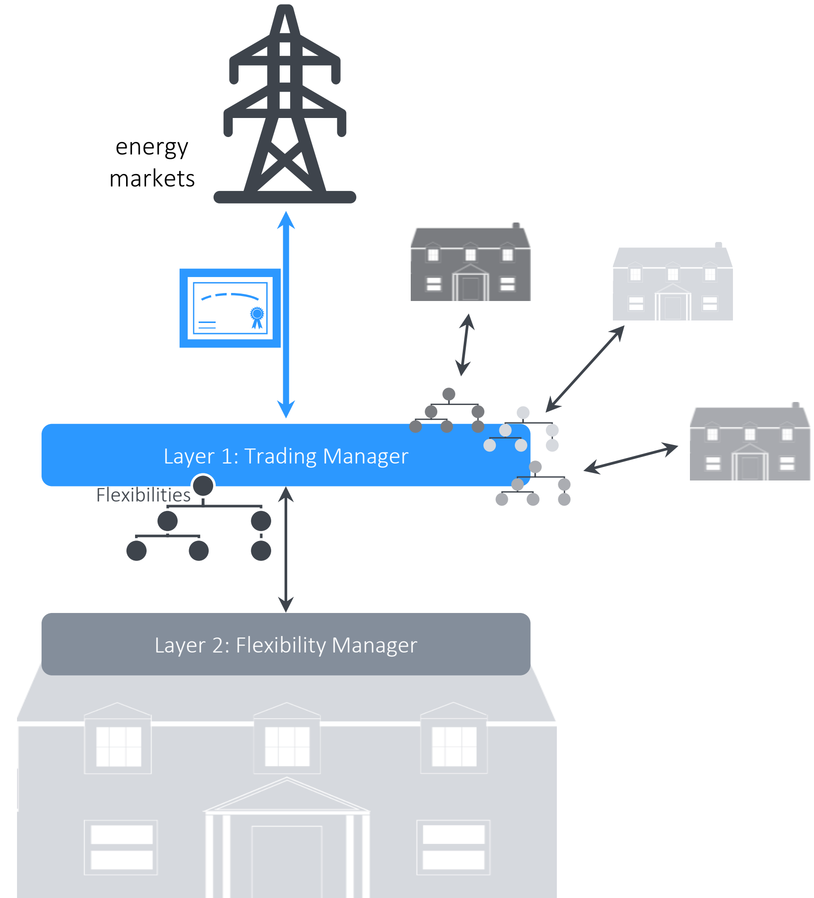
- Optimizes the building's internal operation based on **price signals**, **building usage context,** and **external events** (e.g., weather conditions, traffic, air pollution)
  - Occupants give preferences and feedback on flexibility actions via apps



Trading Manager

Task 1: Bidding in upstream markets

- Pools together the **flexibility from multiple buildings** and **trades it** on energy markets
- Maintains models characterizing the response of the **pooled** buildings to prices based on hierarchies of flexibilities
  - Hierarchies depend on the preferences and constraints of the buildings
- Trades buildings’ flexibilities according to their hierarchy
  - This happens at different times depending on the involved markets (e.g., day-ahead, intra-day balancing, aFRR)



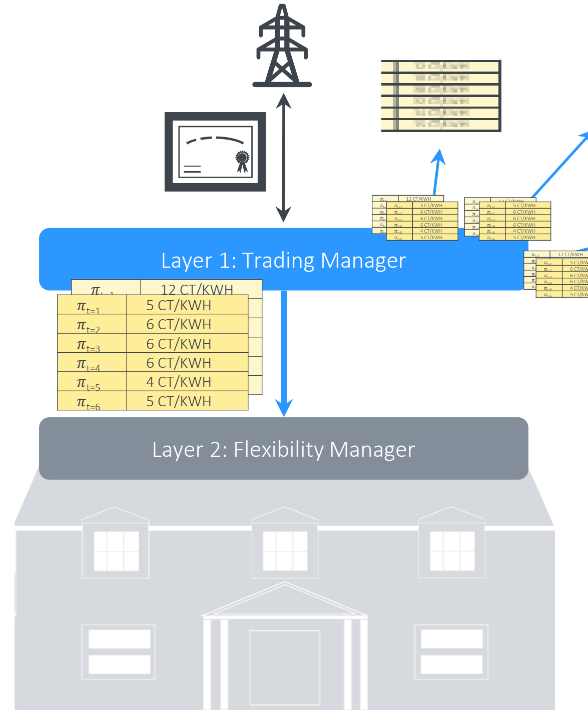
Trading Manager

Task 2: Calculating optimal prices for connected buildings in an iterative manner

- Forecast **internal power price profile** for buildings to **achieve the aggregated power** that **minimizes total power costs** based on accepted bids and activations in markets
  - Considers both monetary **incentives** for DR contracts and **penalties** for deviations

$$min_{\pi t+1,\ldots,\ \pi t+K} \sum_{k=1}^{K} \boldsymbol{c_{buysell}}(\phi_{bids,\ t+k}) + \boldsymbol{c_{penalty}}\left(\phi_{bids,\ t+k} - \sum_{n=1}^{N} \hat{\phi}_{n,\ t+k}(\pi_{t+1},\ldots,\pi_{t+K})\right)$$

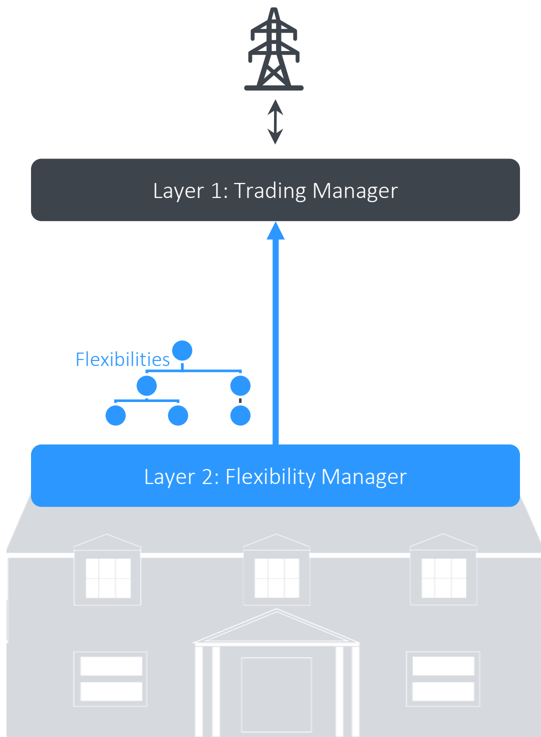
- Send **price profile** forecast for the following K time steps $(\pi_{t+1},\ldots,\pi_{t+K})$ to the buildings



Flexibility Manager

Task 1: Build and trade a hierarchical model of available **building flexibilities**

- **Technical flexibility:**
  - **Balance on-site resources** with controllable loads and energy storage
    - HVAC: Accumulate heat/cold in the building structure and air
    - Energy storage (e.g., EV chargers with V2G, batteries)
  - Optimize energy consumption **across all energy carriers** of the building (e.g., switch between local renewables and the external grid)
- **Social flexibility**: Preferences and acceptability ranges of residents



Flexibility Manager

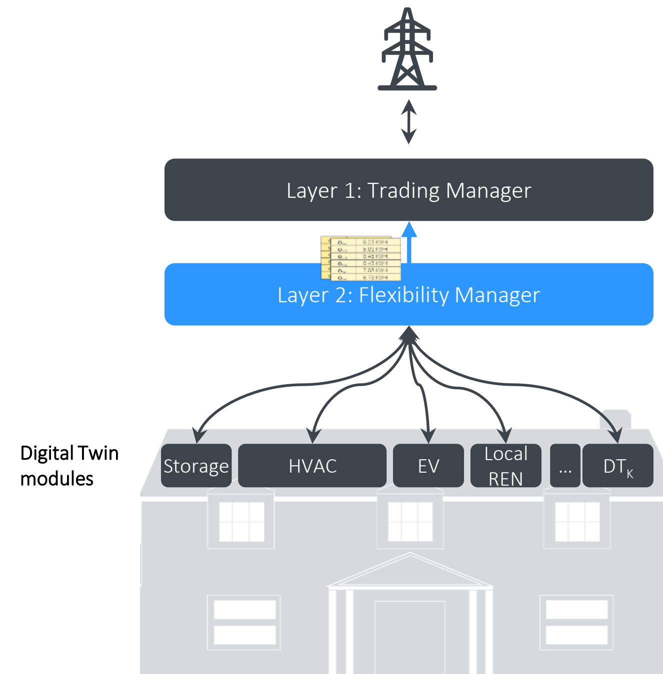
Task 2: Determine the building's demand (or supply) for grid power

- Send **price profile** forecast to each digital twin
- Receive forecasts of required (or offered) **power** given the received price profile
- Calculate total power demand (or supply) of the building for the following K time steps and send it to the Trading Manager

positive: refill battery

negative: use stored energy for internal consumption or for trading in energy markets

$\phi_{t=1}$	$\phi_{t=1,HVAC} + \phi_{t=1,EV} + \phi_{t=1,REN} + \boxed{\phi_{t=1,storage}}$
$\phi_{t=2}$	$\phi_{t=2,HVAC} + \phi_{t=2,EV} + \phi_{t=2,REN} + \phi_{t=2,storage}$
$\phi_{t=3}$	…
$\phi_{t=4}$	…
$\phi_{t=5}$	…
$\phi_{t=6}$	…



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positive: receive power to charge EVs

negative: 2-way charging stations supply power for trading in energy markets

$\phi_{t=1}$	$\phi_{t=1,HVAC} + \boxed{\phi_{t=1,EV}} + \phi_{t=1,REN} + \phi_{t=1,storage}$
$\phi_{t=2}$	$\phi_{t=2,HVAC} + \phi_{t=2,EV} + \phi_{t=2,REN} + \phi_{t=2,storage}$
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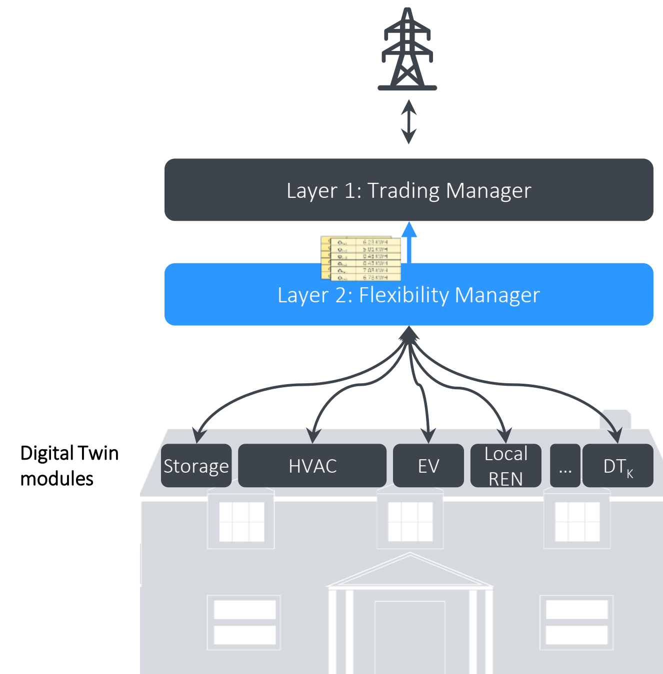

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always negative: use generated power for internal consumption or for trading in energy markets

$\phi_{t=1}$	$\phi_{t=1,HVAC} + \phi_{t=1,EV} + \boxed{\phi_{t=1,REN}} + \phi_{t=1,storage}$
$\phi_{t=2}$	$\phi_{t=2,HVAC} + \phi_{t=2,EV} + \phi_{t=2,REN} + \phi_{t=2,storage}$
$\phi_{t=3}$	...
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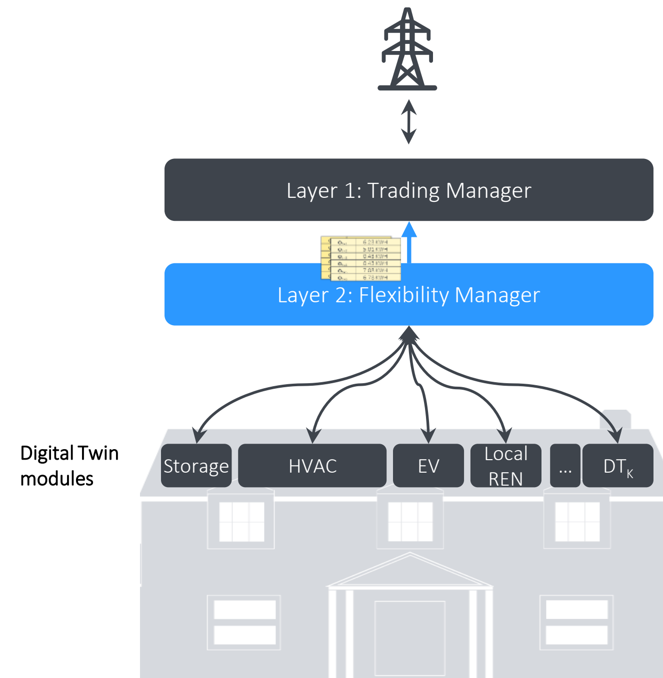

Flexibility Manager

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- Calculate total power demand (or supply) of the building for the following K time steps and send it to the Trading Manager

always positive: receive power to maintain temperature within constraints

$\phi_{t=1}$	$\boxed{\phi_{t=1,HVAC}} + \phi_{t=1,EV} + \phi_{t=1,REN} + \phi_{t=1,storage}$
$\phi_{t=2}$	$\phi_{t=2,HVAC} + \phi_{t=2,EV} + \phi_{t=2,REN} + \phi_{t=2,storage}$
$\phi_{t=3}$	…
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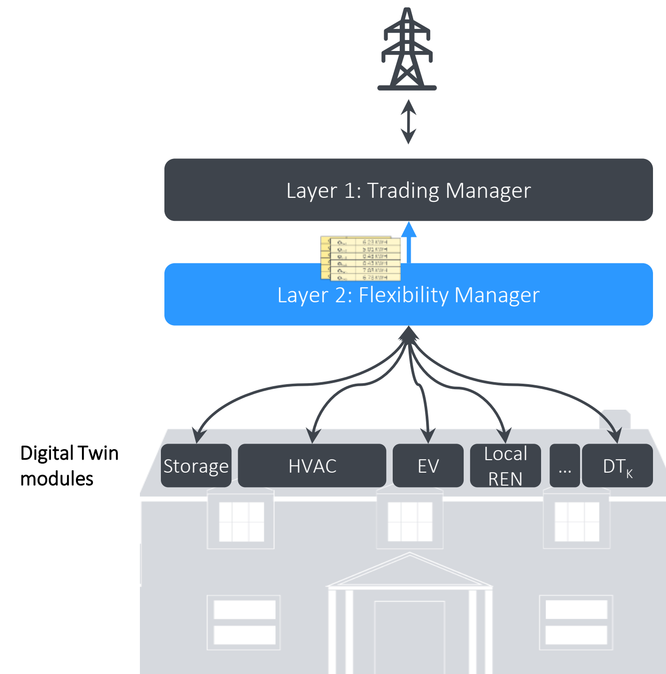
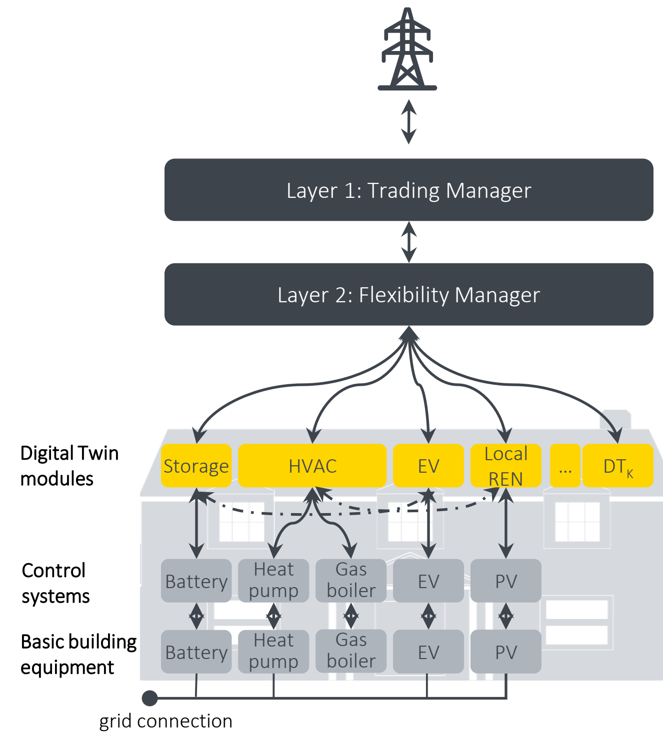


Digital twins

Task 1: Virtualize the building's underlying technological landscape

- Predicting optimal power profiles is simple for batteries or EV (level of charging)
- It is more complex for **HVAC** due to thermal inertia of buildings
  - Accumulate heat/cold in the building structure and air
  - When switched off, it takes some time before comfort/ safety constraints are violated



Digital twins

Task 2: Economic Model Predictive Control

- Predict optimal power consumption ($\hat{\phi}_{t+1},\ldots,\hat{\phi}_{t+K}$) for future K time steps that minimizes power costs given the external price profile ($\hat{\phi}_{t+1},\ldots,\hat{\phi}_{t+K}$) and internal costs ($\hat{c}_{t+1},\ldots,\hat{c}_{t+K}$)

$$min_{ut+1,\ldots,ut+K} \quad \sum_{k=1}^{K} \pi_{t+k}\, \hat{\phi}_{t+k}\,(x_t,\, u_{t+1},\ldots,u_{t+K},\, d_{t+1},\ldots,d_{t+K}) + \hat{c}_{t+k}\,(x_t,\, u_{t+1},\ldots\,,u_{t+K},\, d_{t+1},\ldots\,,d_{t+K})$$

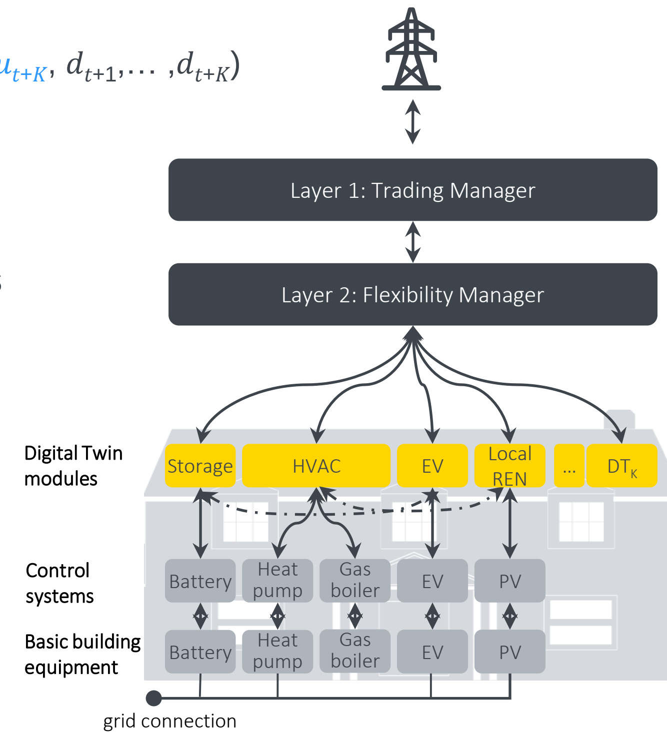
$$subject\ to \quad u_{min,t+k} \leq u_{t+k} \leq u_{max,t+k}$$

$$x_{min,t+k} \leq \hat{f}_{t+k}\,(x_t,\, u_{t+1},\ldots,u_{t+K},\, d_{t+1},\ldots,d_{t+K}) \leq x_{max,t+k}$$

- **Control variables $\boldsymbol{u}$** are set-points that are subject to constraints

const
- **Operating constraints $\boldsymbol{u_{\min}/u_{max}}$** (bounds for control variable)
  - minimum heat pump startup temperature,…
- **Service level constraints $\boldsymbol{x_{\min}/x_{max}}$** (bounds for service level)

func
  - Temperature for expected occupants and their preferences



Digital twins
Task 2: Economic Model Predictive Control

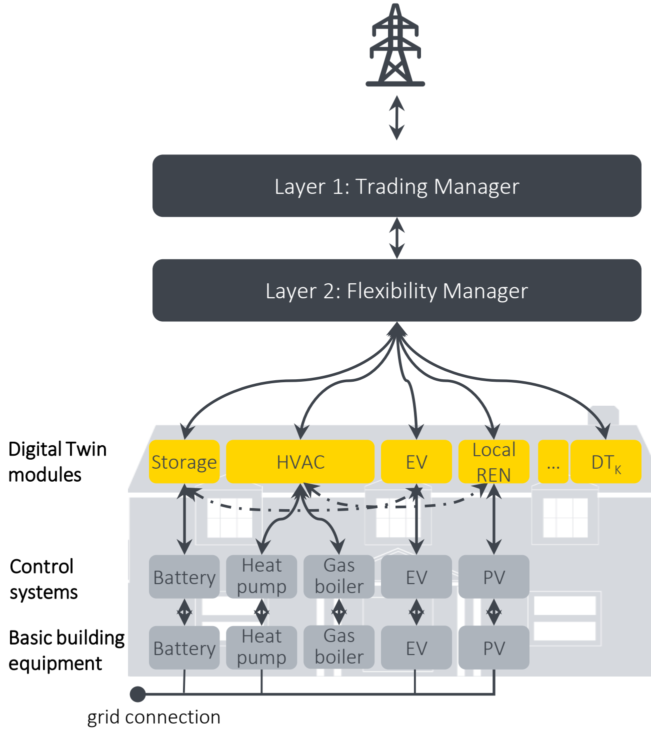
- **Objective**: Find the heating sequence (i.e., shift heating levels) that minimizes power costs

$$\min_{heat_{,t+1},\ldots,\, heat_{,t+K}} \quad \sum_{k=1}^{K} \pi_{t+k}\, \hat{\phi}_{t+k}\,(T_t,\, \boldsymbol{heat}_{t+1},\ldots,\, \boldsymbol{heat}_{t+K},\, d_{t+1},\ldots,d_{t+K})$$

$$\text{subject to} \quad heat_{min,t+k} \le heat_{t+k} \le heat_{max,t+k}$$

$$T_{min,t+k} \le \boxed{T_{t+k}} \le T_{max,t+k}$$

- **Operating constraints $\boldsymbol{heat}_{\min}/\boldsymbol{heat}_{max}$**: Heating level must be within HVAC system specifications
- **Service level constraints**: Indoor temperature $\boldsymbol{T_{t+k}}$ must be within occupants' comfort bounds



Digital twins
Task 2: Economic Model Predictive Control

- **State-space model** predicts room temperature as a function of current temperature, disturbances, and heating set-point

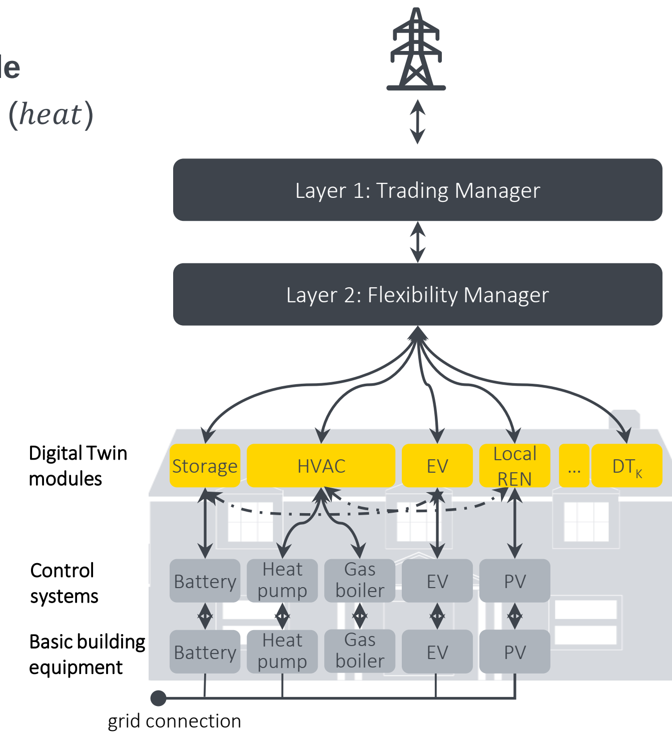
State variables
- Indoor temperature T_i
- Envelope temperature T_e (floor, walls etc.)

Disturbances
- Ambient temperature (T_a)
- Solar radiation (G_v)

Control variable
- Heating level ($heat$)

$$dT_i = \frac{1}{C_i}\left(\underbrace{\boxed{\frac{1}{R_{ie}}(T_e - T_i)}}_{\text{State variables}} + \underbrace{\frac{1}{R_{ia}}(T_a - T_i) + \eta A_w G_v}_{\text{Disturbances}} + heat\right) d_t + \sigma_i dw_i$$

$$dT_e = \frac{1}{C_e}\left(\boxed{\frac{1}{R_{ie}}(T_i - T_e)} + (1-\eta) A_w G_v\right) d_t + \sigma_e dw_e$$

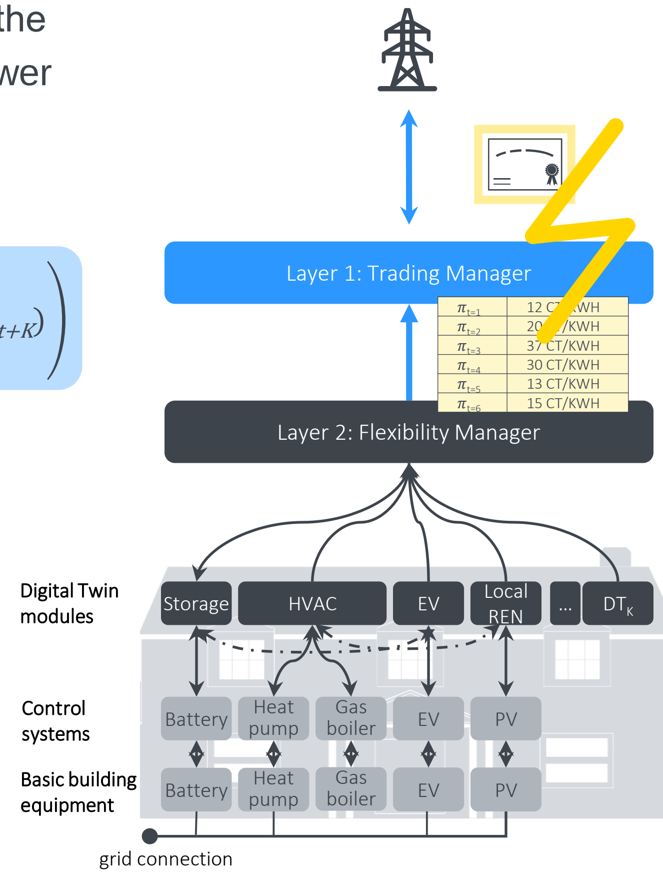


What happens if the predicted power profile deviates from the Trading Manager’s forecasted demand?

- If the building‘s intended power profile violates the contracts that the trading manager has entered in the energy markets, the initial power profile is no longer optimal due to additional incurred penalties

$$\min_{\pi_{t+1},\ldots,\ \pi_{t+K}} \sum_{k=1}^{K} \boldsymbol{c}_{\boldsymbol{buysell}}(\phi_{bids,\ t+k}) + \boldsymbol{c}_{\boldsymbol{penalty}}\left(\phi_{bids,\ t+k} - \sum_{n=1}^{N} \hat{\phi}_{n,\ t+k}(\pi_{t+1}, \ldots, \pi_{t+K})\right)$$

- The trading manager recalculates the price profile based on the received power consumption profiles
- The iterative price setting process continues until convergence



Project Rollout
Pilot sites

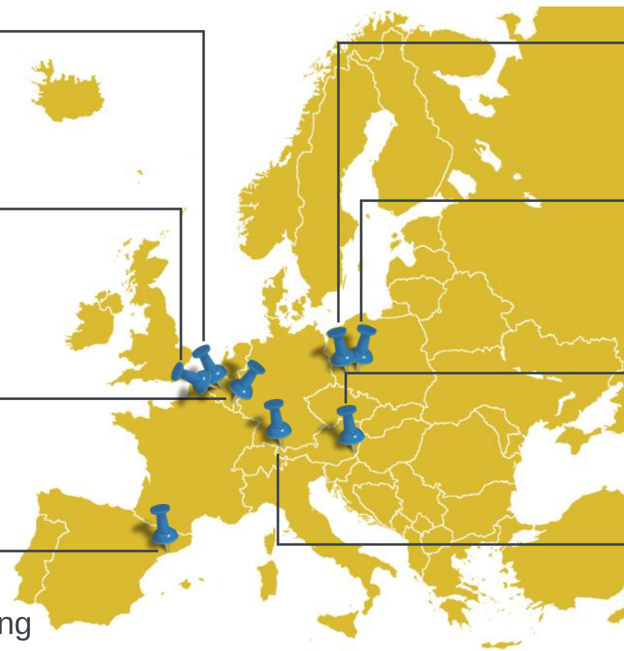
- The BlueBird framework will be implemented at **8 European pilot sites**

Tour & Taxis [Brussels, Belgium]
Energy community with mixed-use buildings and local PV

Greenbizz [Brussels, Belgium]
Business incubator with local renewable energy generation

KARNO [Profondeville, Belgium]
Residential buildings with geothermal heat and local PV

AMB [Barcelona, Spain]
Public buildings with local PV, geothermal and gas-based heating



ENEA [Kuczyna, Poland]
Power station with electric HVAC

ENEA [Poznan, Poland]
Office building with district heating

ENK Waterworks [Oberwart, Austria]
Local PV, battery, and water tanks as energy storage

EWH [Bad Hindelang, Germany]
Hotels with local PV, biomass driven combined heat and power, and EV charging