A general intro to the course

Industrial IoT for Digitization of Electronic Assets

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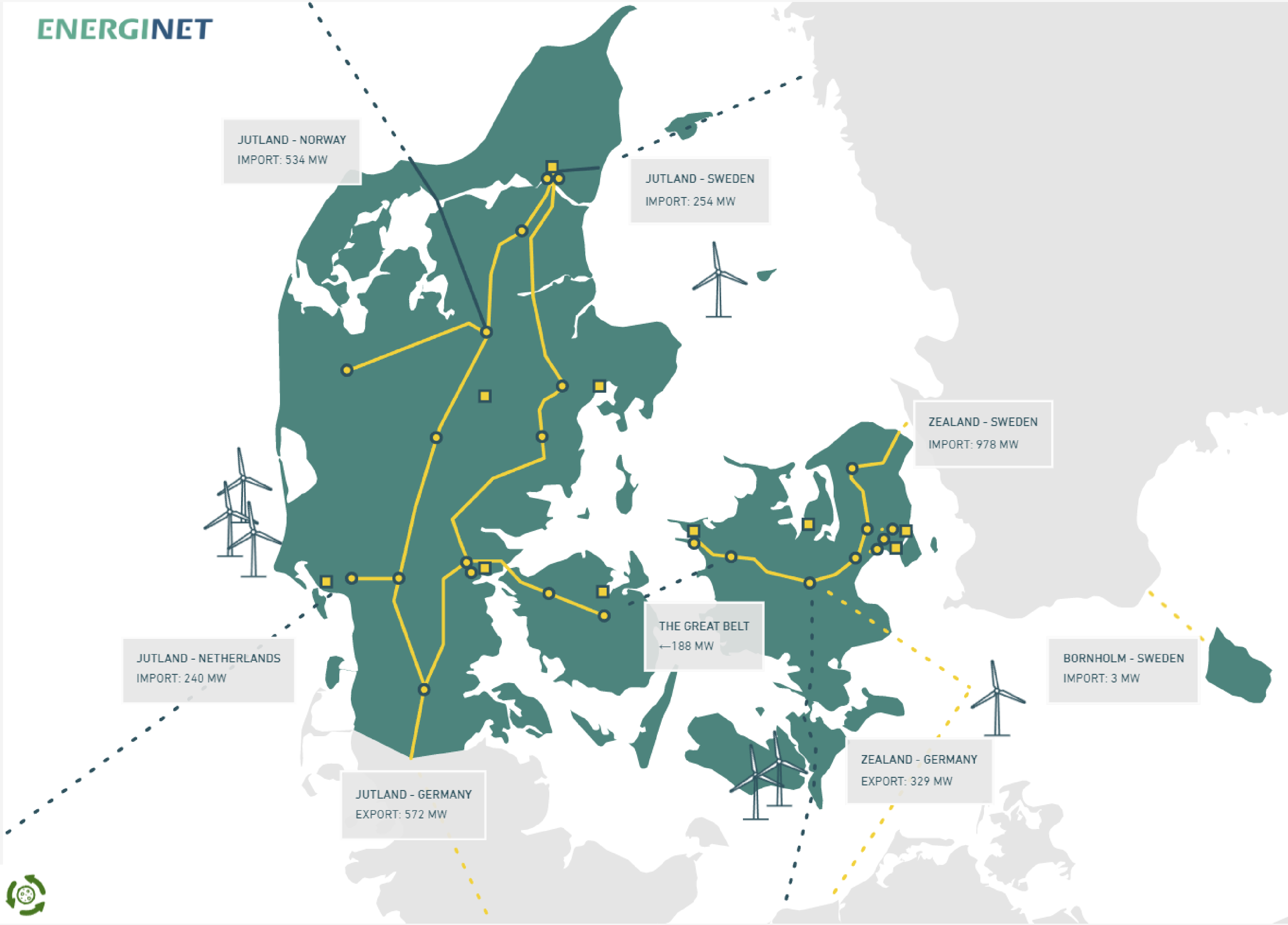
ENERGINET



POWER RIGHT NOW

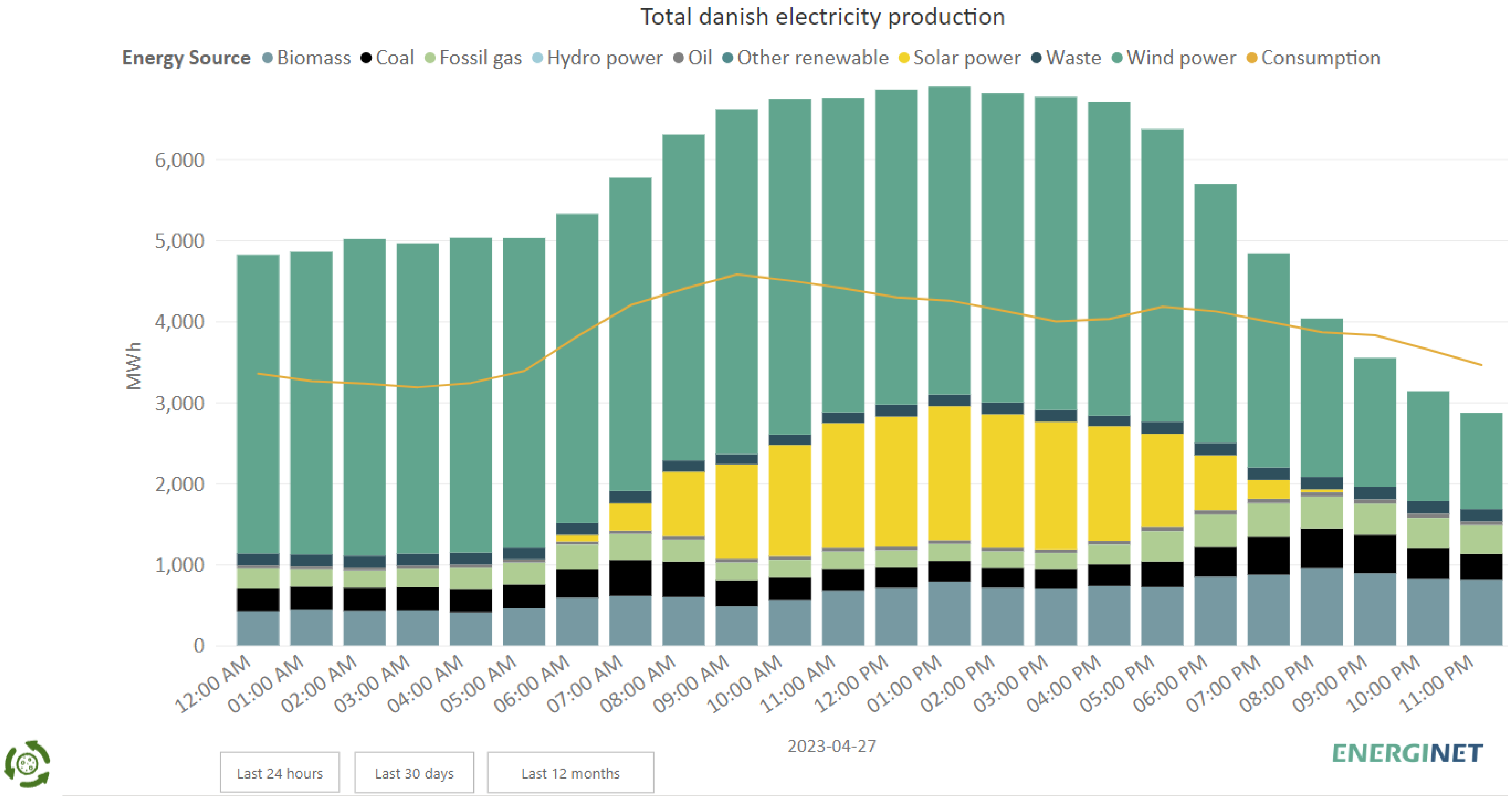
POWER PLANTS (> 100 MW)	842 MW
POWER PLANTS (< 100 MW)	400 MW
WIND TURBINES	389 MW
SOLAR CELLS	1,762 MW
NET EXCHANGE IMPORT	1,109 MW
CONSUMPTION IN DENMARK	4,502 MW
CO2 EMISSIONS	76 g/kWh

SYMBOL DESCRIPTION

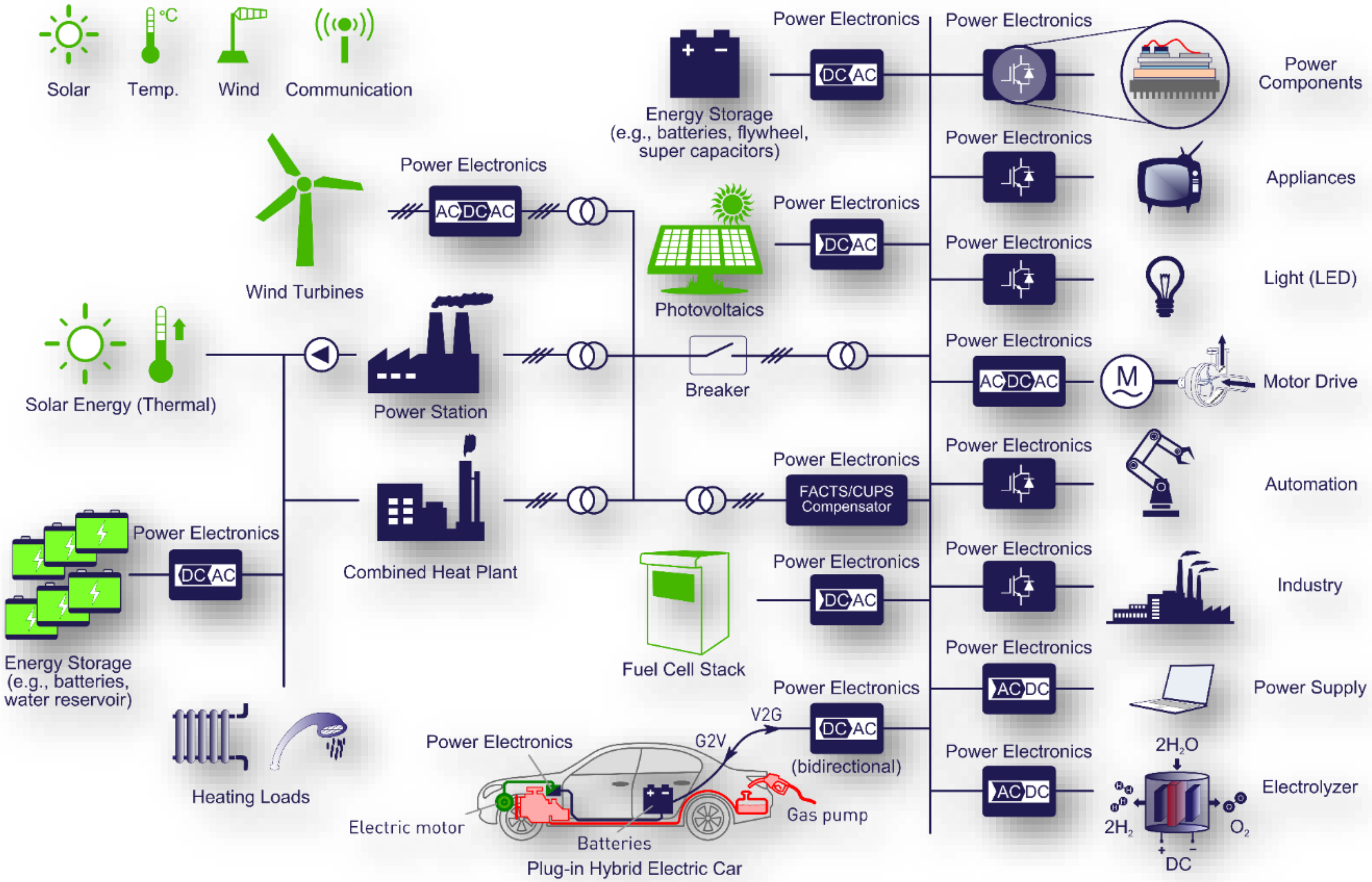
- POWER PLANT (>100 MW)
- OFFSHORE WIND FARM
- CONVERTER SUBSTATION
- OVERHEAD LINES, AC
- CABLE, AC
- OVERHEAD LINES, DC
- CABLE, DC

LAST UPDATE
APR 28, 2023, 10:38 AM

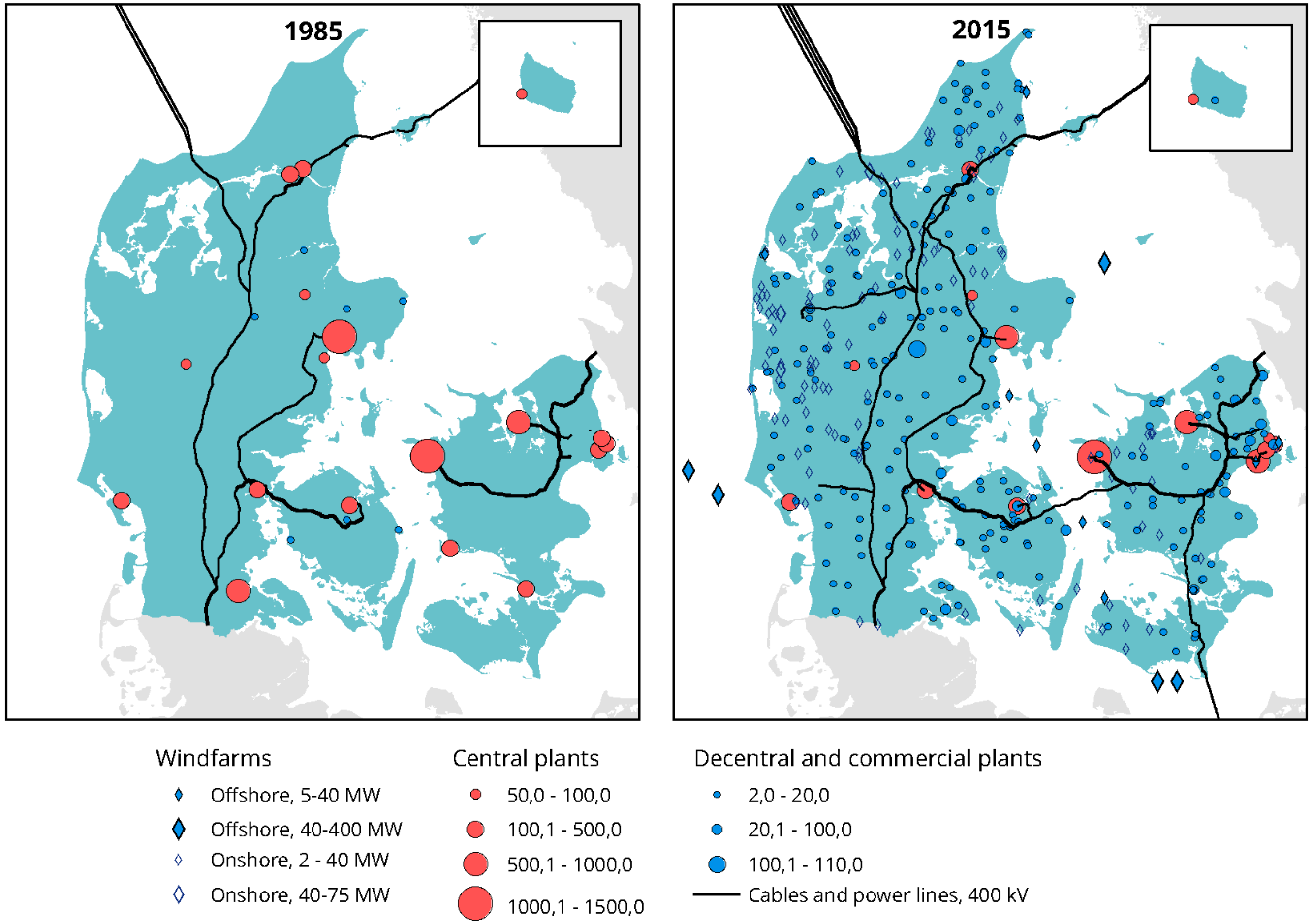
TOTAL PRODUCTION



Power Electronics Centered



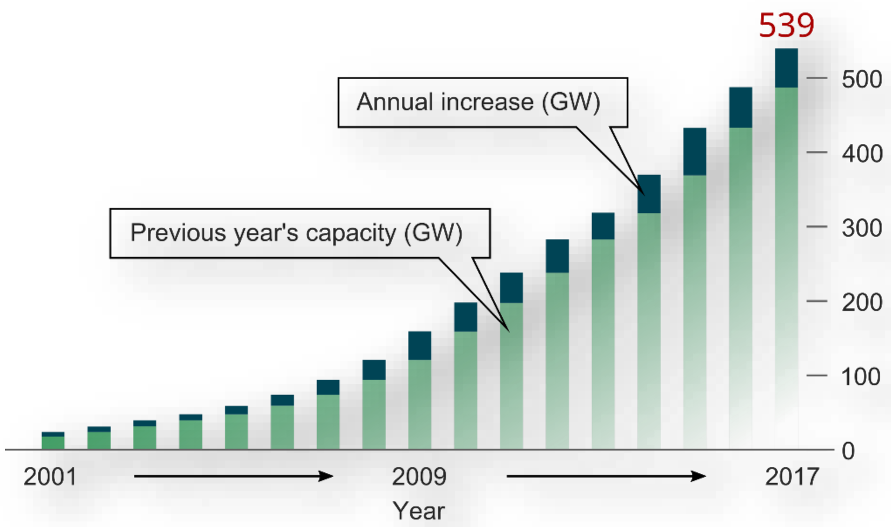
Development of Electric Power System in Denmark

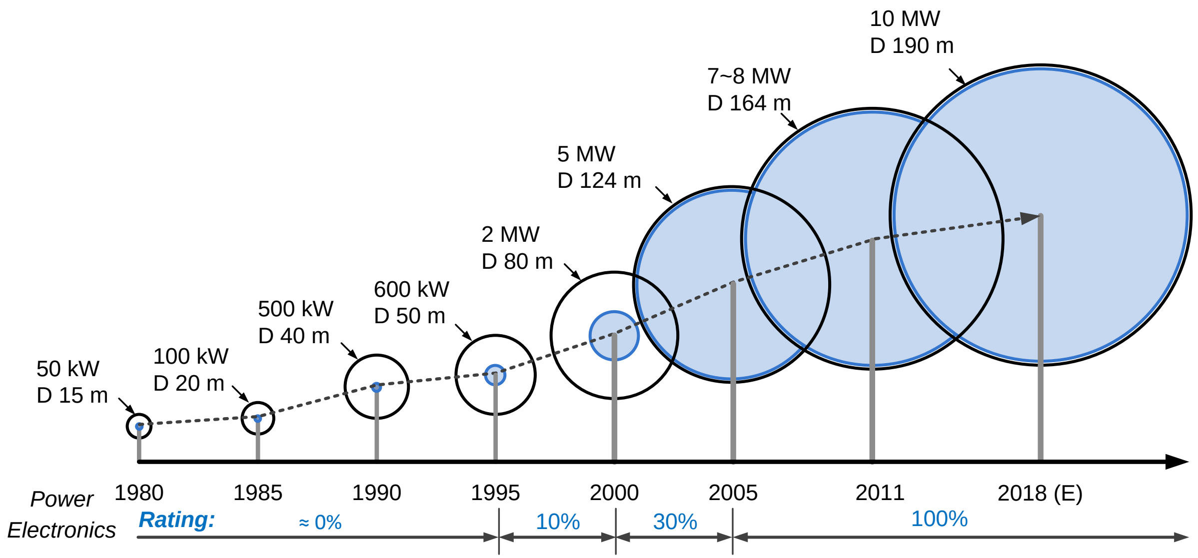


From centralized to decentralized power production, the Danish Energy Agency 2017, ens@ens.dk

From Central to De-central Power Generation

State of the Art Development – Wind Power

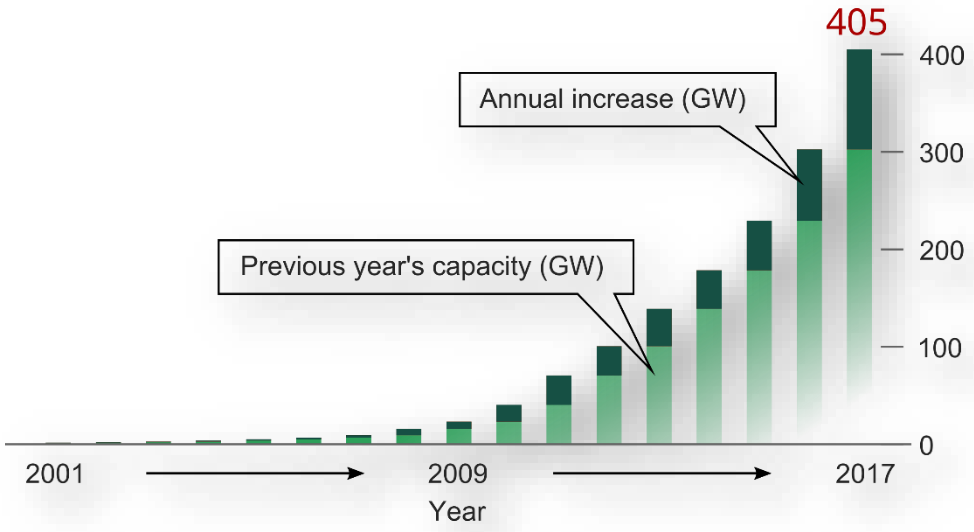


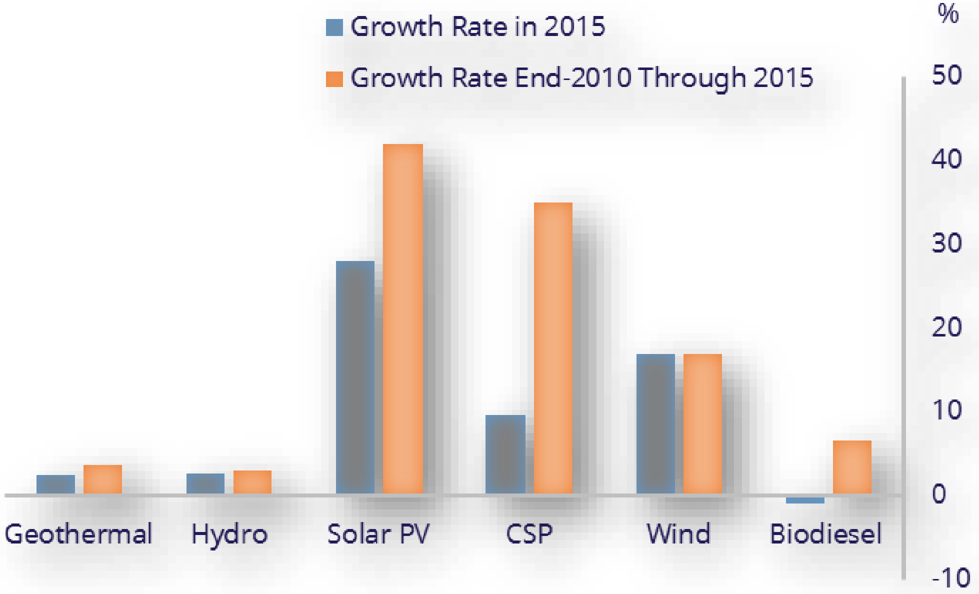


Global installed wind capacity (until 2017): 539 GW, 2017: 52.3 GW

- Higher total capacity (+50% non-hydro renewables).
- Larger individual size (average 1.8 MW, up to 6-8 MW, even 10 MW).
- More power electronics involved (up to 100 % rating coverage).

State of the Art Development – Photovoltaic Power





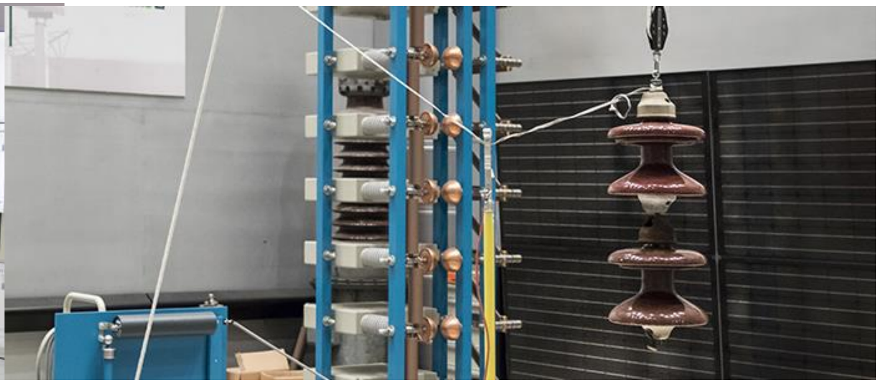
Global installed solar PV capacity (until 2017): 405 GW, 2017: 102 GW

- More significant total capacity (29 % non-hydro renewables).
- Fastest growth rate (42 % between 2010-2015).

Our facilities at DTU

Smart Converter Lab

Control Center Lab



High Power Lab

Electric Vehicle Lab

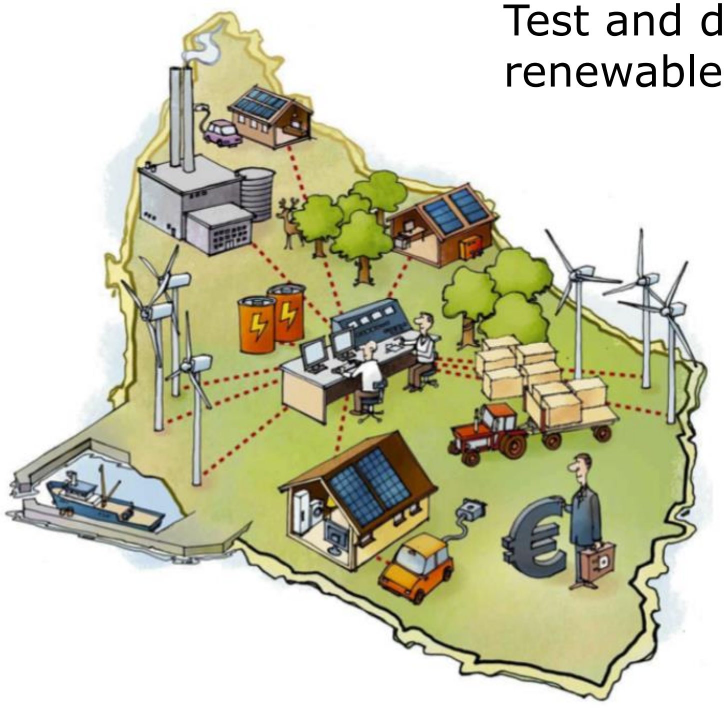
High Voltage Lab

Electric Lab

https://www.powerlab.dk/facilities

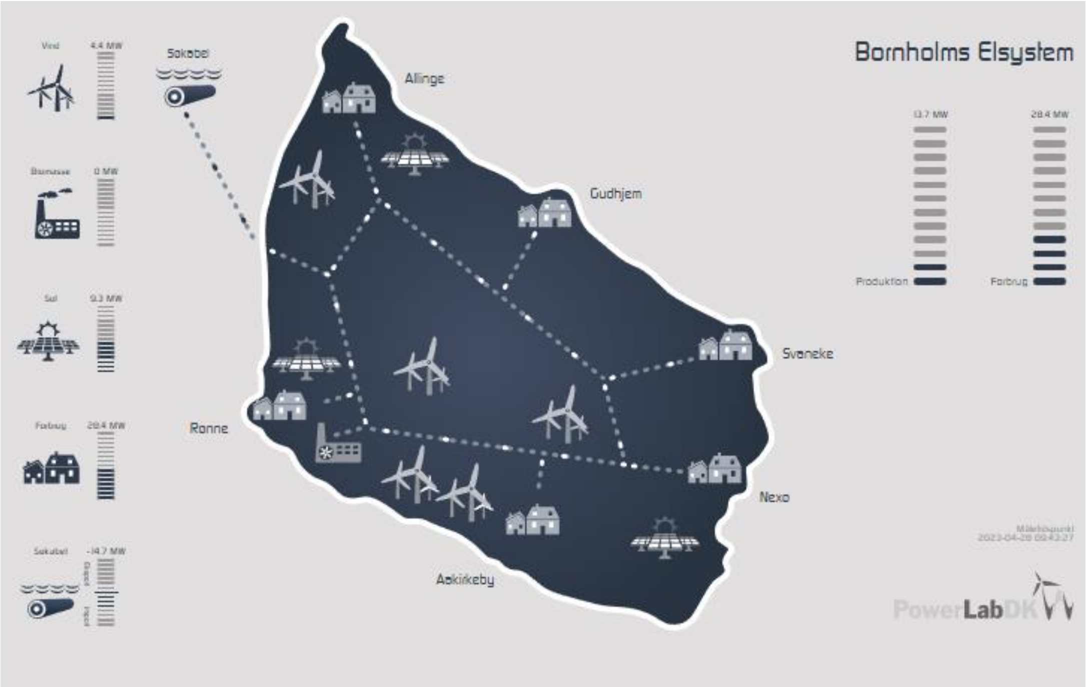
Smart Community Bornholm

Test and demonstration in full-scale renewable energy laboratory



Equivalent to 1% of Denmark concerning area, population, and energy consumption.

Generators	
1 CHP steam turbine (wood/coal/oil chips)	37 MW
35 wind turbines	30 MW
SOLAR PV (2012)	5 MW
2 gas engines (biogas)	2 MW
14 backup diesel generators (oil)	34 MW
1 backup steam turbine (oil)	25 MW
Electric vehicles (under roll-out)	
Grid	
60 kV grid	131 km
Number of 60/10 kV substations	16
10 kV grid	927 km
Number of 10/0.4 kV substations	1039
0.4 kV grid	1913 km
District heating	
Number of district heating systems	5
Total heat demand (in 2007)	560 GWh
Normal operation mode	Interconnected Nordel
Customers	
Number of customers	~28.000
Number of customers (> 100.000 kWh/year)	~300
Total energy consumed	250 GWh
Peak load	55 MW

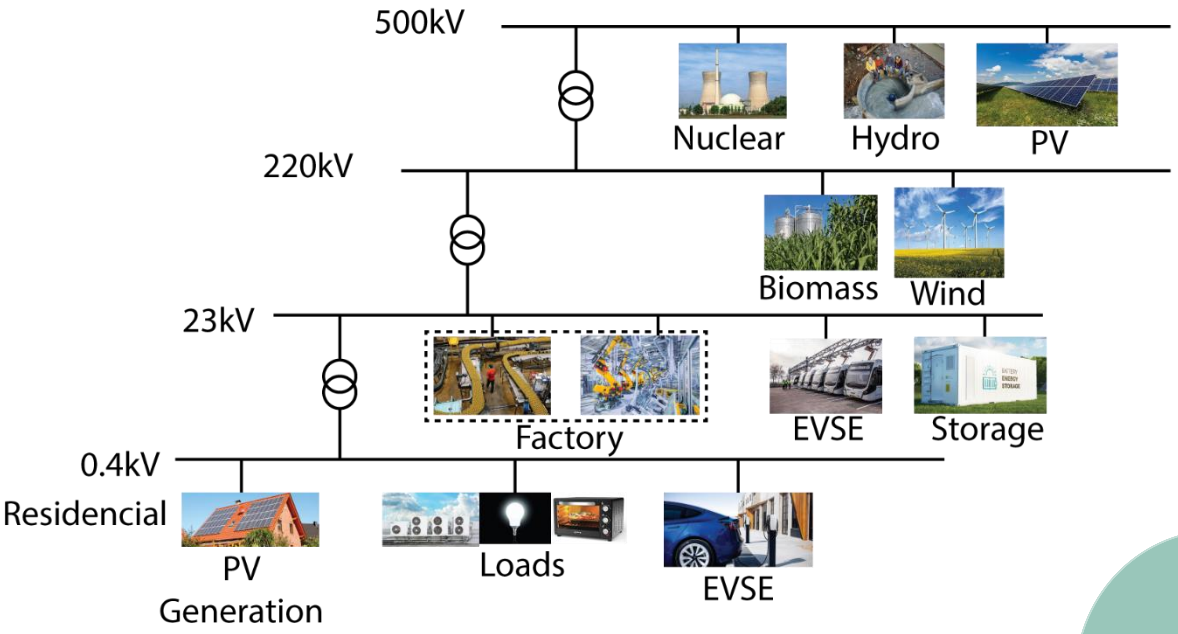


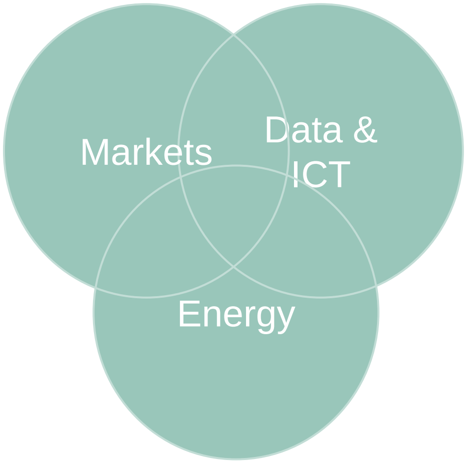
https://www.powerlab.dk/facilities/bornholmpowersystem

Motivation for the course

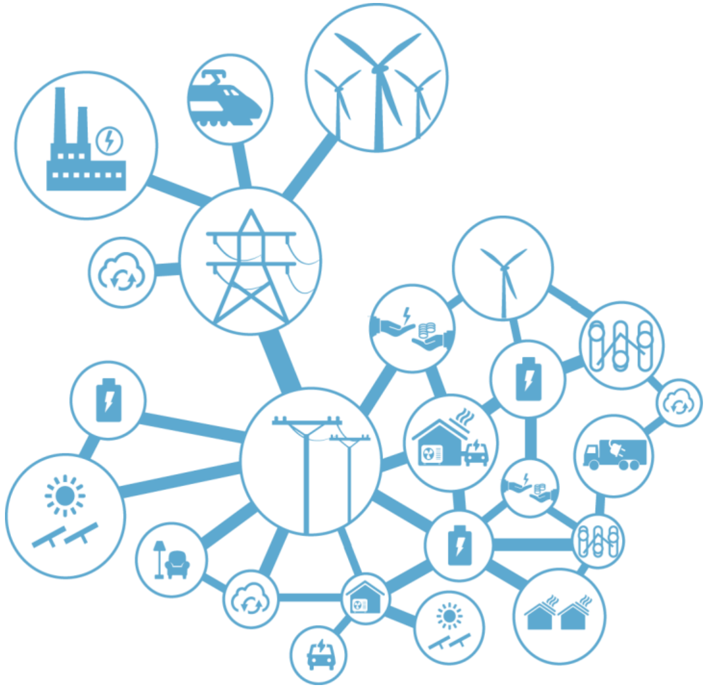
Motivation

Centralize

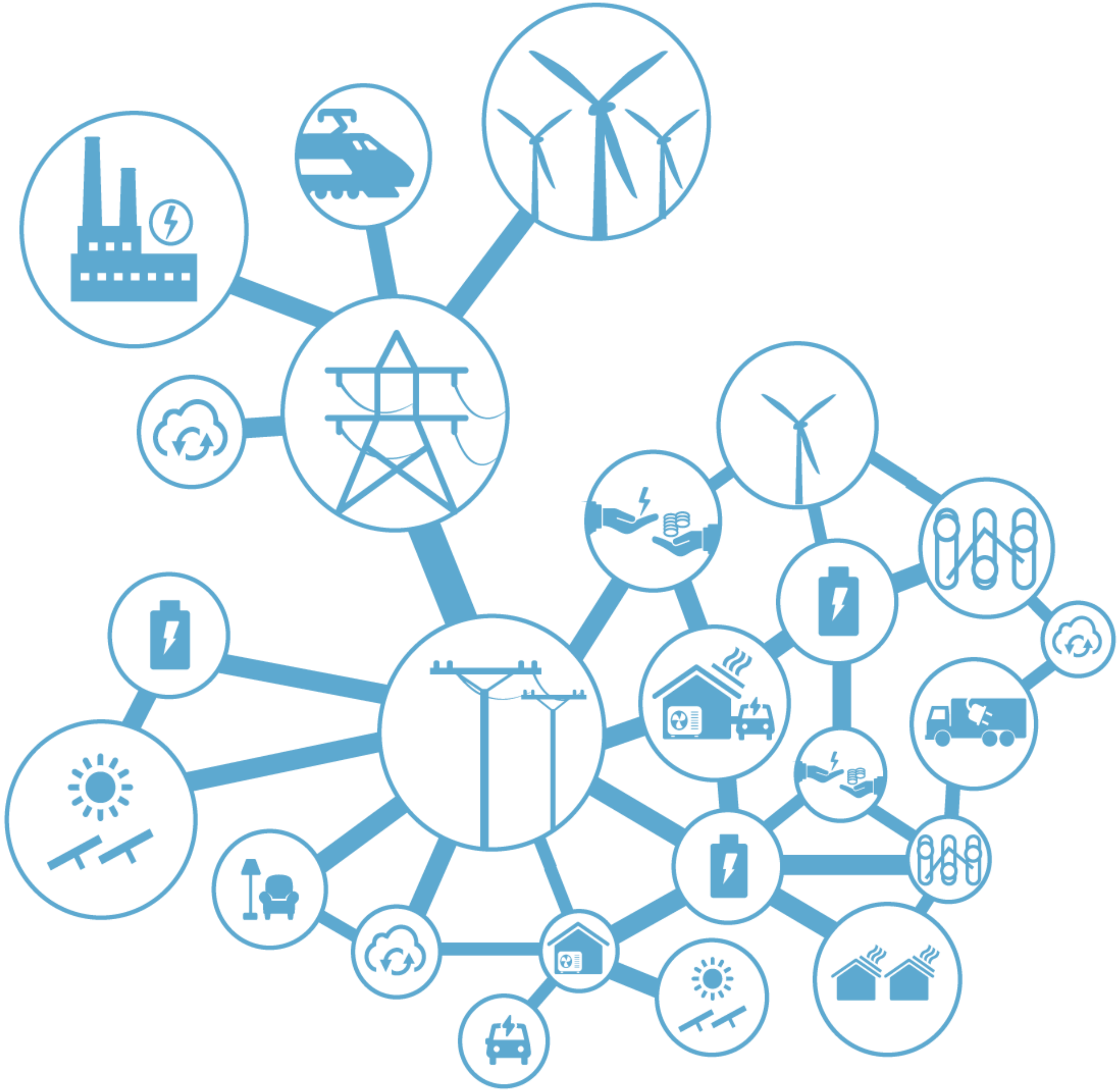


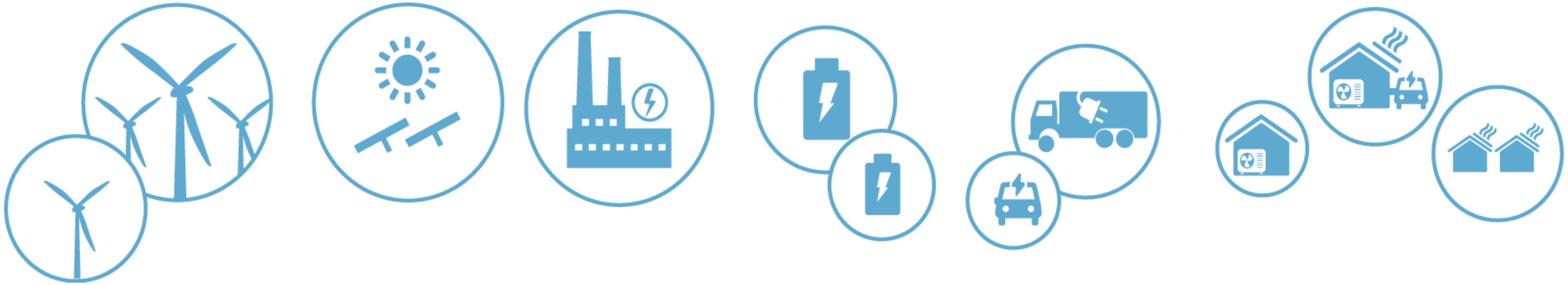


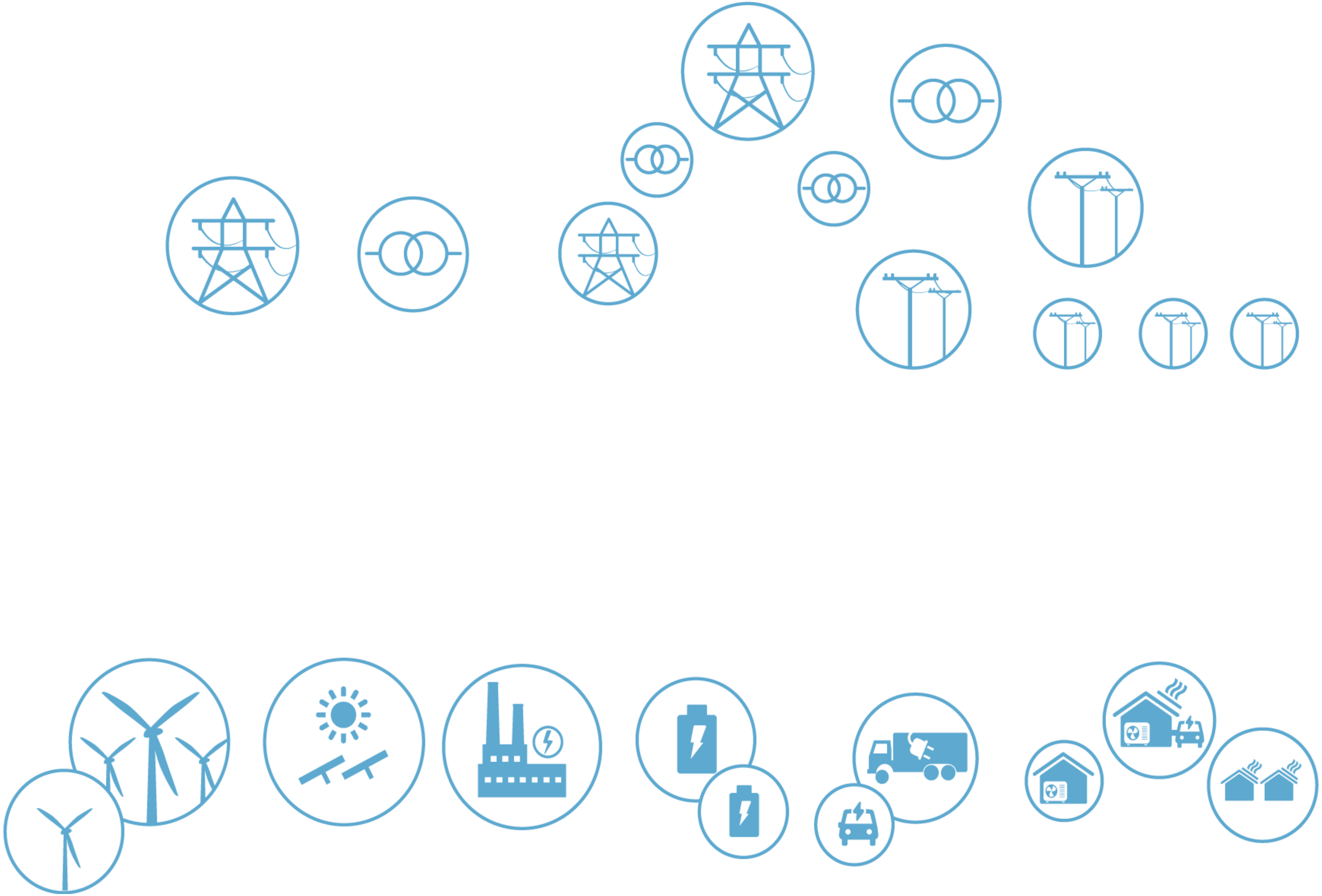
Decentralize

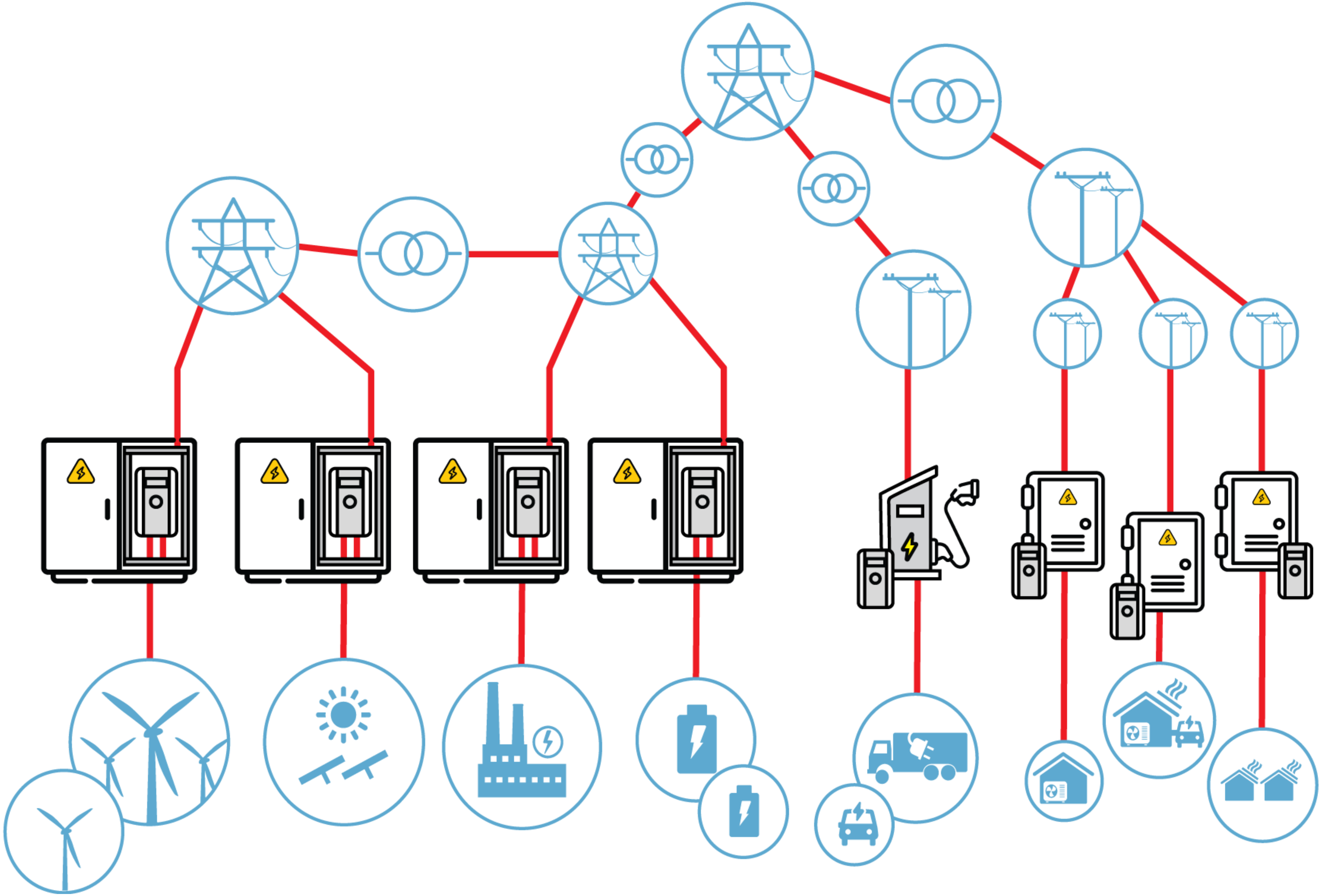


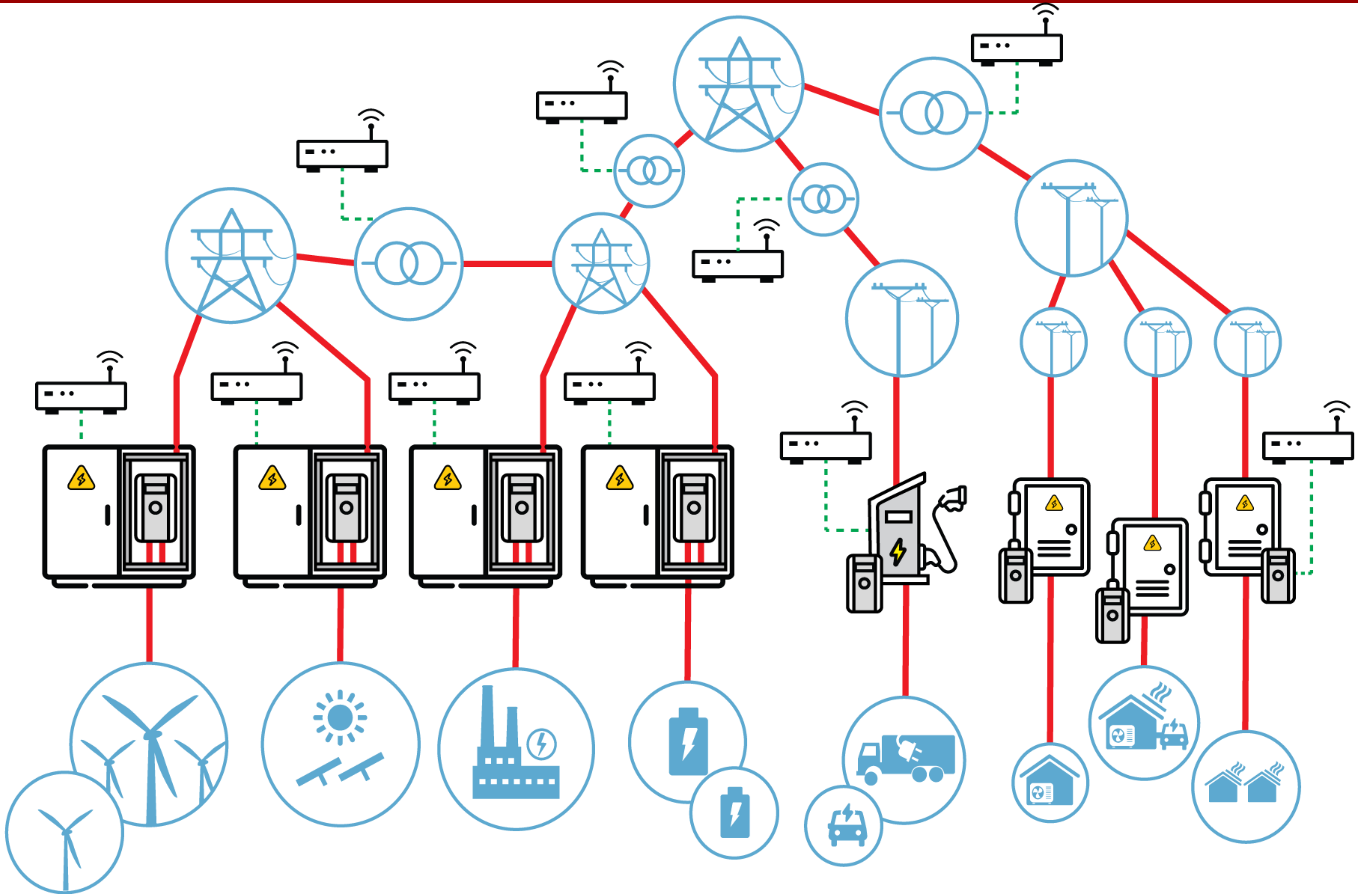
Digitalization







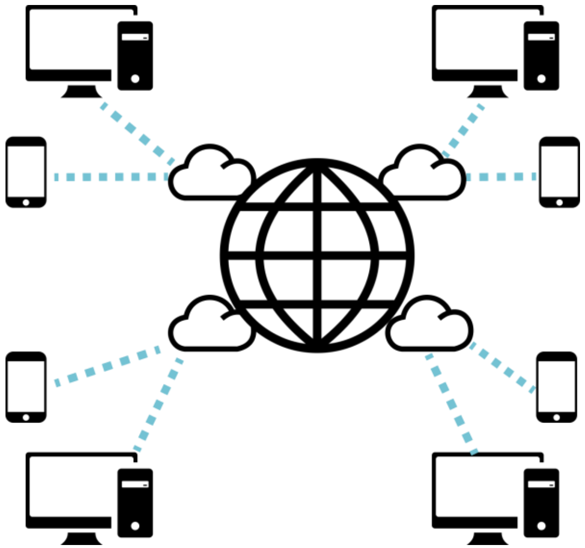




What is the Cloud?

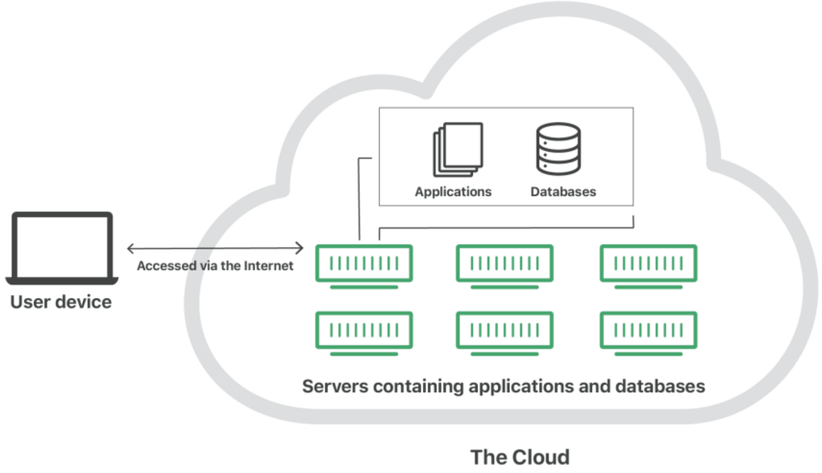
Servers that are accessed over the Internet, along with the software and databases that run on those servers.

Cloud servers are located in data centers all over the world.



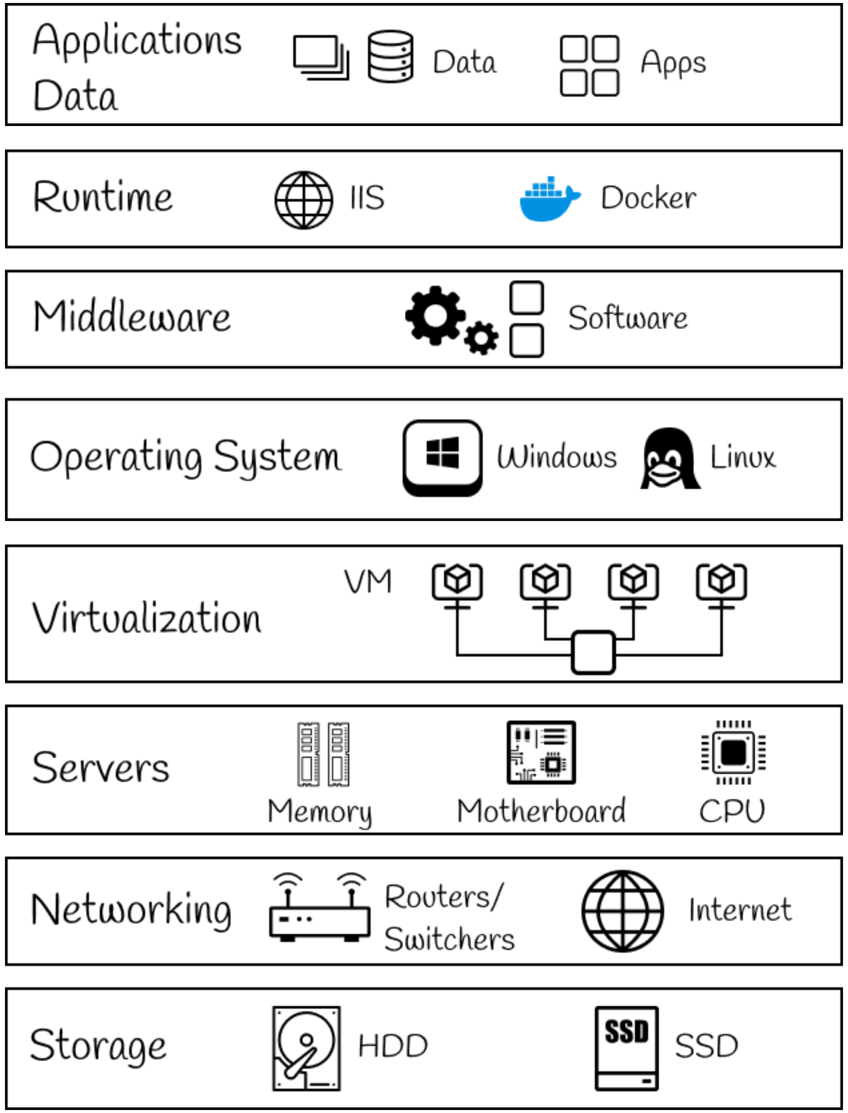
Users and companies do not have to manage physical servers themselves or run software applications on their own machines.

The computing and storage takes place on servers in a data center, instead of locally on the user device.



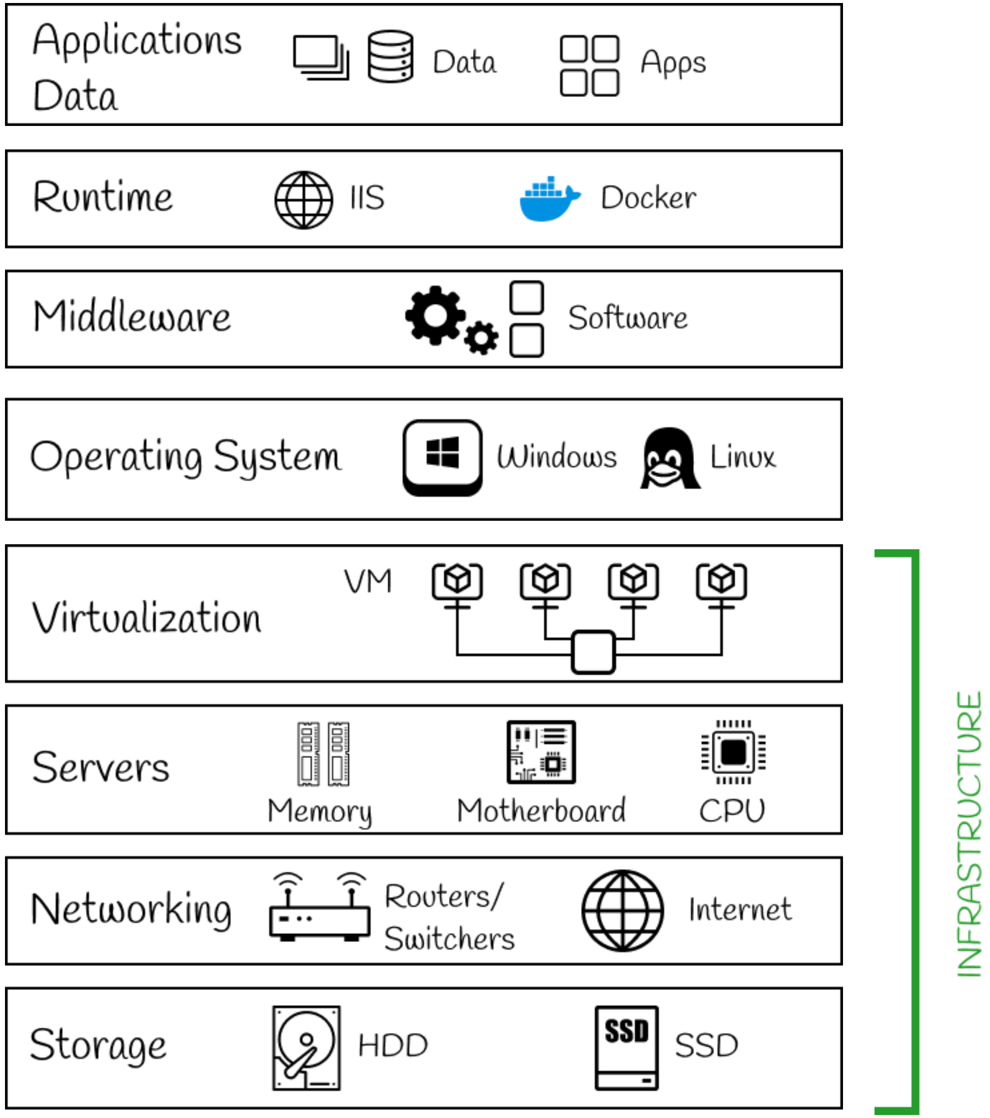
CloudFlare

Cloud Service Model



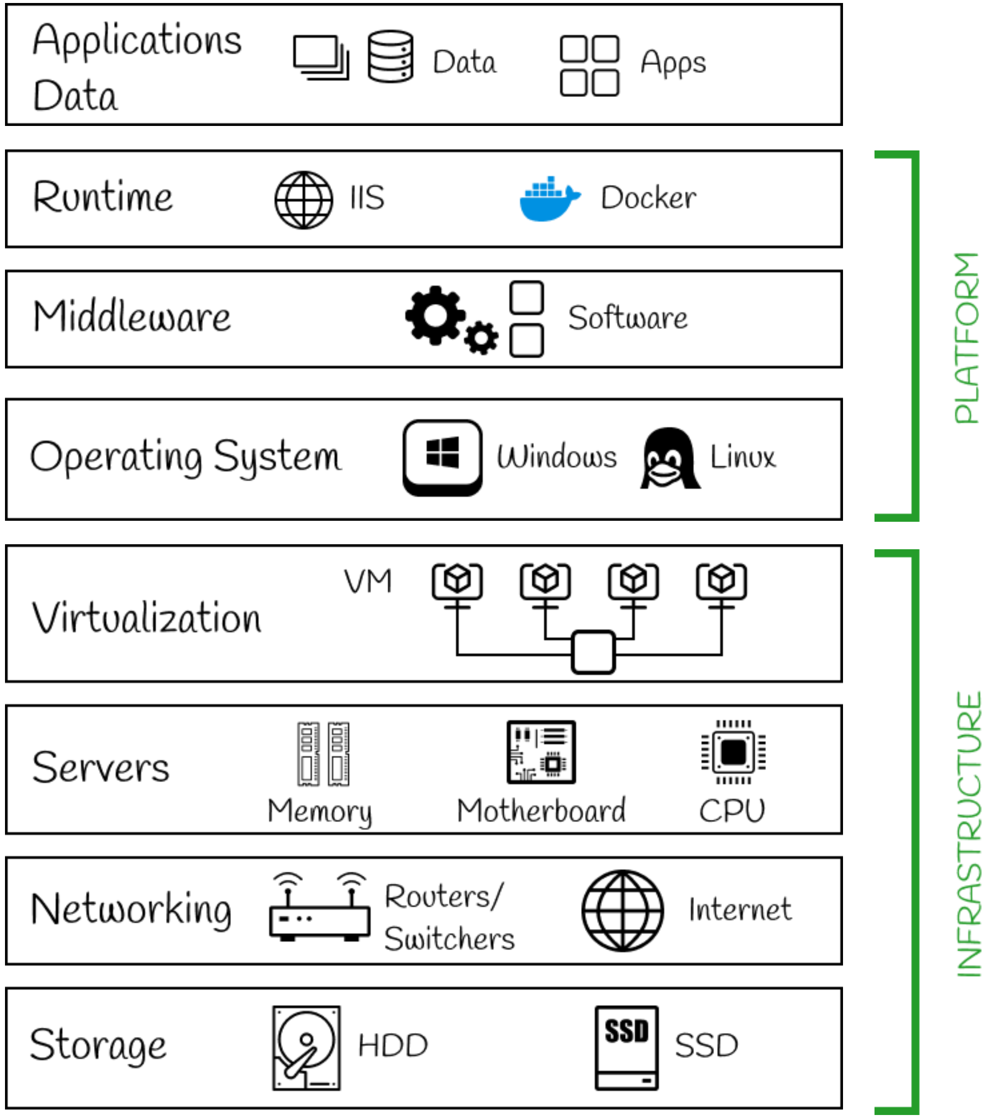
Microsoft Certified Fundamentals

Cloud Service Model



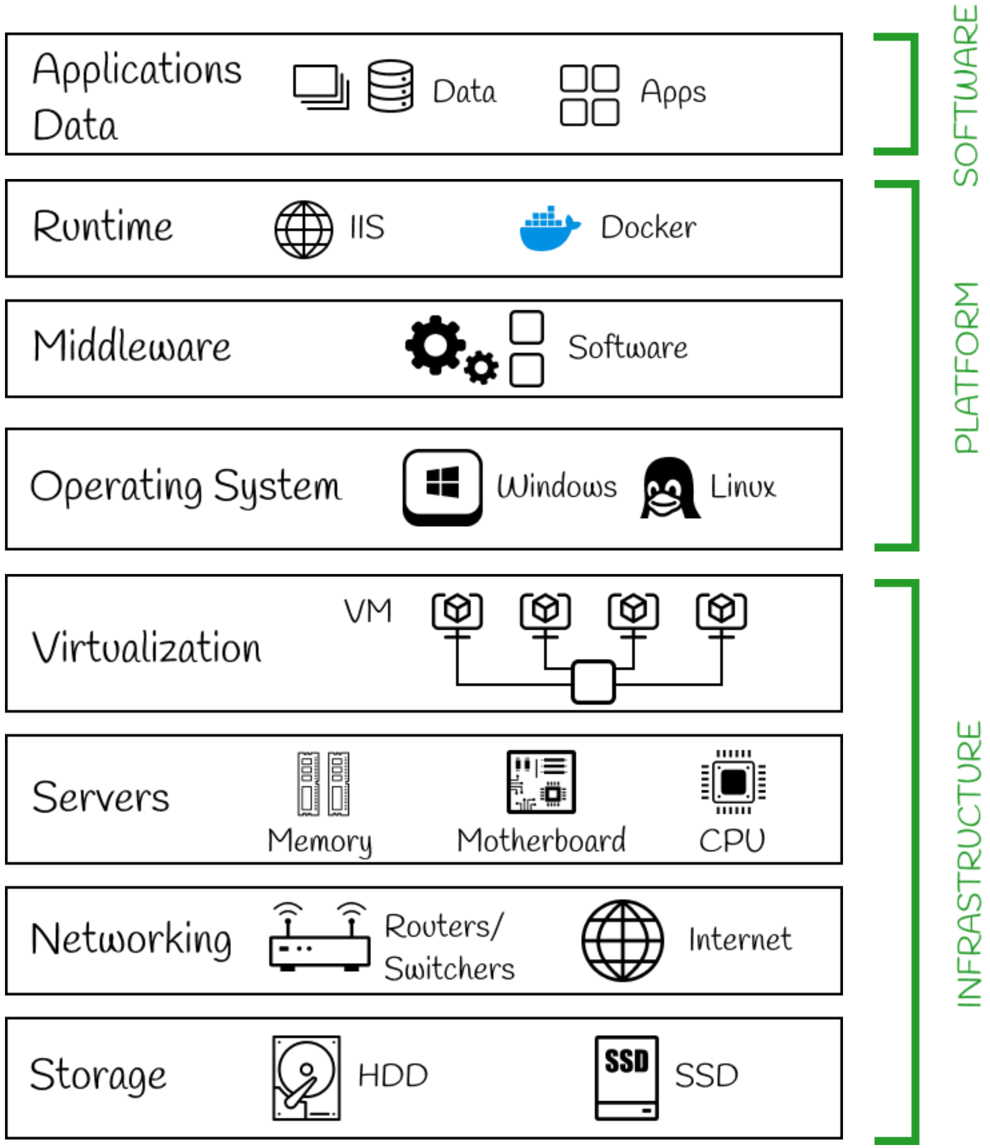
Layers related with the hardware and virtualization

Cloud Service Model



Layers related with the system and configuration that is required for you to run the application.

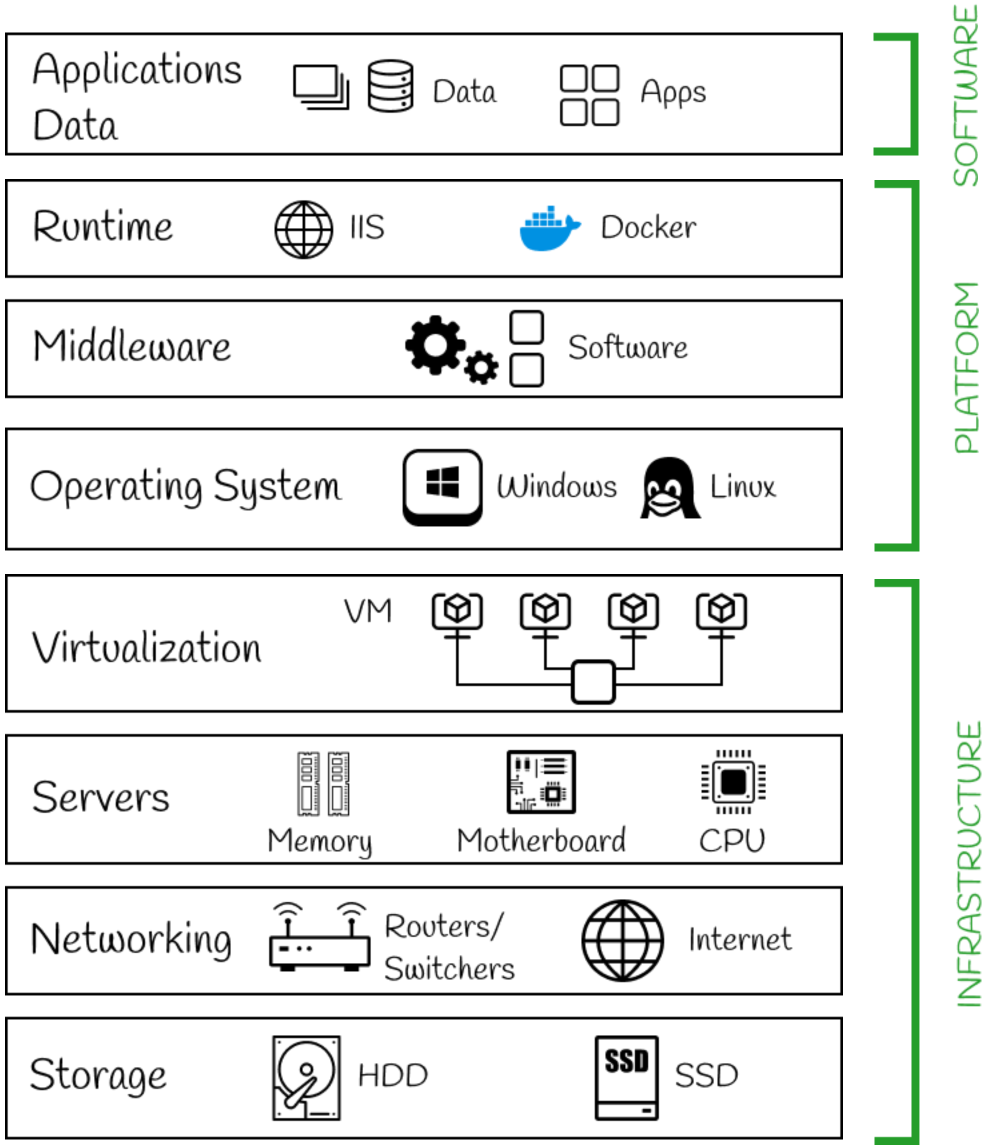
Cloud Service Model



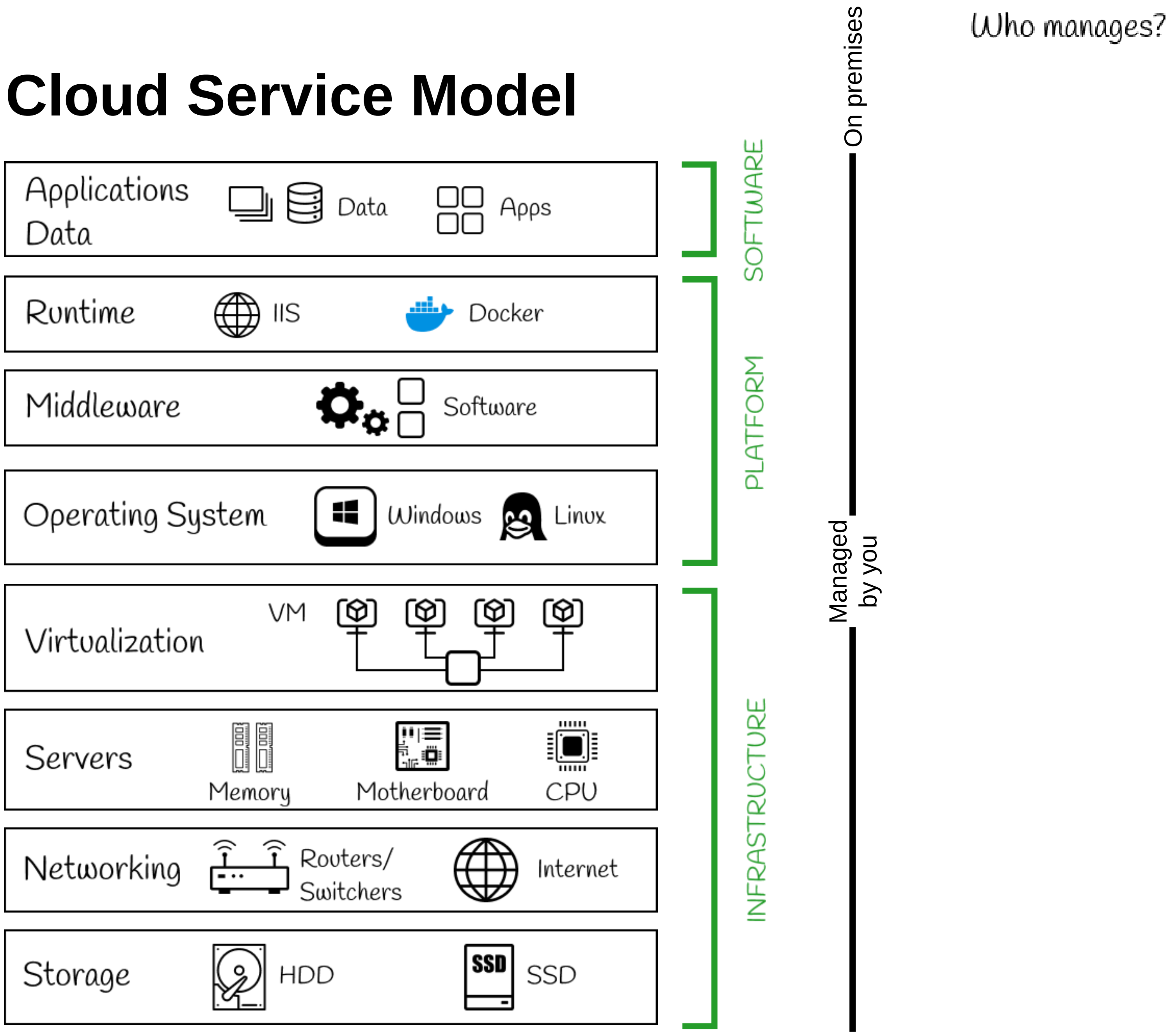
Layer related with the application itself.

Who manages?

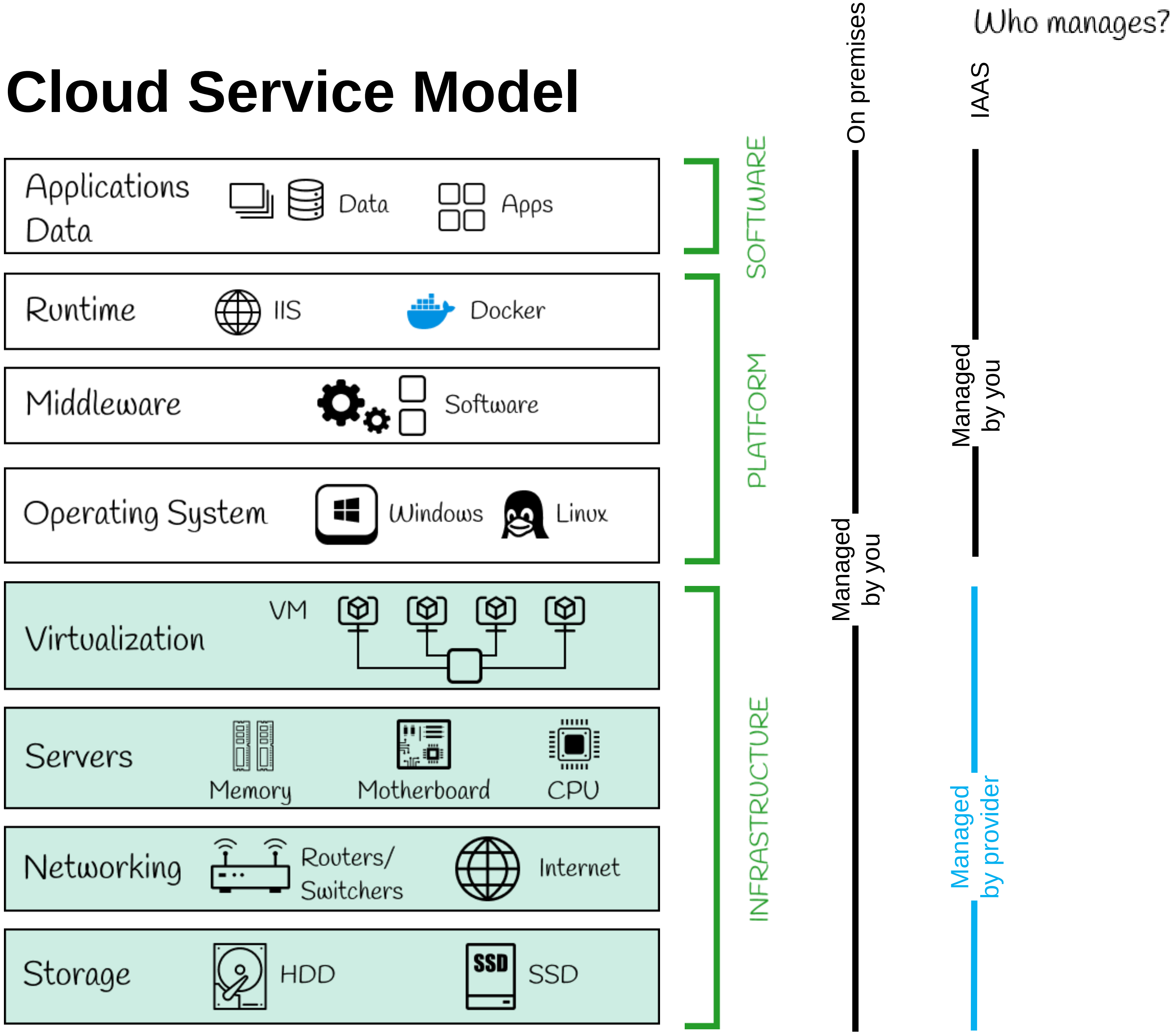
Cloud Service Model



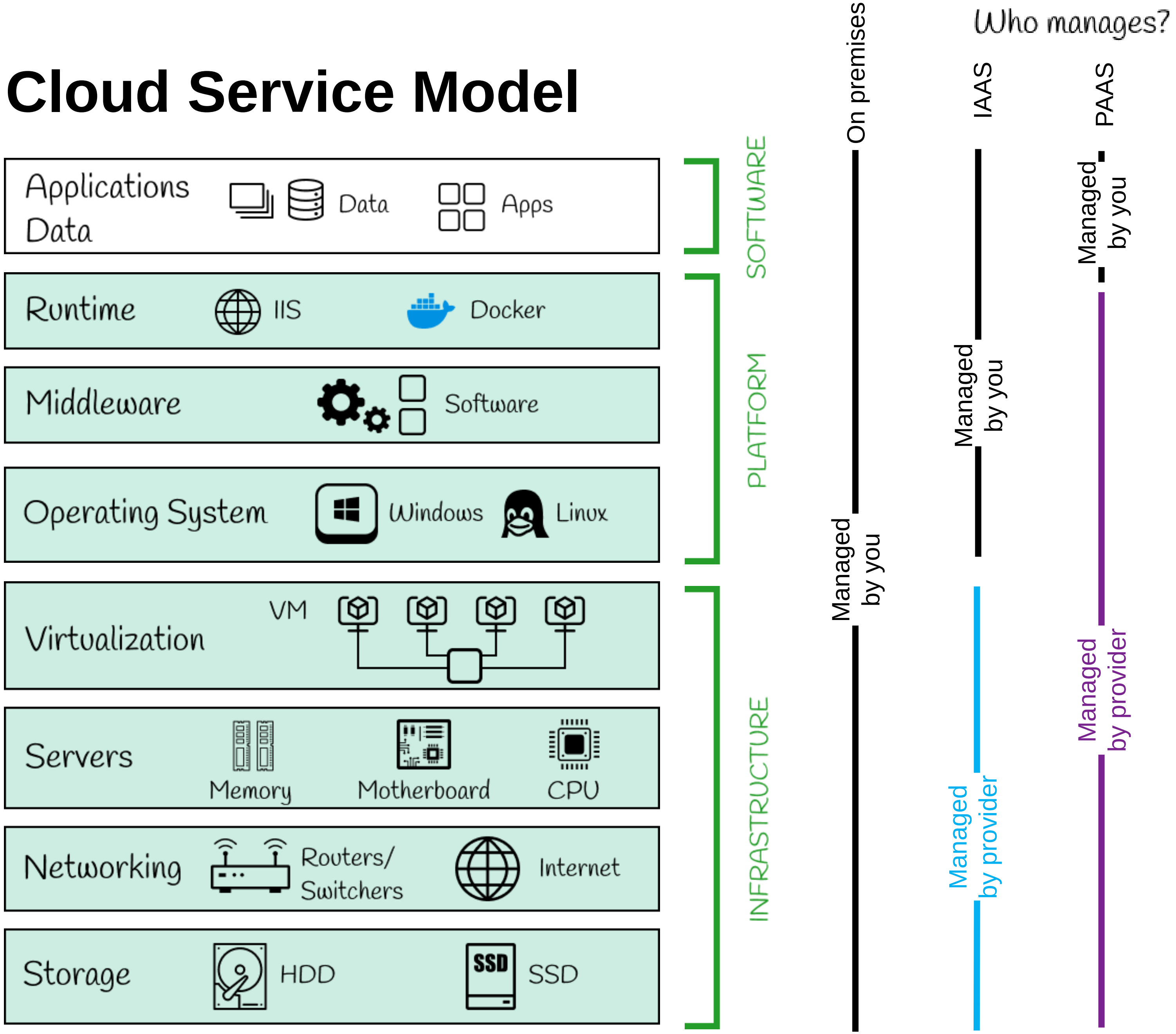
Cloud Service Model



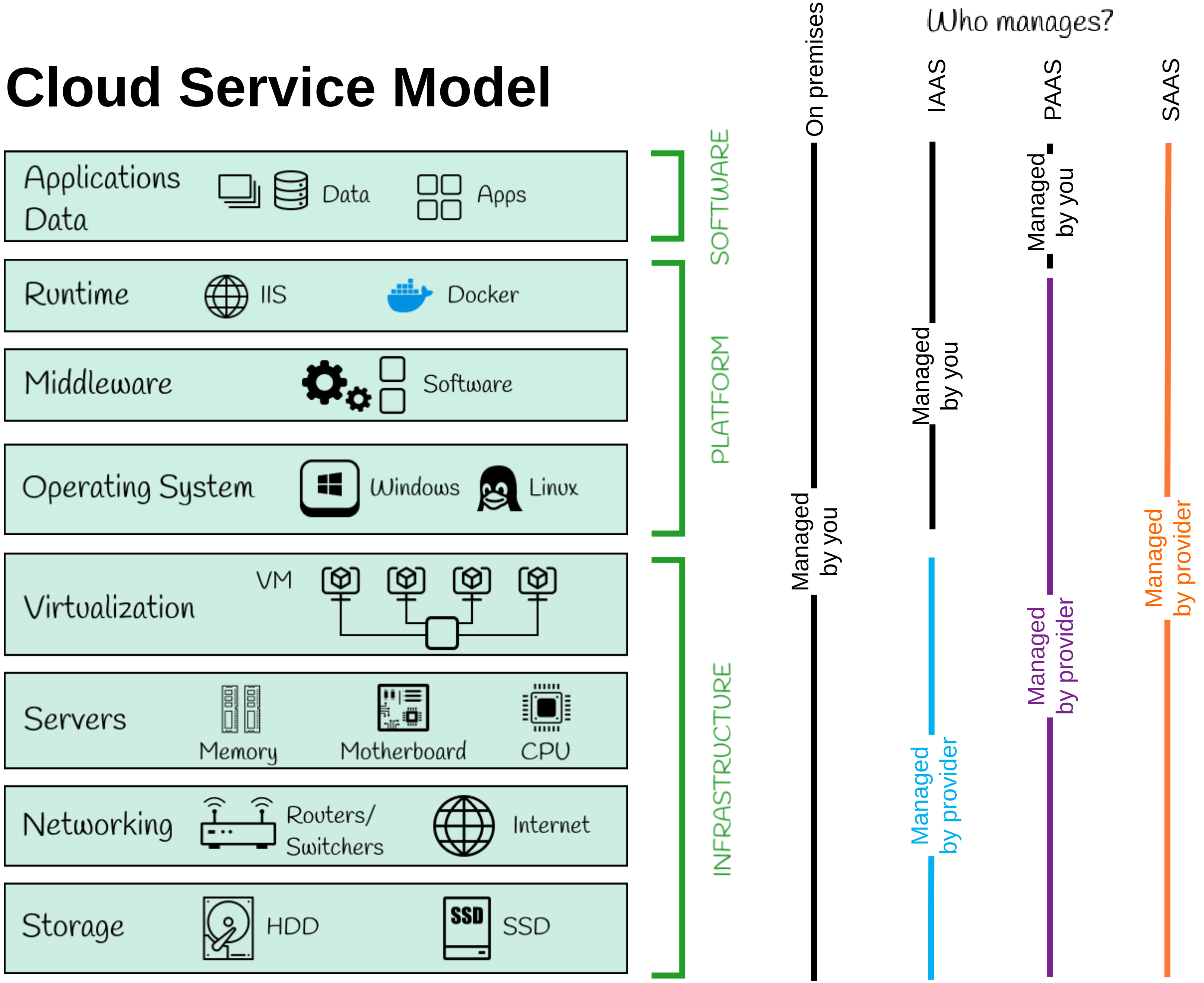
Cloud Service Model

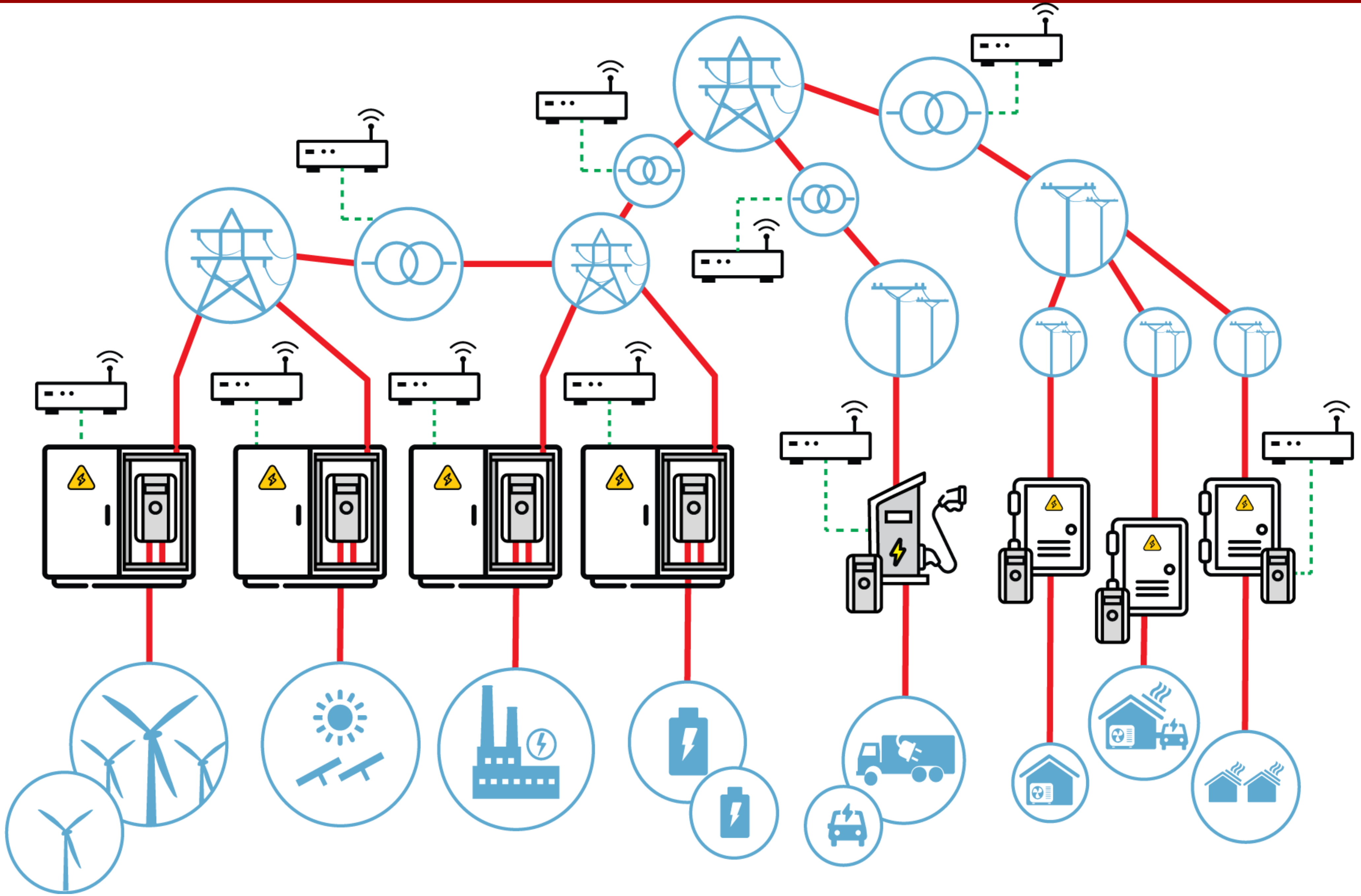


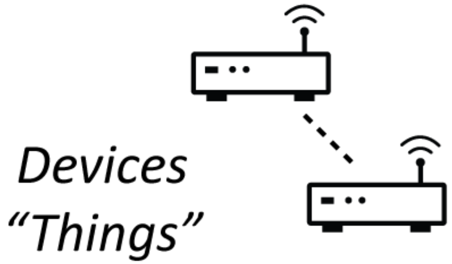
Cloud Service Model

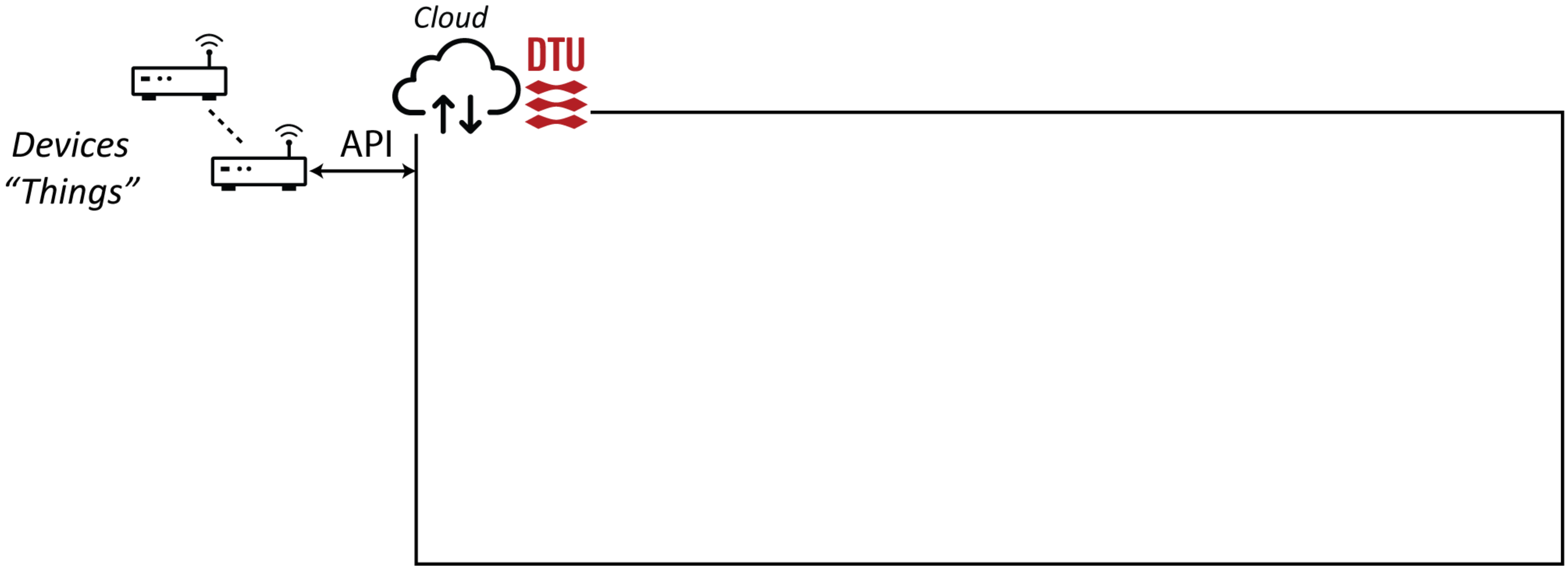


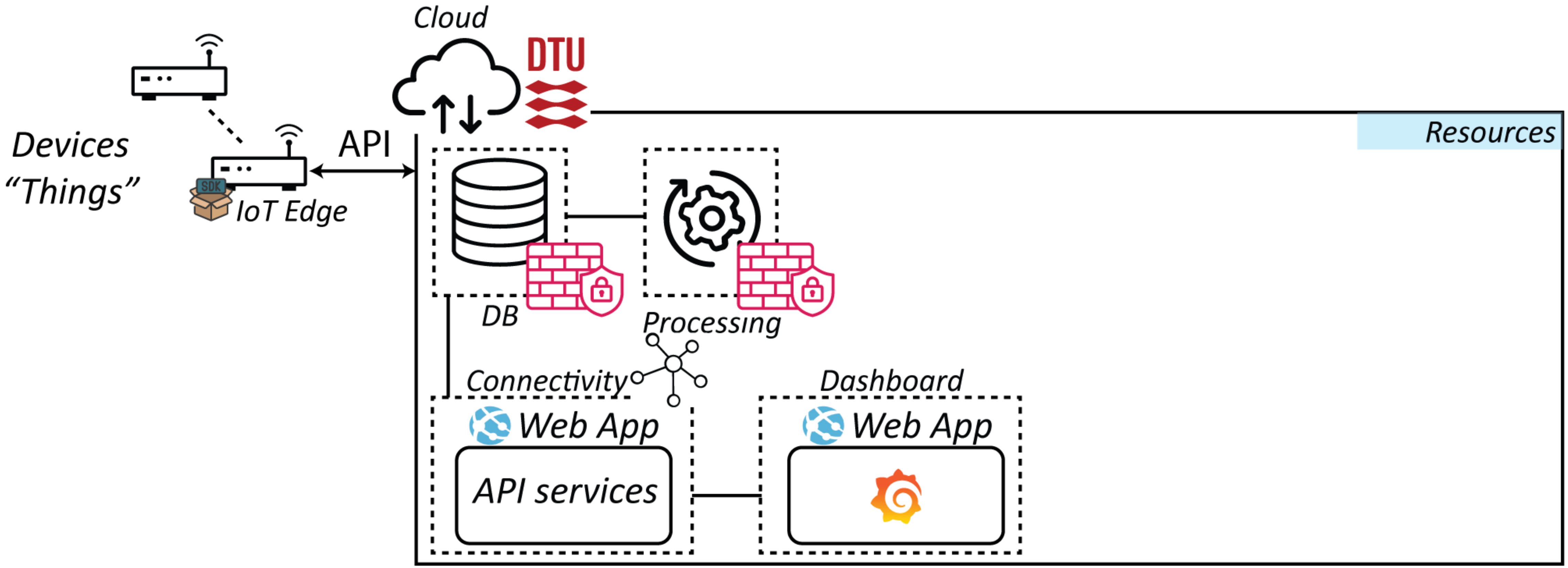
Cloud Service Model

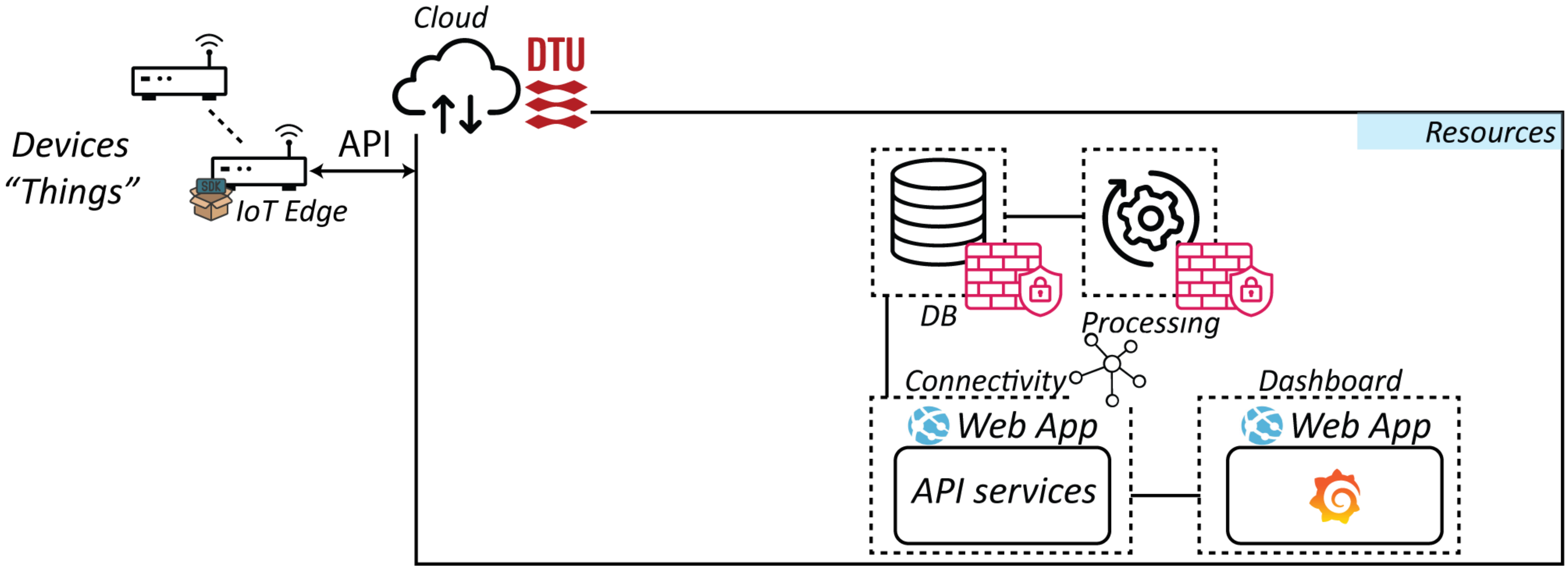





Devices
“Things”


Cloud
DTU
Devices
"Things"
API


Cloud
DTU
Resources
Devices
"Things"
API
SDK
IoT Edge
DB
Processing
Connectivity
Dashboard
Web App
API services
Web App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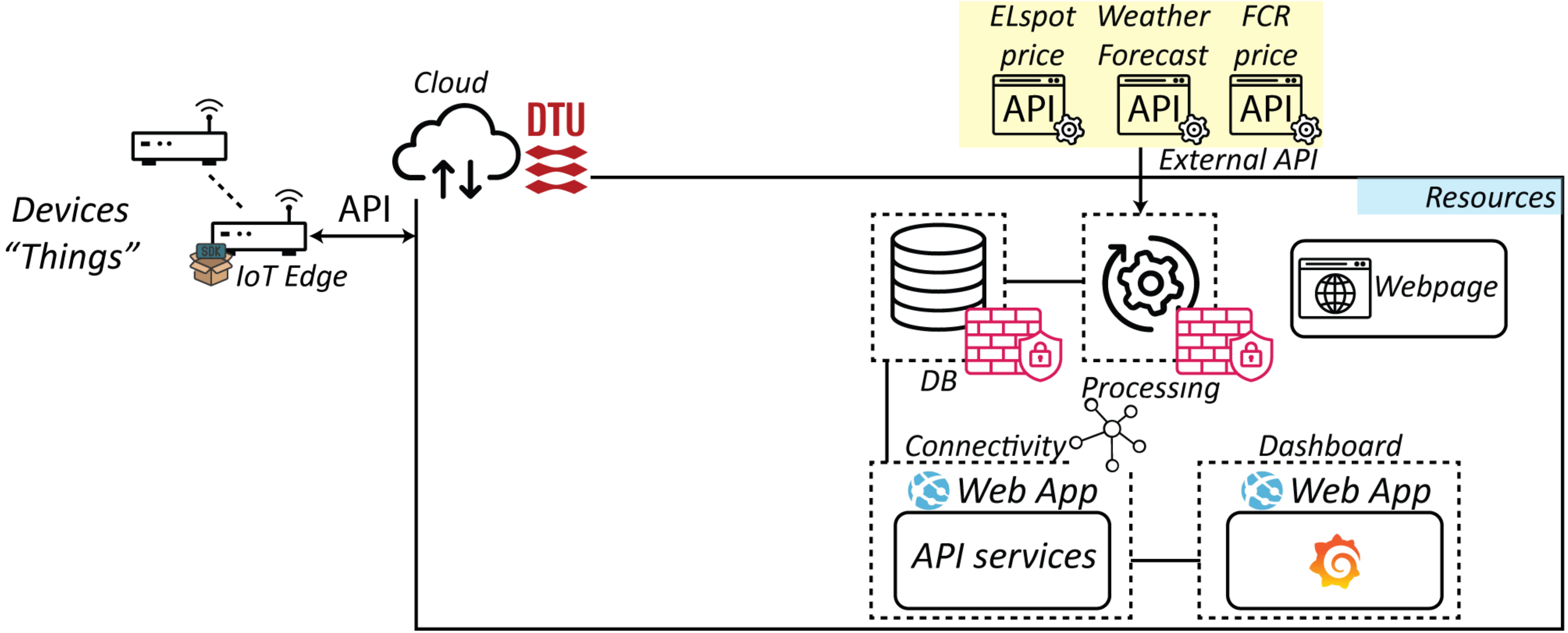
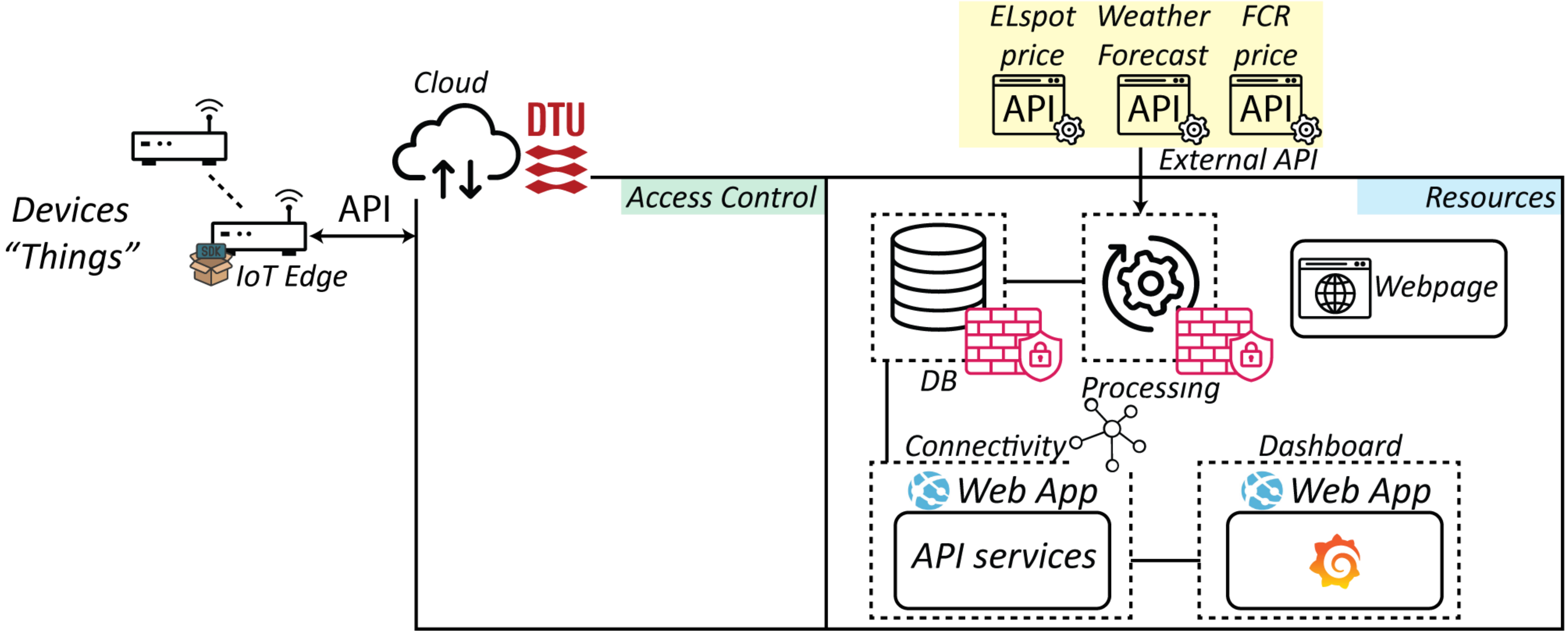


Devices
"Things"
IoT Edge
SDK
API
Cloud
DTU
ELspot price
Weather Forecast
FCR price
API
API
API
External API
Resources
DB
Processing
Webpage
Connectivity
Dashboard
Web App
API services
Web App


ELspot price
Weather Forecast
FCR price
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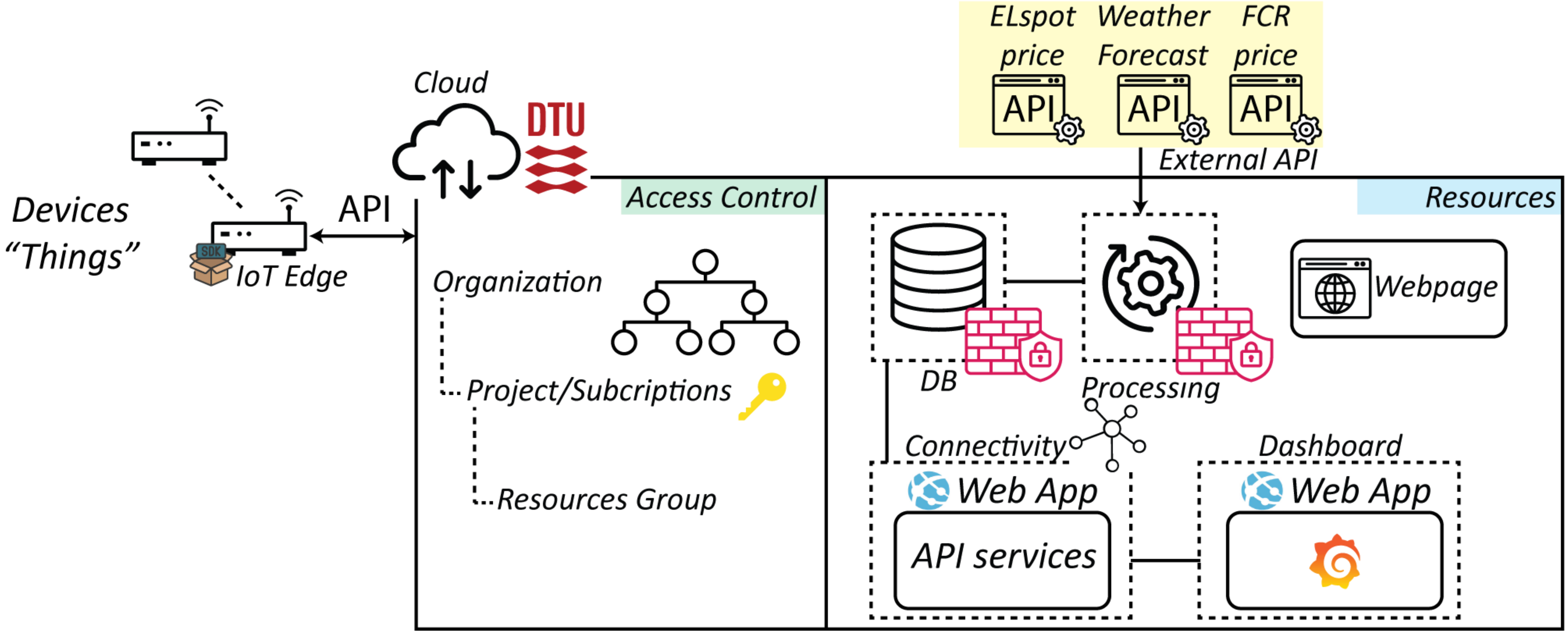
SDK
IoT Edge
Access Control
Resources
DB
Processing
Webpage
Connectivity
Dashboard
Web App
API services
Web App


ELspot price
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IoT Edge
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Access Control
Organization
Project/Subcriptions
Resources Group
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Webpage
Connectivity
Dashboard
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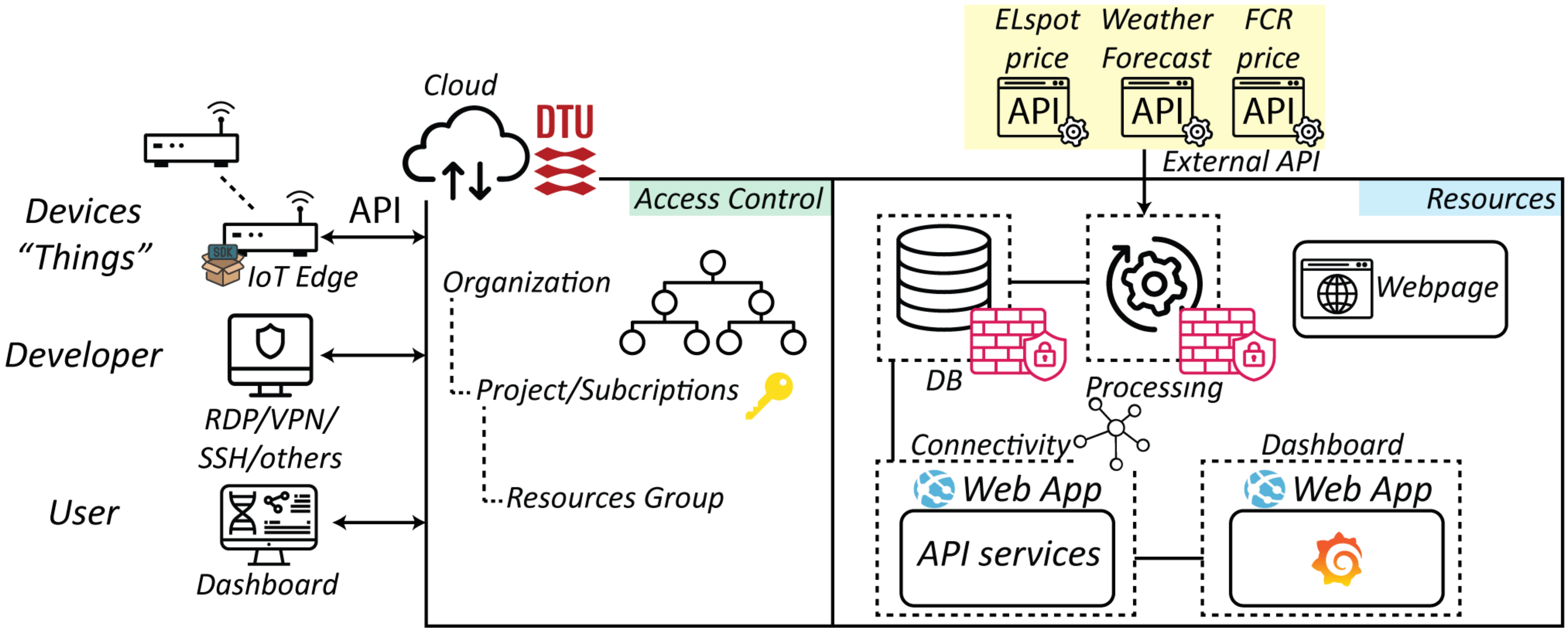
API services
Web App



ELspot price
Weather Forecast
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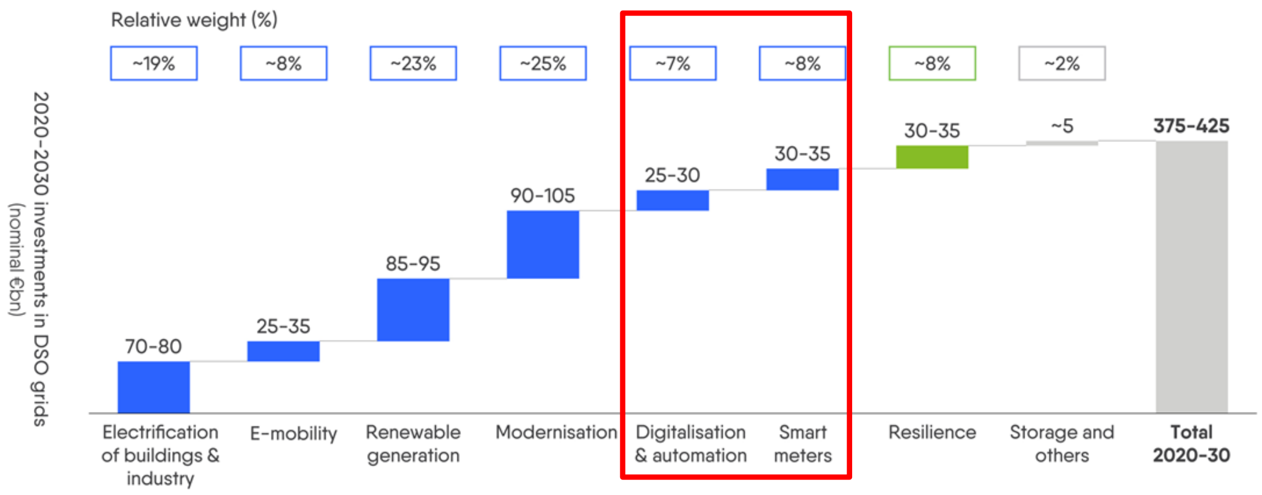
Devices "Things"
SDK
IoT Edge
API
Access Control
Resources
Organization
Project/Subcriptions
Resources Group
Developer
RDP/VPN/
SSH/others
User
Dashboard
DB
Processing
Webpage
Connectivity
Dashboard
Web App
API services
Web App

▶ Market perspectives

Key investment drivers: modernisation, renewables and electrification



- [1]In January 2021 Euroelectric launched a large analysis work estimating the total investment money for mitigating the green transformation
- [2]Navigant Research estimates that the market size of asset management software licenses will double over the next decade from DKK 9.5 billion - to DKK 19 billion per year in 2028
- Competitors in Denmark (Sustech, Utiligize, Lithium Balance, NUUVE) focus on monitoring grid in general or other components (transformers, batteries, EVs).
- International big players (Wapice, ABB, Schneider, Siemens, Dynatrace) provide generic solutions (customization and development of new functionalities is expensive!)

[1]https://www.eurelectric.org/connecting-the-dots/

[2]Utility Asset Management Systems and Analytics Navigant Research, November 2019

Projects and developments

Ongoing and new projects and initiatives at DTU

Ongoing EUDP funded project ACTION

– Smart control of grid-connected electrical drives

Ongoing InnovationFund DK funded project HEART

– Design and optimal operation of fast EV charger station

Sapere Aude (Independent Research Fund DK) funded project MAGIC

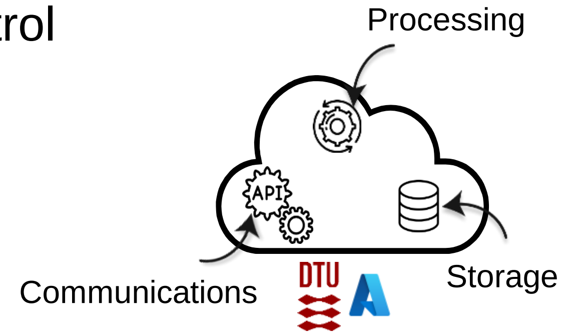
– Smart aggregation of flexible actIve-front-end grid-connected power electronic converters

DTU Discovery grant: Developement of a new DTU Cloud platform

– Integrated to PowerLabDK *Smart Converter Lab*

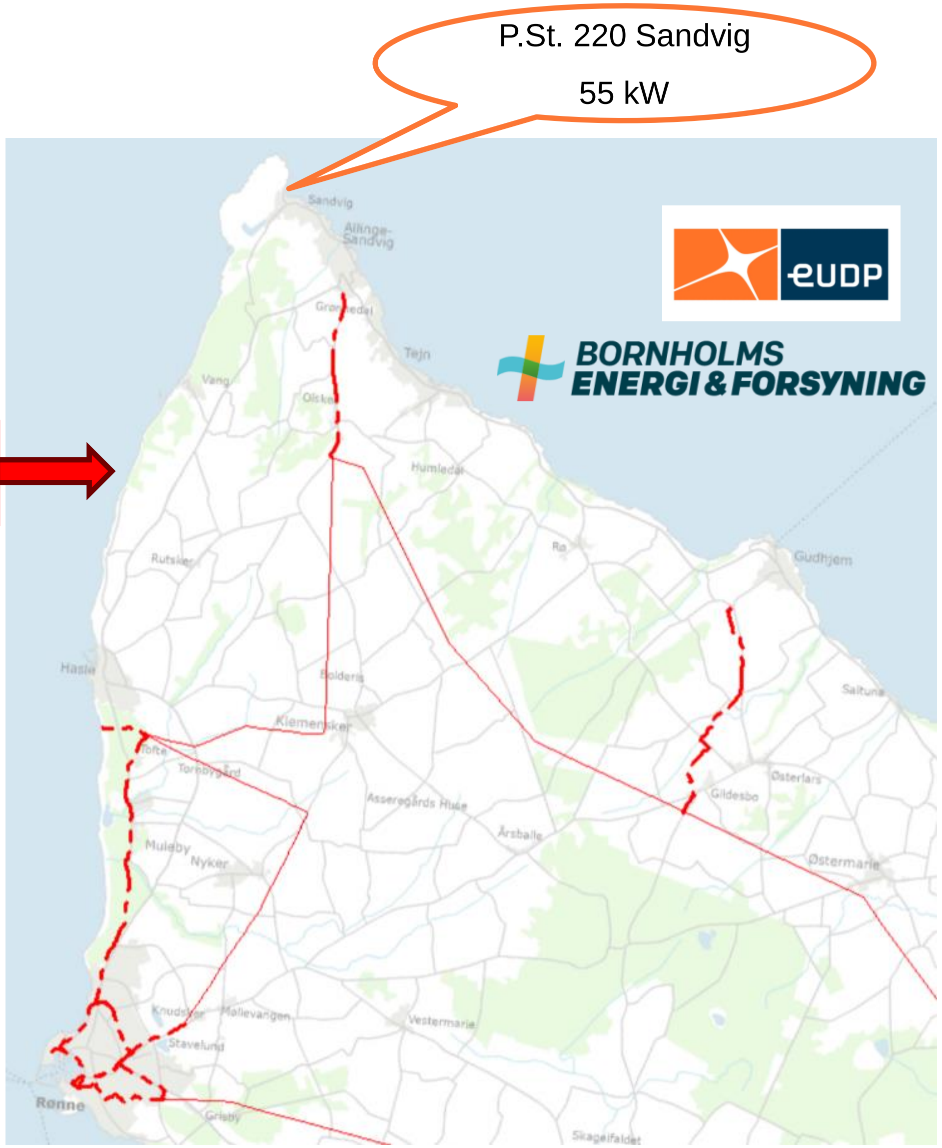
– Most developed algorithms for all projects are deployed via cloud control

Spin-out PHLIT ApS based on two patents and DTU Cloud



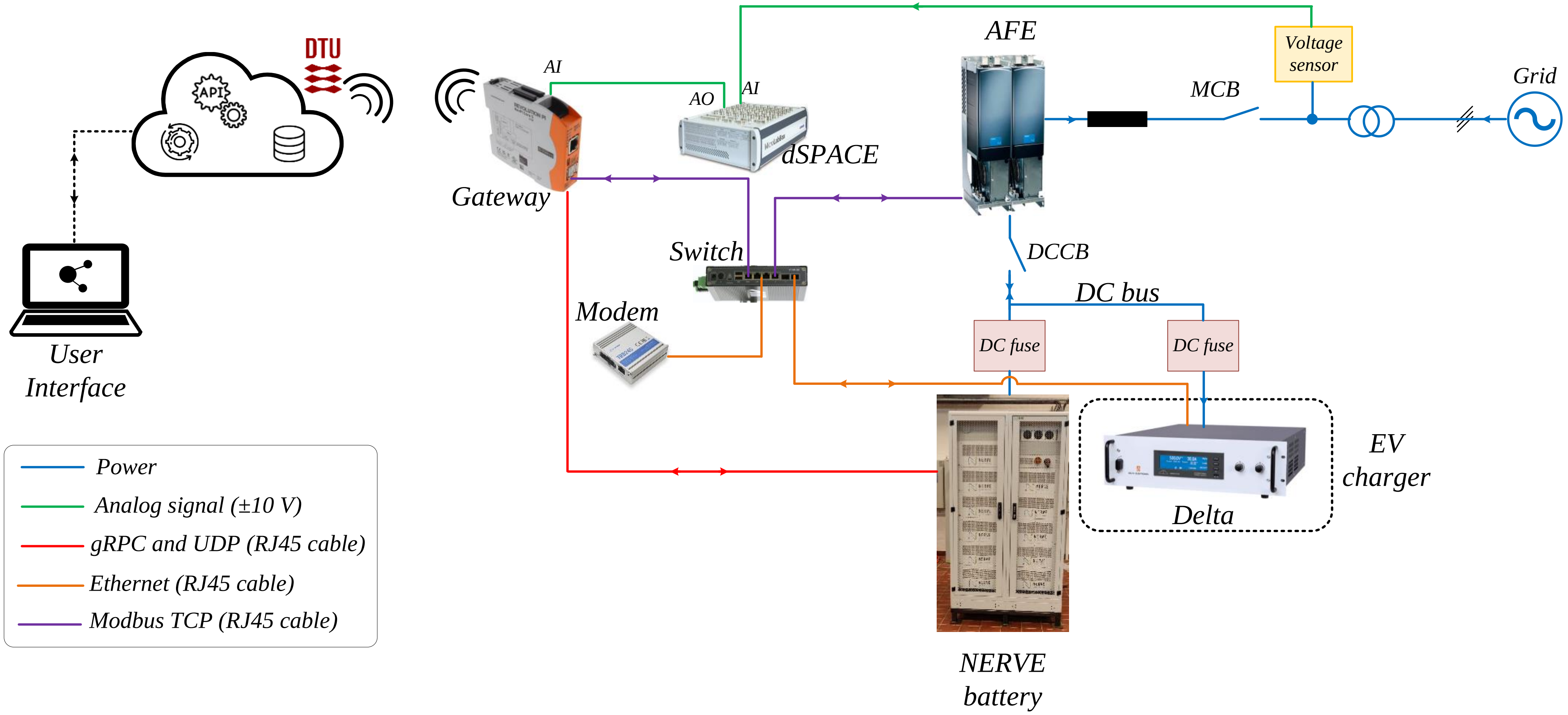
► Real world case study (Bornholm) – ACTION project

- Part of EUDP ACTION project
- Existing wastewater pump drives replaced by Danfoss drives – IoT gateway interfaced with DTU cloud platform: remote data access and controllability.
- Water flow optimized, flexibility in pump stations used as a base for the provision of remunerable grid services, online diagnostics performed.
- Good real-world case study for testing power converter asset management platform.
- **Solution is scalable – can be deployed in the same way in any converter (EV chargers, fans, compressors, electrolyzers)!**



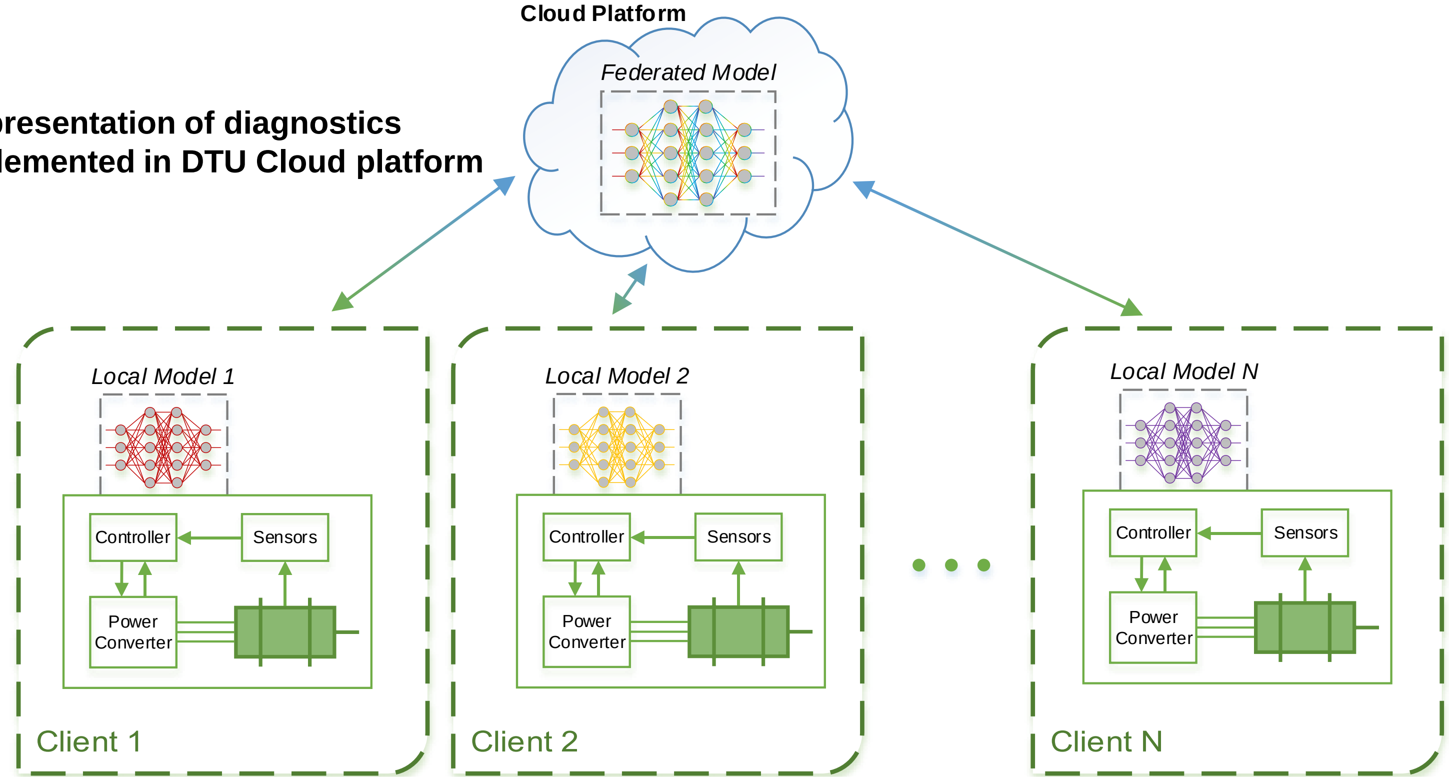
Pump station 220, Strandvejen (Sandvig)

HEART project



Diagnostics software in a nutshell – 2 patents filed in May 2021

Graphical representation of diagnostics software implemented in DTU Cloud platform



Objectives:

1. Converter fleet outlier detection system, with secure, lightweight communication.
2. Estimation of remaining useful lifetime of field converters.

Methods:

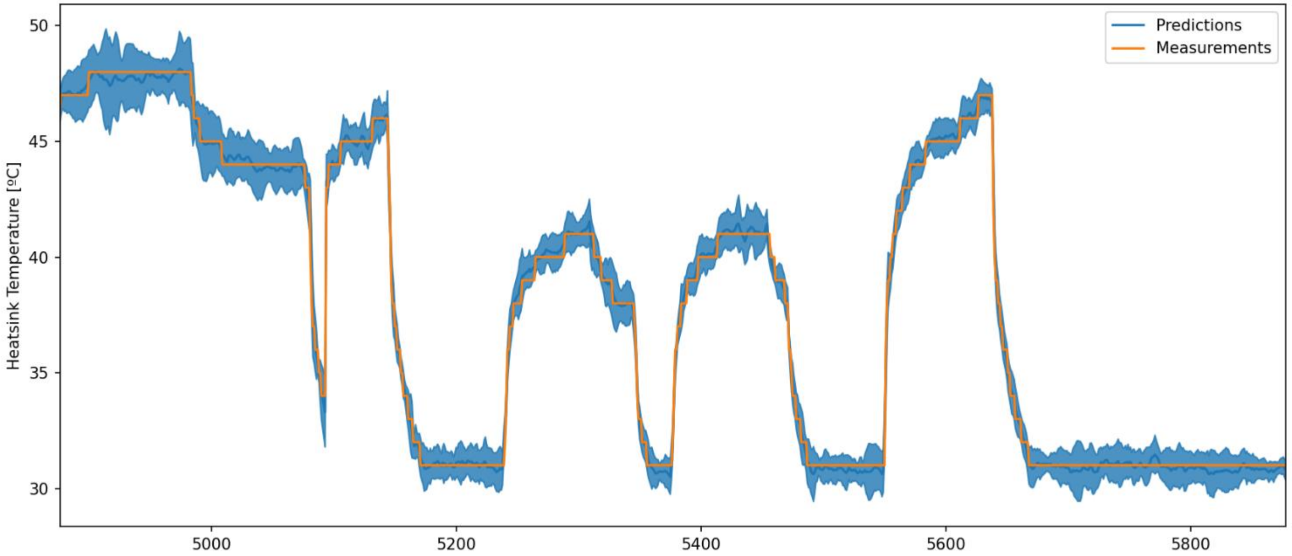
1. Federated learning with edge computation (transmission of models, not data).
2. Combining lab accelerated cycling tests and field data in machine learning model.

Patents filed!

Dev 1: Condition Monitoring

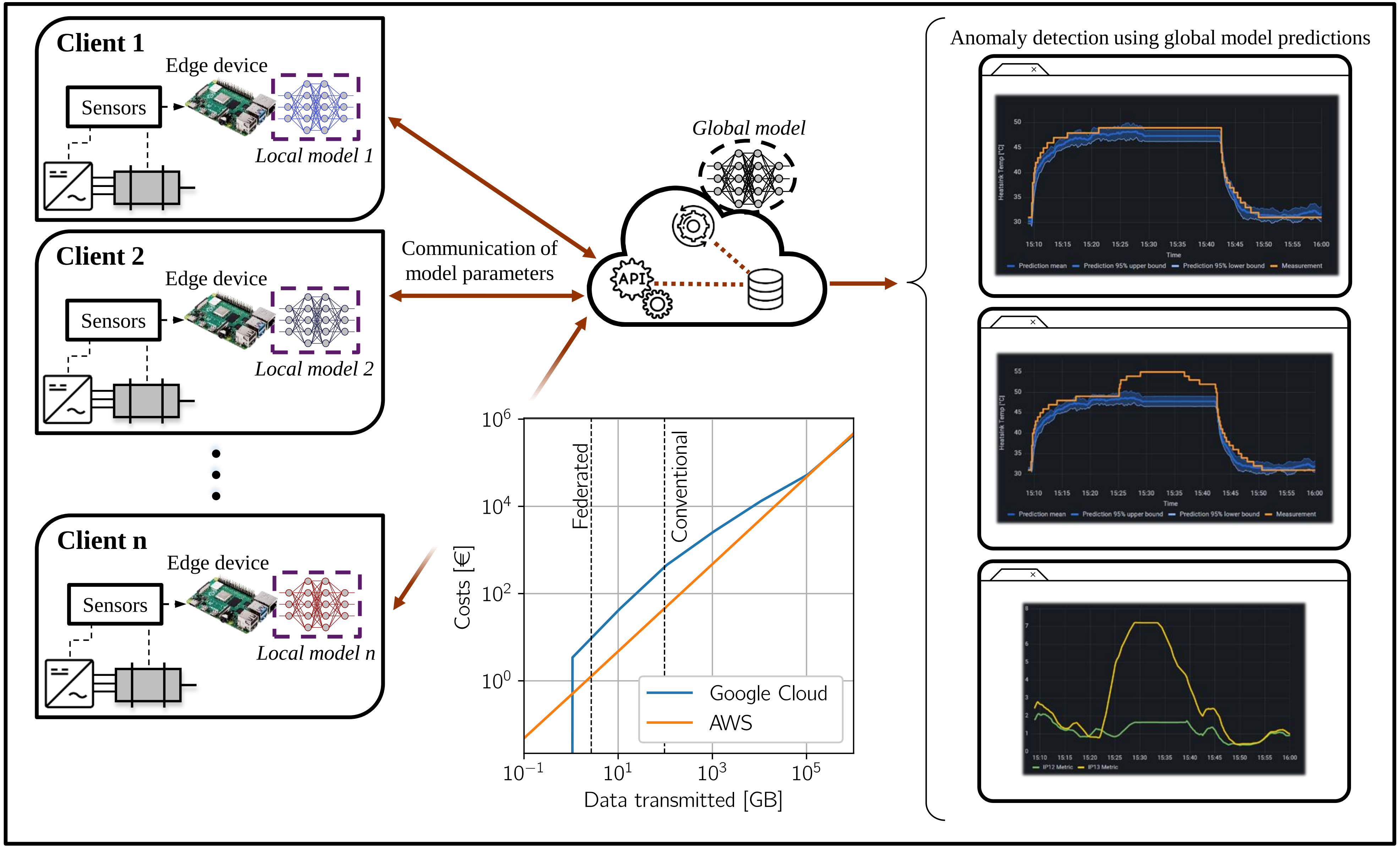
1. Automate data collection with random setpoints and obtain training dataset

2. Training and validation neural network models

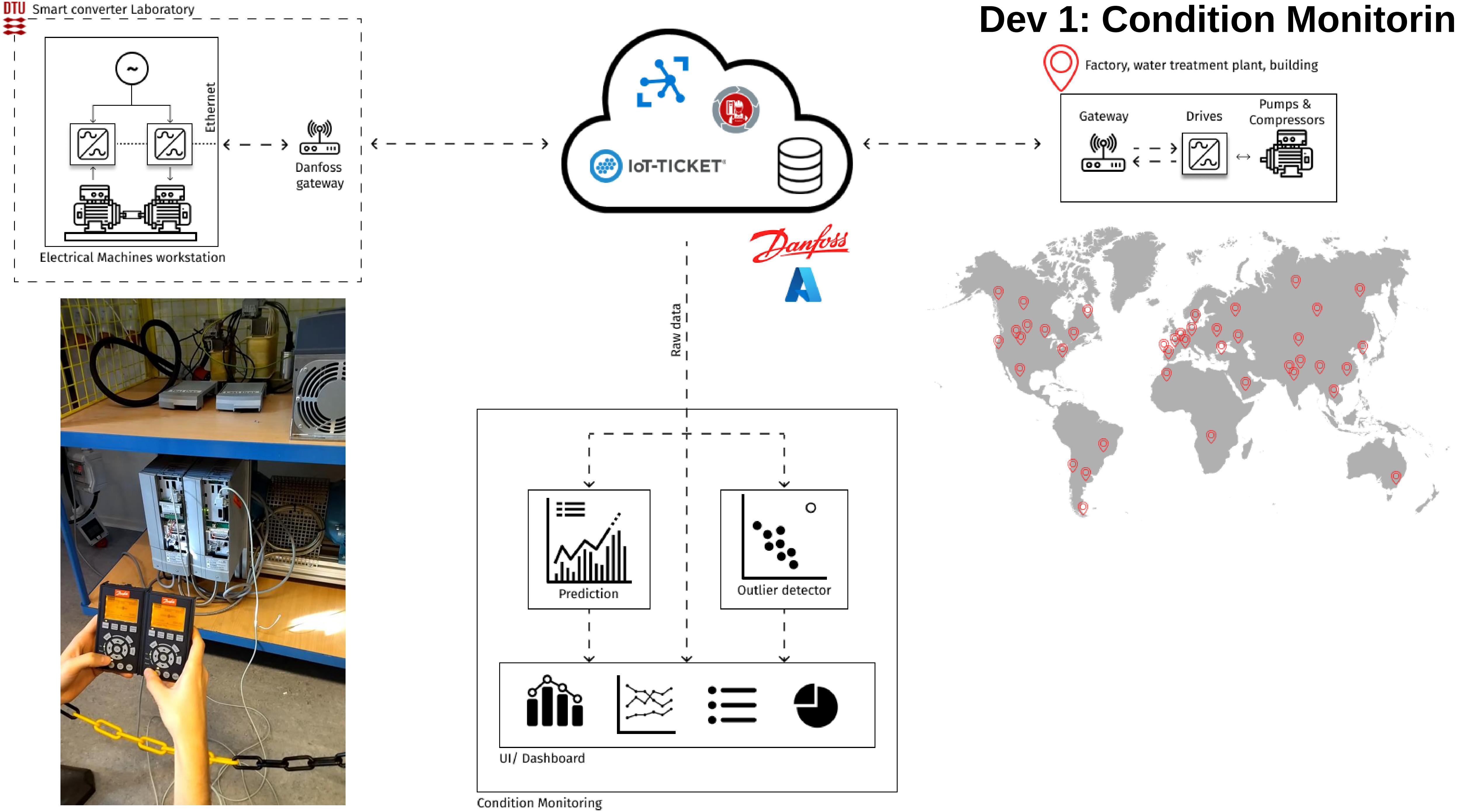


3. Deploy

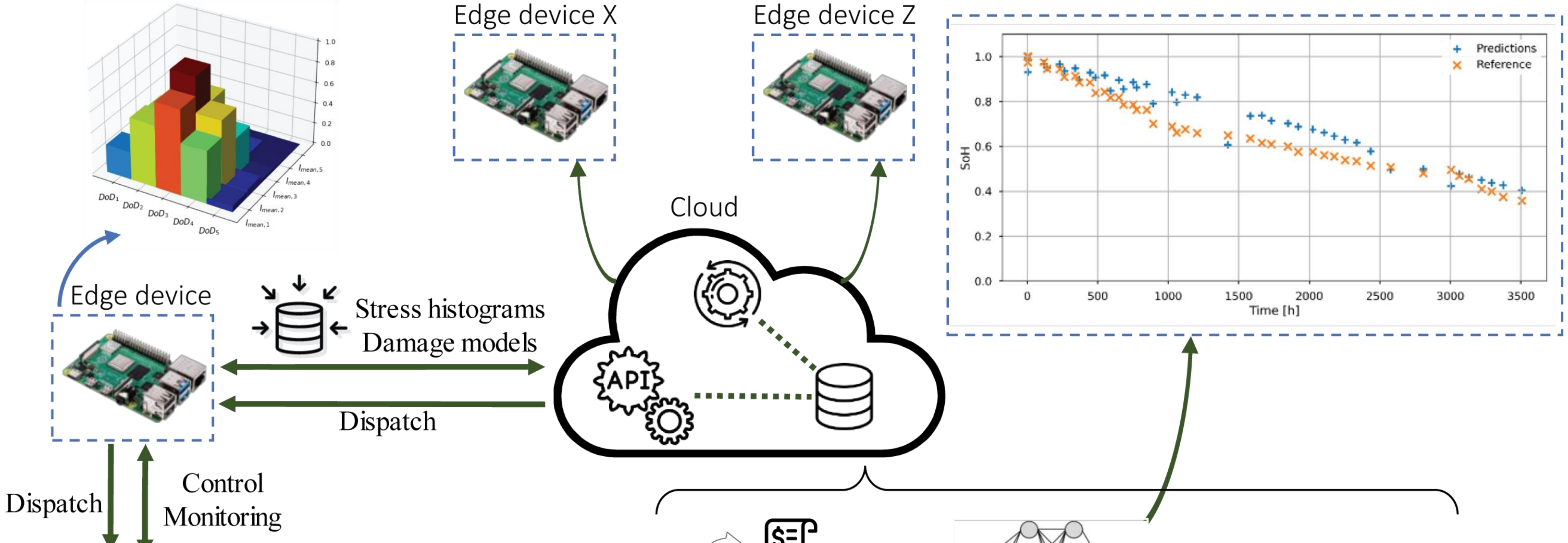
Dev 1: Converter condition monitoring

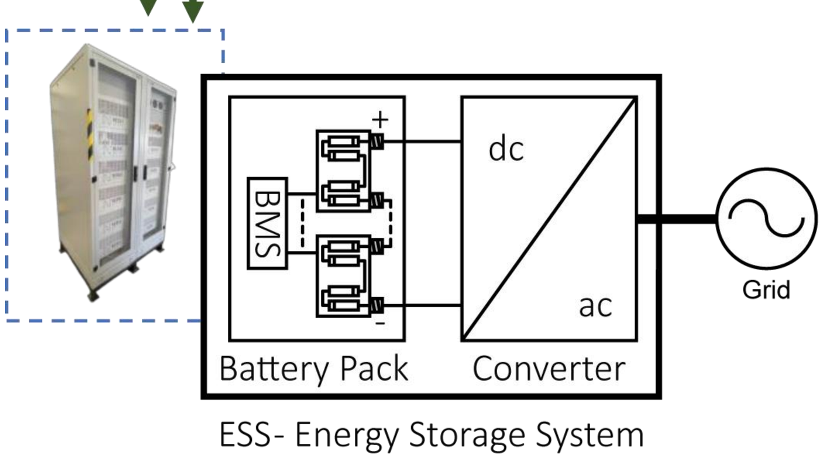


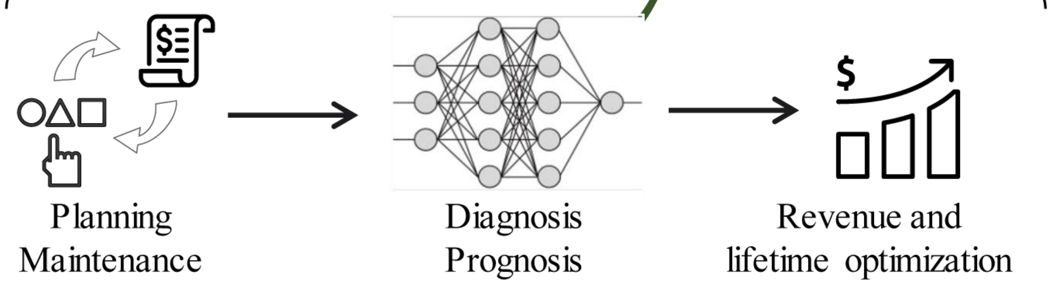
Dev 1: Condition Monitoring



Dev 2: Battery degradation analysis & forecast







- Bidirectional communication and compressed historical data.
- Cloud processing (including data fusion, model training, prediction, and optimization)
- The dispatch of field devices based on the previous results.

“Enhancement of Stress Cycle-counting Algorithms for Li-ion Batteries by means of Fuzzy Logic”, ITEC 2022.
“A ML-based framework for online prediction of battery ageing trajectory and lifetime using histogram data”, Elsevier, Journal of Power Sources.

▶ Generic physics-informed data-driven battery aging model

- **Problem description**
  - $E \xrightarrow{f} \Delta C$

  E : extracted information from battery operations, e.g., stress factors, battery capacity

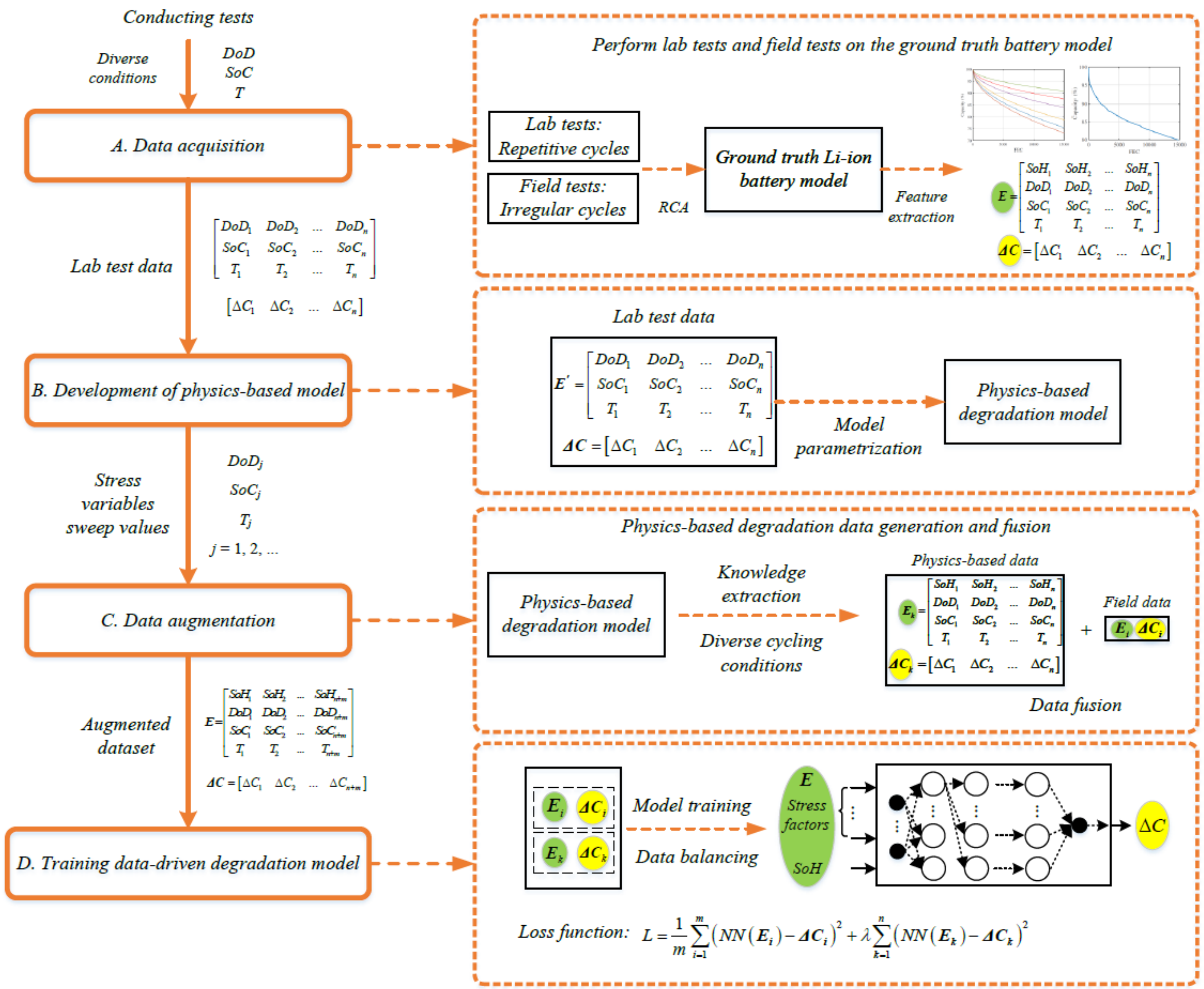
  f : modeling methods

  ΔC: capacity losses

- **Physics-based model**
  - Semi-empirical model [1]

  $$L = 1 - \alpha_{sei} e^{-N\beta_{sei} f_{d,1}} - (1-\alpha_{sei}) e^{-N f_{d,1}}$$

- **Main ideas**
  - Generic degradation learning method for <u>any battery system</u>
  - Combining strengths of physics-based and data-driven degradation models
  - Balancing the training with the two data sources



▶ Results

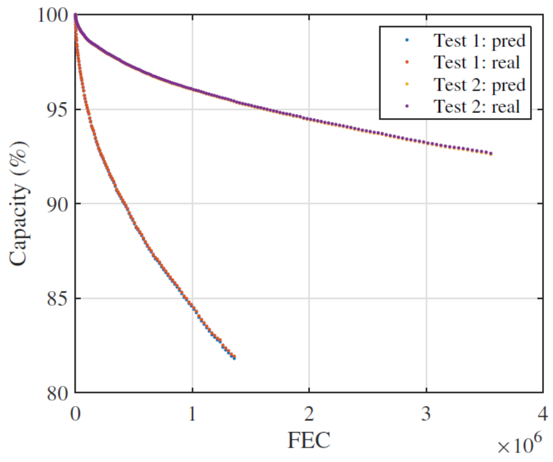
- **Comparison among different models for a battery [2]**

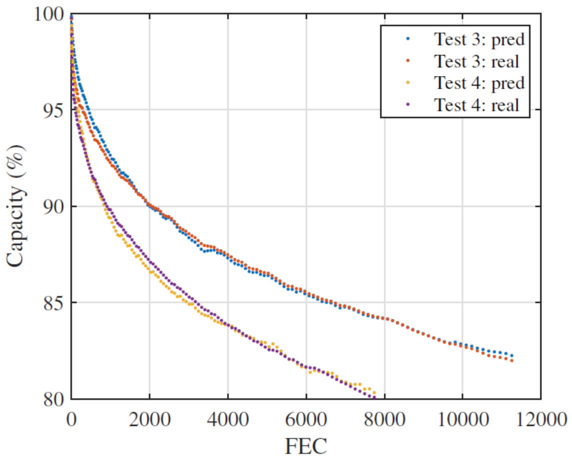
Indicators	Pure data-driven model	Proposed physics-informed data-driven model
MAE	0.98%	0.042%
RMSE	1.16%	0.075%
MAPE	0.459	0.138

Performance comparison for predicted loss and actual loss for all the identified cycles across degradation to end-of-life
MAE: average prediction error between predicted and actual loss
RMSE: average deviation between the predicted and actual loss
MAPE: average value between the error and the actual loss (in percentage)

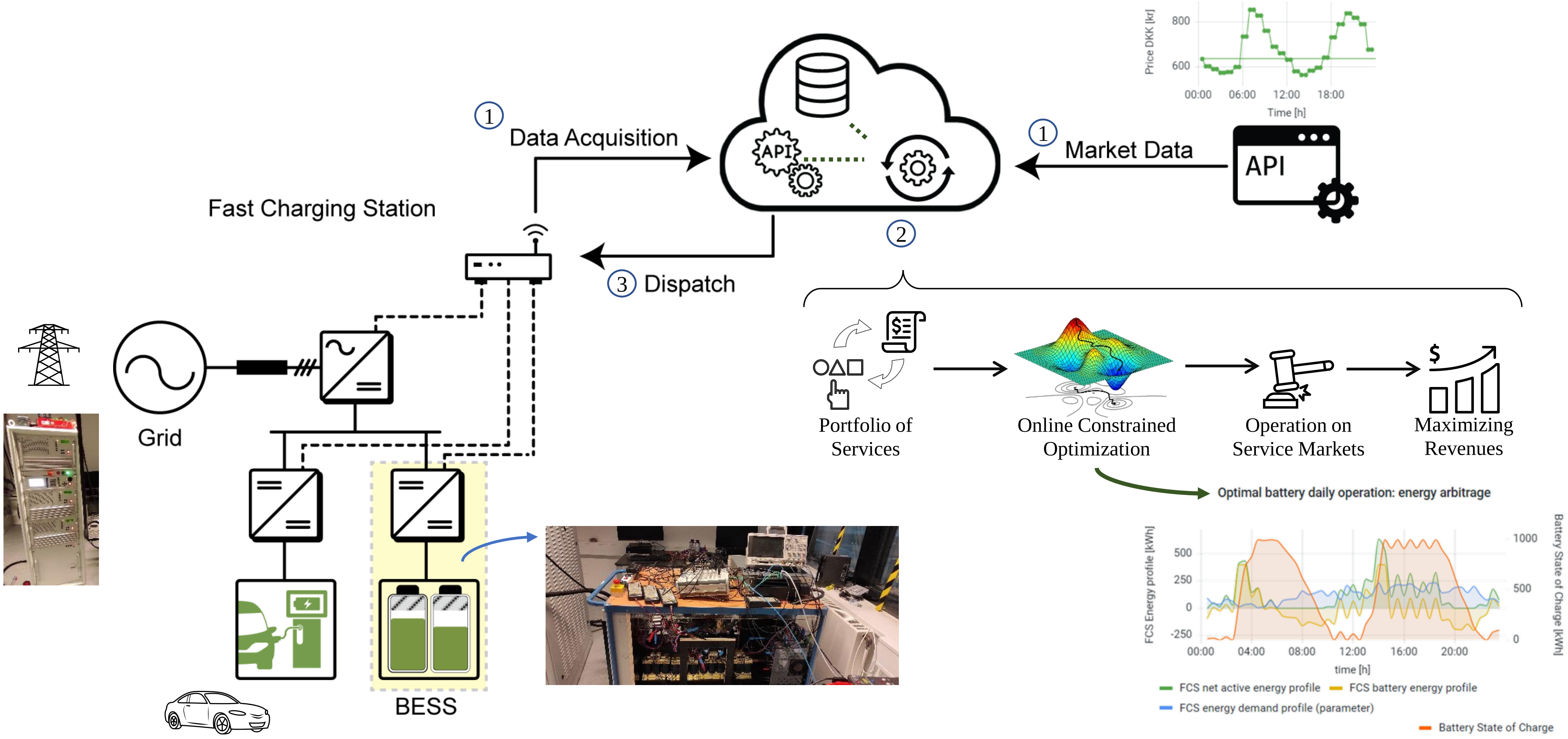
- **Performance of projecting degradation process**
  - Dynamic test conditions
  - Different battery types

Battery	Stress factors
$Li(NiMnCo)O_2$ [3]	DoD
$LiFePO_4$ [4]	C-rate, SoC_{avg}, DoD





Dev 3: Fast-charging station dispatch optimization

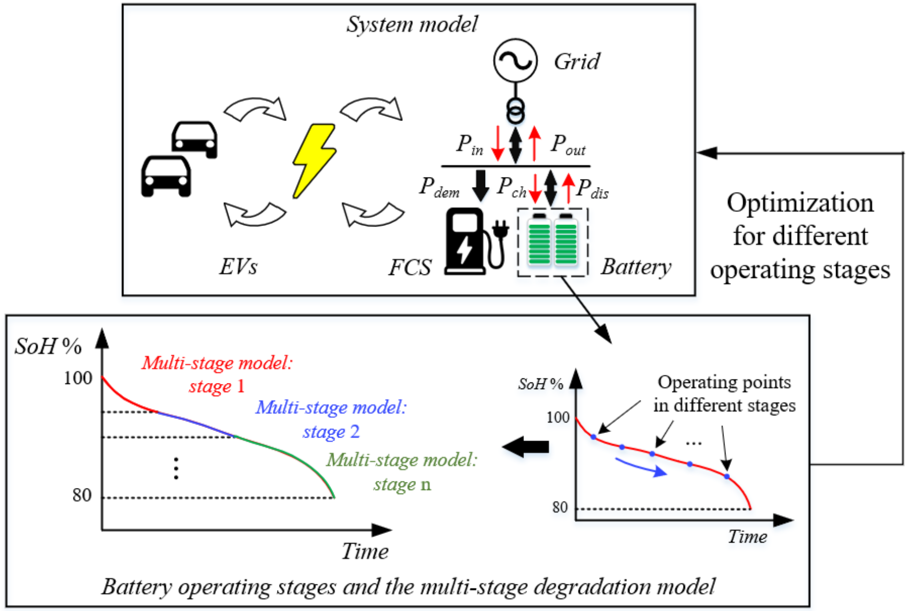


"BESS Optimal Sizing and Scheduling for Energy Arbitrage and Frequency Containment Reserve via Dual-Loop Optimization", ITEC 2022.
https://www.energidataservice.dk/tso-electricity/FcrReservesDK2
https://www.coordinador.cl/desarrollo/documentos/actualizaciones-del-sistema-de-informacion-publica/api-publica-del-sip/

► Day-ahead scheduling with multi-stage battery degradation model

- **Background**
  - **Accurate formulation of battery aging cost** for the operational planning problem is critical;
  - Battery degradation process is a complex and nonlinear process, where the **degrading pattern** varies among different stages;
  - Conventional methods use **single-stage models** to evaluate battery degradation for the scheduling problem across the whole operational lifetime, resulting in **suboptimal operations** and increase in **overall operation cost**.

- **Contributions**
  - A novel multi-stage battery degradation modeling method;
  - An adaptive scheduling framework with the multi-stage degradation model;
  - Analysis regarding the number of divided stages and validations on various models.



► Implementation procedure

- **Multi-stage battery degradation modeling method**
  - Stressing factors: C-rate, DoD, etc.;
  - Segmentation of the aging experimental data[1] for different degradation stages;
  - Model parameterization for different aging stages with the experimental data.

- **Scheduling model**
  - Objective function

$$J_t = \min_{P_t^{ch}, P_t^{dis}} \sum_{t=1}^{T} \left(P_t^{in} - P_t^{out}\right) \cdot p_t + \lambda_k \cdot C_t$$

  - Constraints
    - Energy balance:

$$P_t^{in} - P_t^{out} = P_t^{ch} - P_t^{dis} + P_{dem}$$

    - Battery operation:

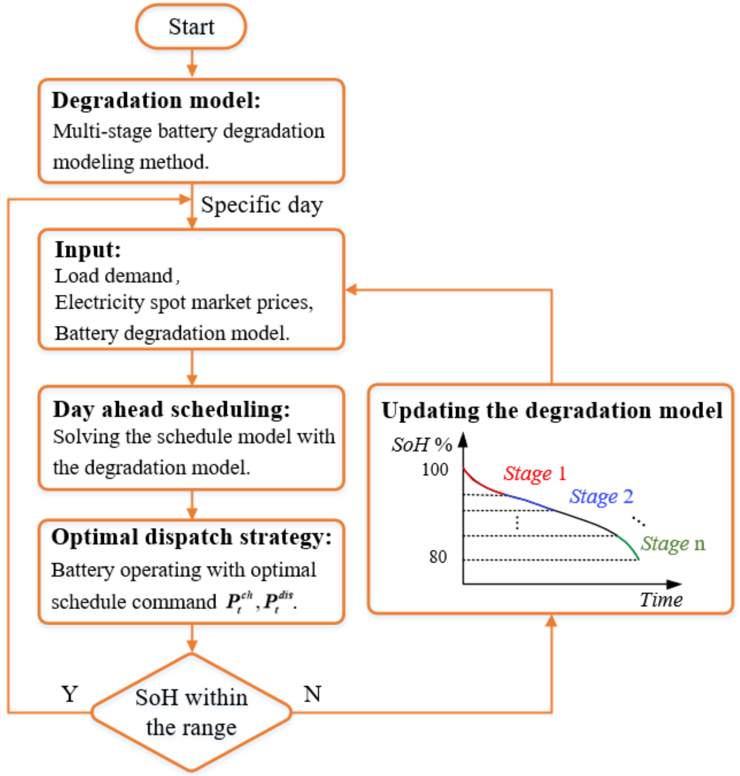
$$SoC_t = SoC_{t-1} + \frac{1}{C_{bat}}\left(\eta_{ch} P_t^{ch} - \frac{P_t^{dis}}{\eta_{dis}}\right),$$

$$SoC_{t=T} = SoC_{end},$$

$$SoC_{\min} \le SoC_t \le SoC_{\max},$$

    - Power limits
  - Formulation of battery aging cost
    - Battery degradation model [2]

$$Q_{loss} = \sum_{t=1}^{T} \frac{\left(\Delta DoD_t\right)^{\frac{1}{\alpha}} \cdot \left(2 I_t^{ch/dis}\right)^{\frac{1}{\alpha}} \cdot \exp\left[-\varphi\left(\frac{1}{T_a} - \frac{1}{25}\right)\right]}{N_{cref}}$$



Nomenclature:

P_t^{ch}, P_t^{dis}: dispatch command; P_{dem}: load demand;

P_t^{in}, P_t^{out}: energy flow from/to grid to/from FCS;

p_t: electricity spot market price,

λ_k: replacement cost, C_t: battery capacity loss;

Q_{loss}: formulation of battery degradation;

SoC_t: battery state-of-charge; DoD_t: depth-of-discharge

C_{bat}: nominal battery capacity.

► Case study

- **Comparison**
  - Multi-stage modeling on a cycle life model (three stages)

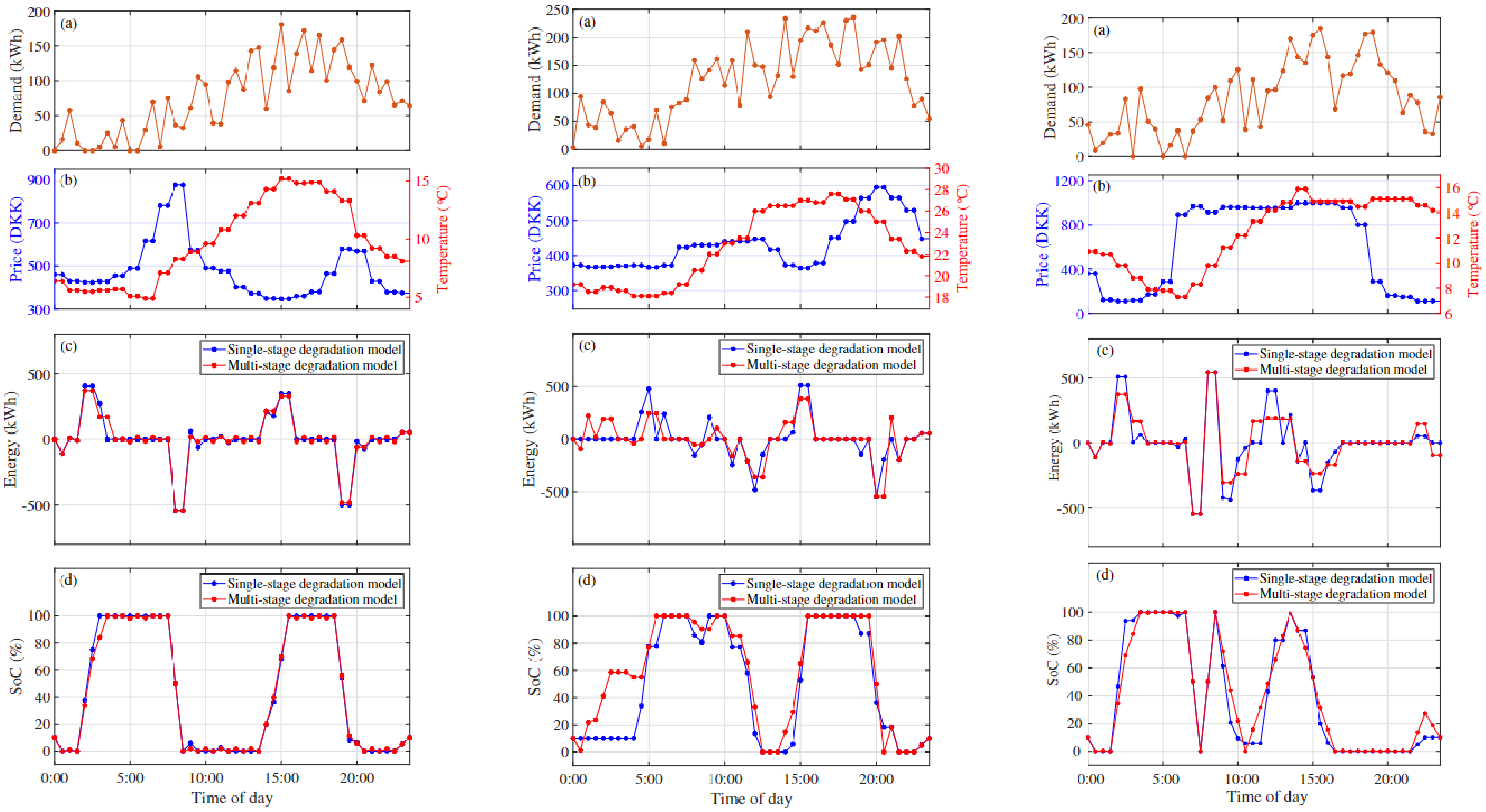
Tests/RMSE	Stages	Single-stage model	Multi-stage model
Test 1	Stage 1	0.78%	0.50%
	Stage 2	2.21%	0.42%
	Stage3	3.15%	1.10%
Test 2	Stage 1	1.00%	0.78%
	Stage 2	2.37%	0.75%
	Stage3	2.86%	1.28%

  - Day-ahead scheduling for three example days (representing different stages)

Cases	Case 1		Case 2		Case 3	
	Single-stage model	Multi-stage model	Single-stage model	Multi-stage model	Single-stage model	Multi-stage model
Battery degradation (%)	0.0327	0.0290	0.0594	0.0458	0.0505	0.0222
Energy arbitrage revenue (DKK)	1213.12	1212.42	685.75	697.48	1420.74	1419.08
Operation cost (DKK)	459.45	453.94	2032.24	1997.14	1452.07	1404.42

▶ Case study

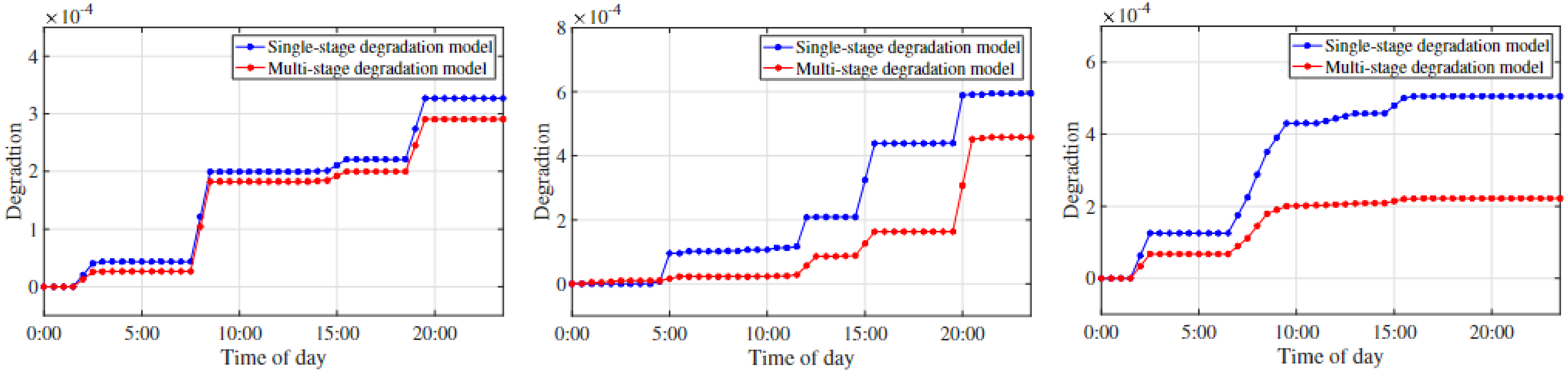
- **Scheduling results**



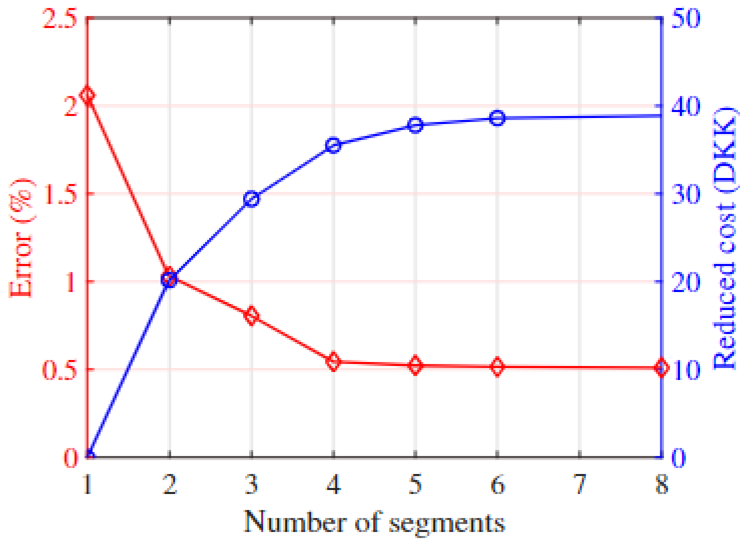
Case 1 Case 2 Case 3

► Case study

- **Accumulative battery degradation across a day**



- **Sensitive analysis regarding the number of divided stages**

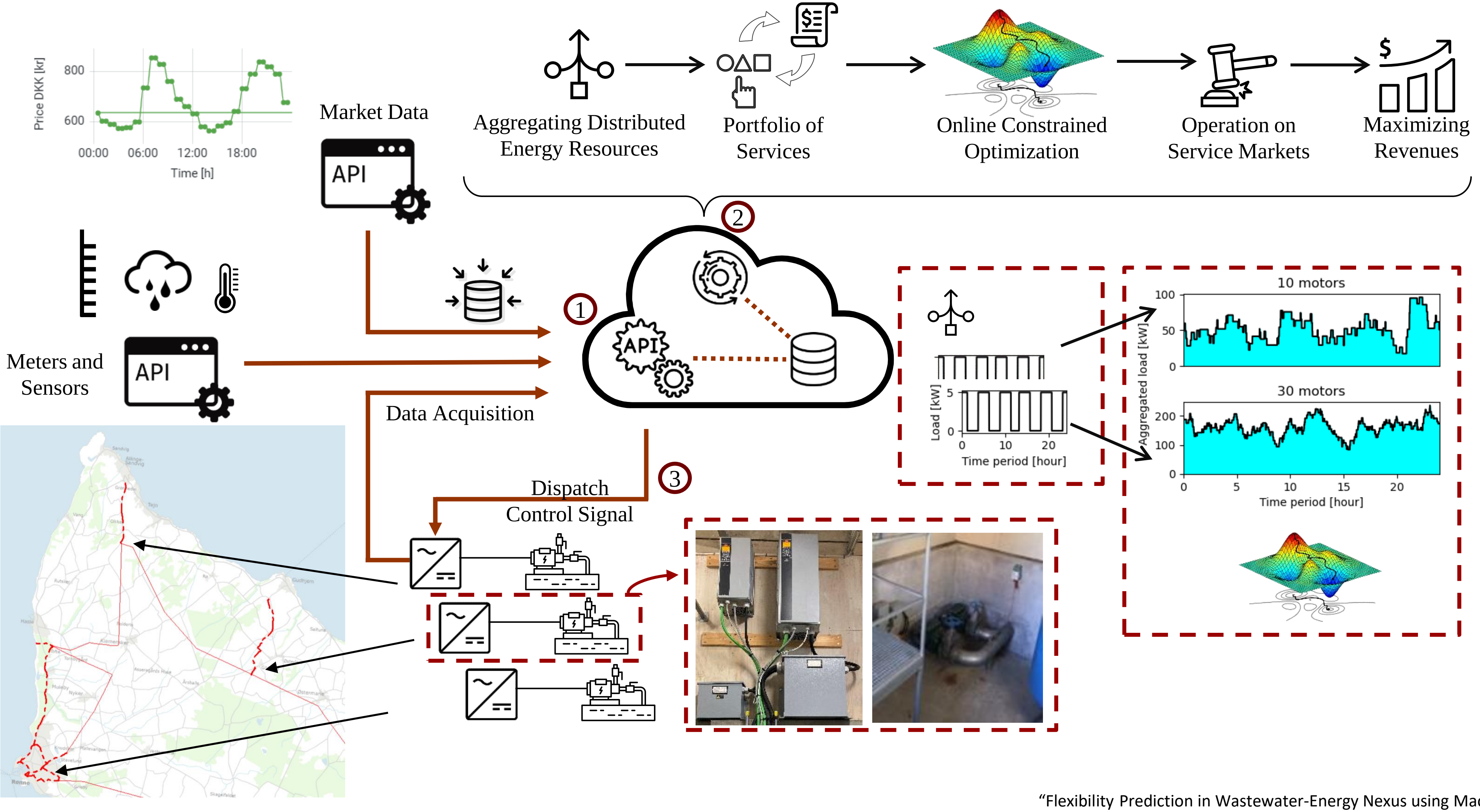


Blue line: reduced operation cost

(compared with the basic single-stage model)
Red line: model accuracy for validation dataset

(RMSE in percentage)

Dev 4: Distributed wastewater pumping system coordination



“Flexibility Prediction in Wastewater-Energy Nexus using Machine Learning”, IECON 2022.

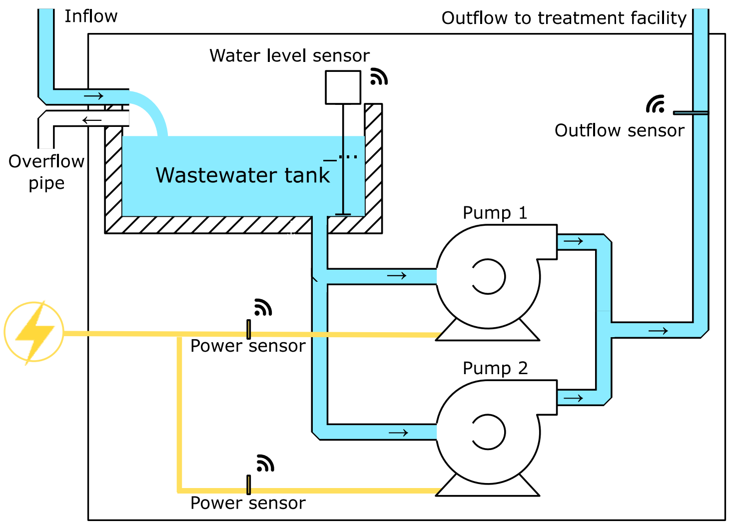
FlexGate® solution

- **Transforms wastewater tanks into virtual batteries** by modifyng the outflow pumping rate:
  - ✓ Before expected rain, tank is emptied to give more buffer and prevent (excessive) overflows
  - ✓ Optimal pumping rate enforced whenever water in the tank is at moderate level
  - ✓ Pumping reduced or increased from the baseline level to support the grid (in coordination with other flexible assets)

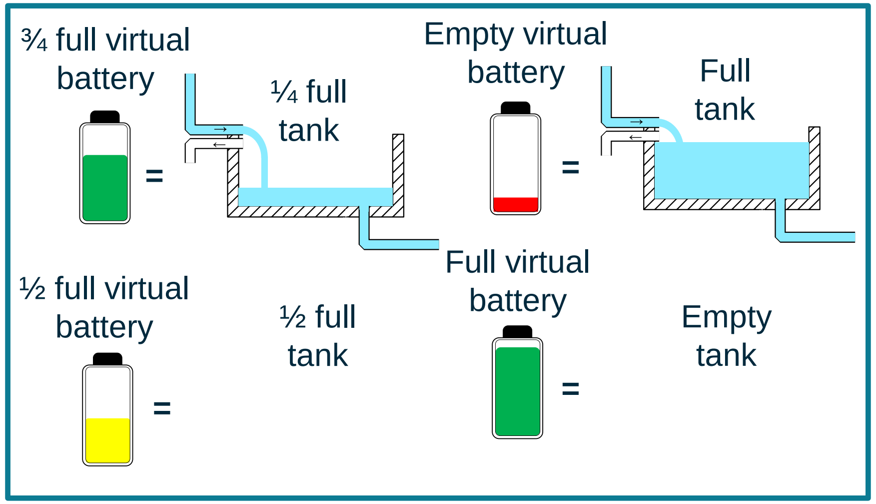
- **Virtual battery characteristics:**
  - Tank capacity does not degrade
  - No use of critical raw materials or footprint
  - Losless round trip charge cycle (because overall volume is pumped anyway)
  - Provides short-term storage (up to 15 min)

Solution demonstrated in a real-world wastewater pumping station (Rønne, Denmark)

Wastewater pumping station

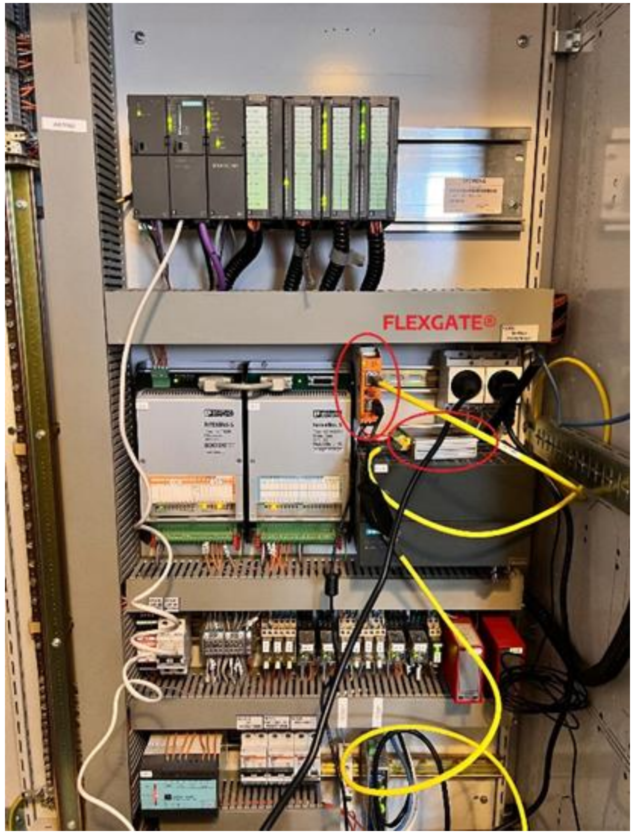


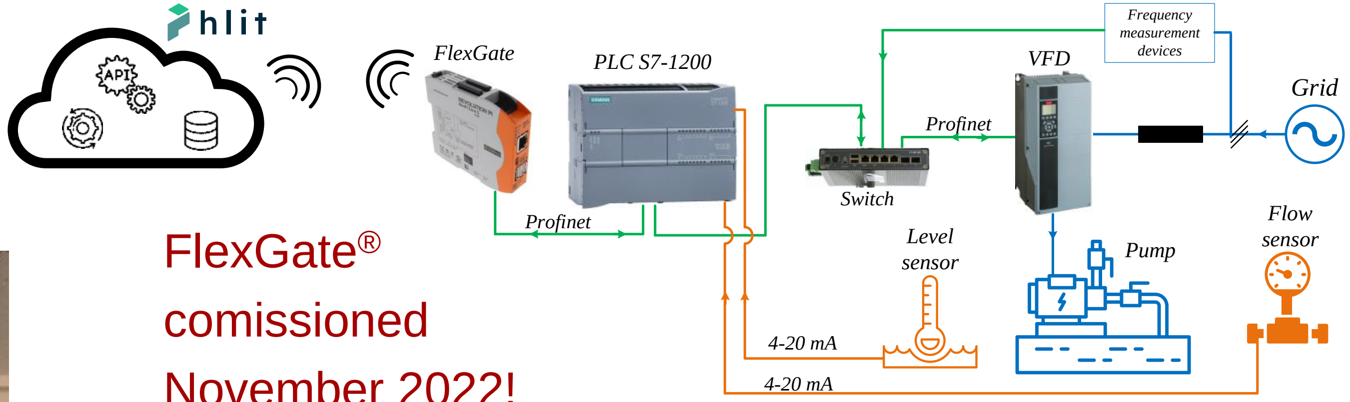
Distributed fleet of virtual batteries



Bornholm's Spildevand A/S: pilot project

FlexGate installed at 3 other test sites, more trial projects planned

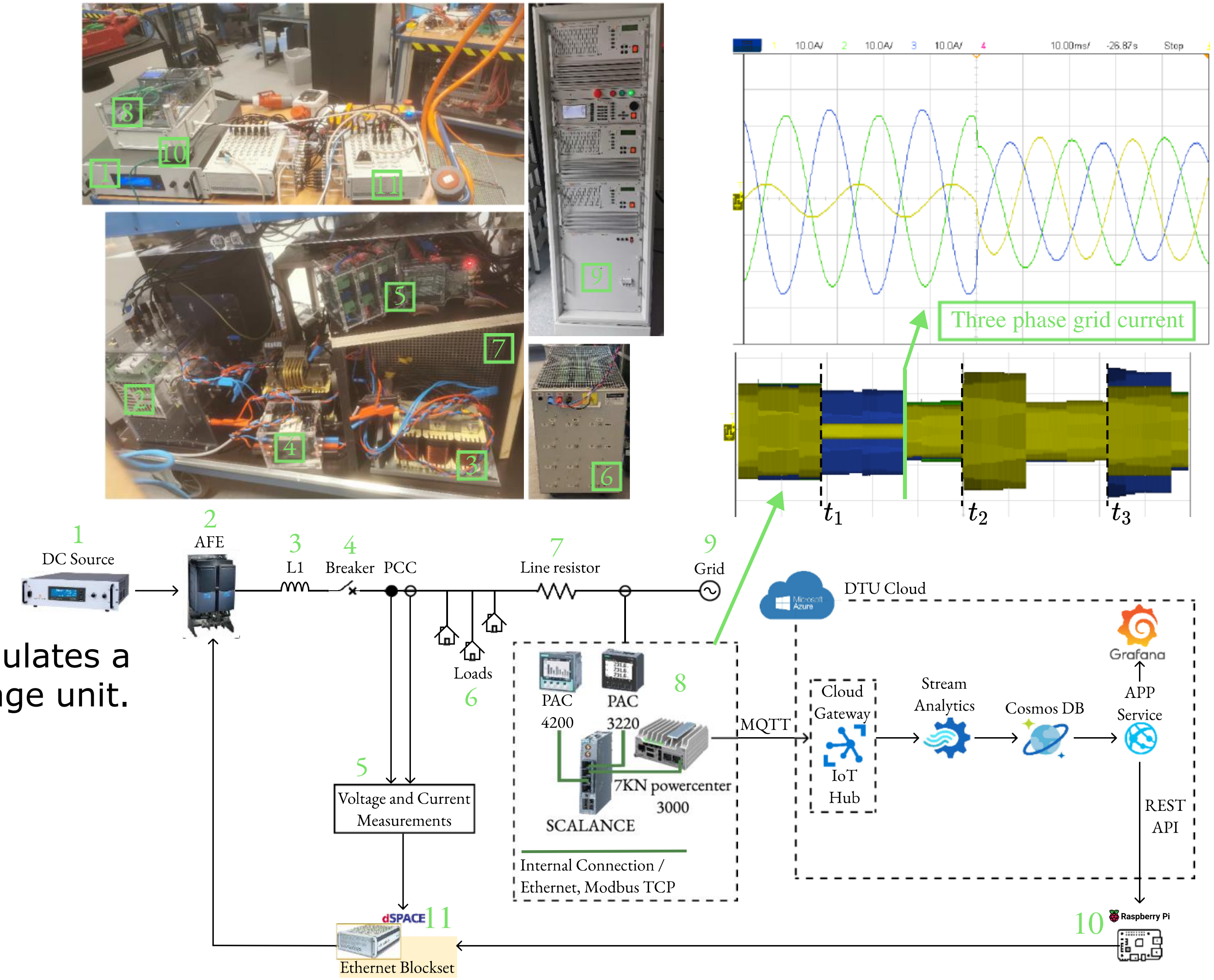




FlexGate® comissioned November 2022!

- **Data collected from the PLC with 1 sec update rate**
  - Water level, outflow, pump speeds, pump powers
  - Data processing and controller synthesis automation fully streamlined
- **5 kW / 5 kWh virtual battery unlocked:**
  - Up to 10% efficency improvement enabled
  - Aggregation with other flexible assets for grid service provision enabled
  - Performance validated with grid operator

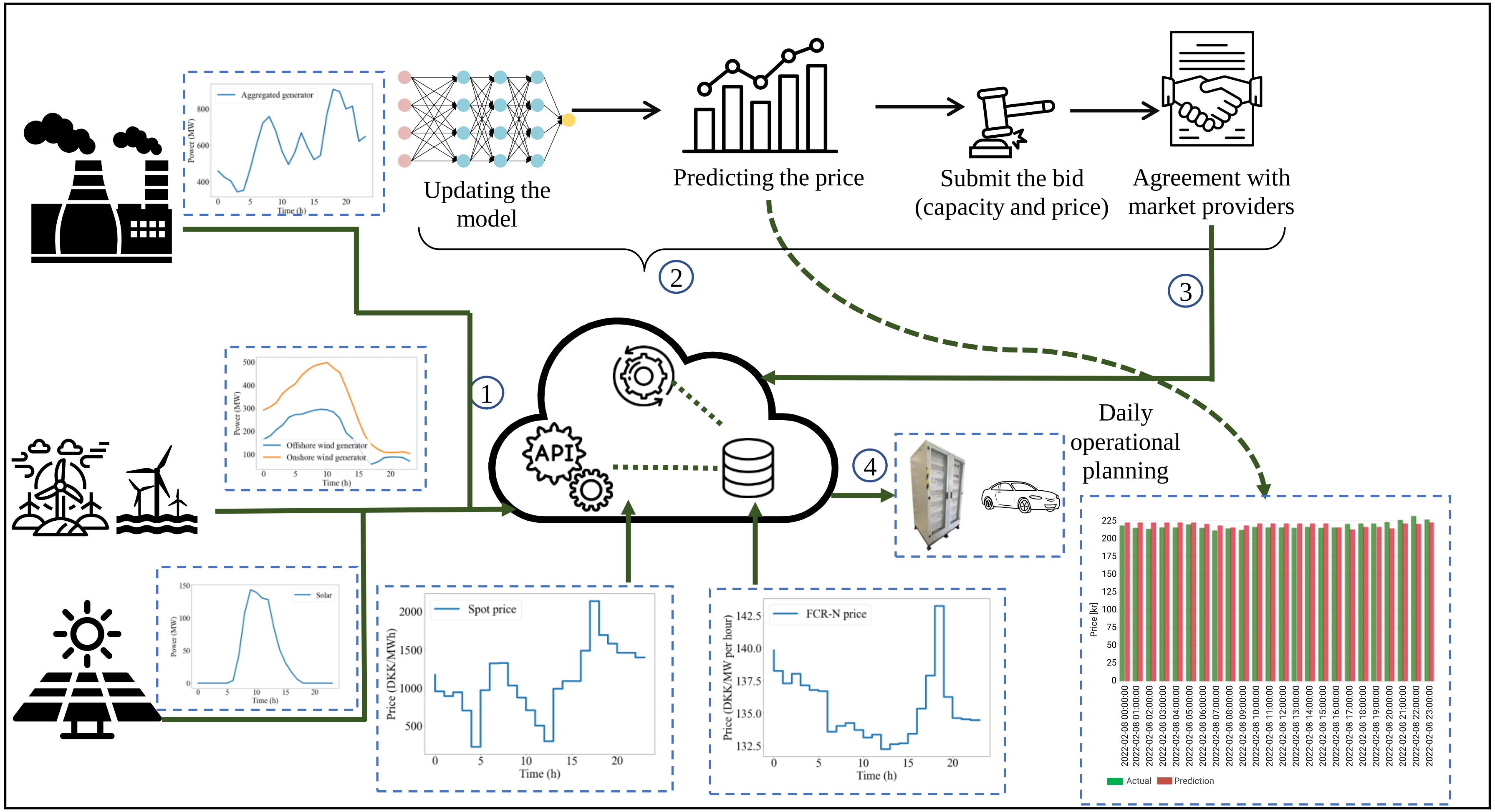
Dev 5: Voltage imbalance compensation



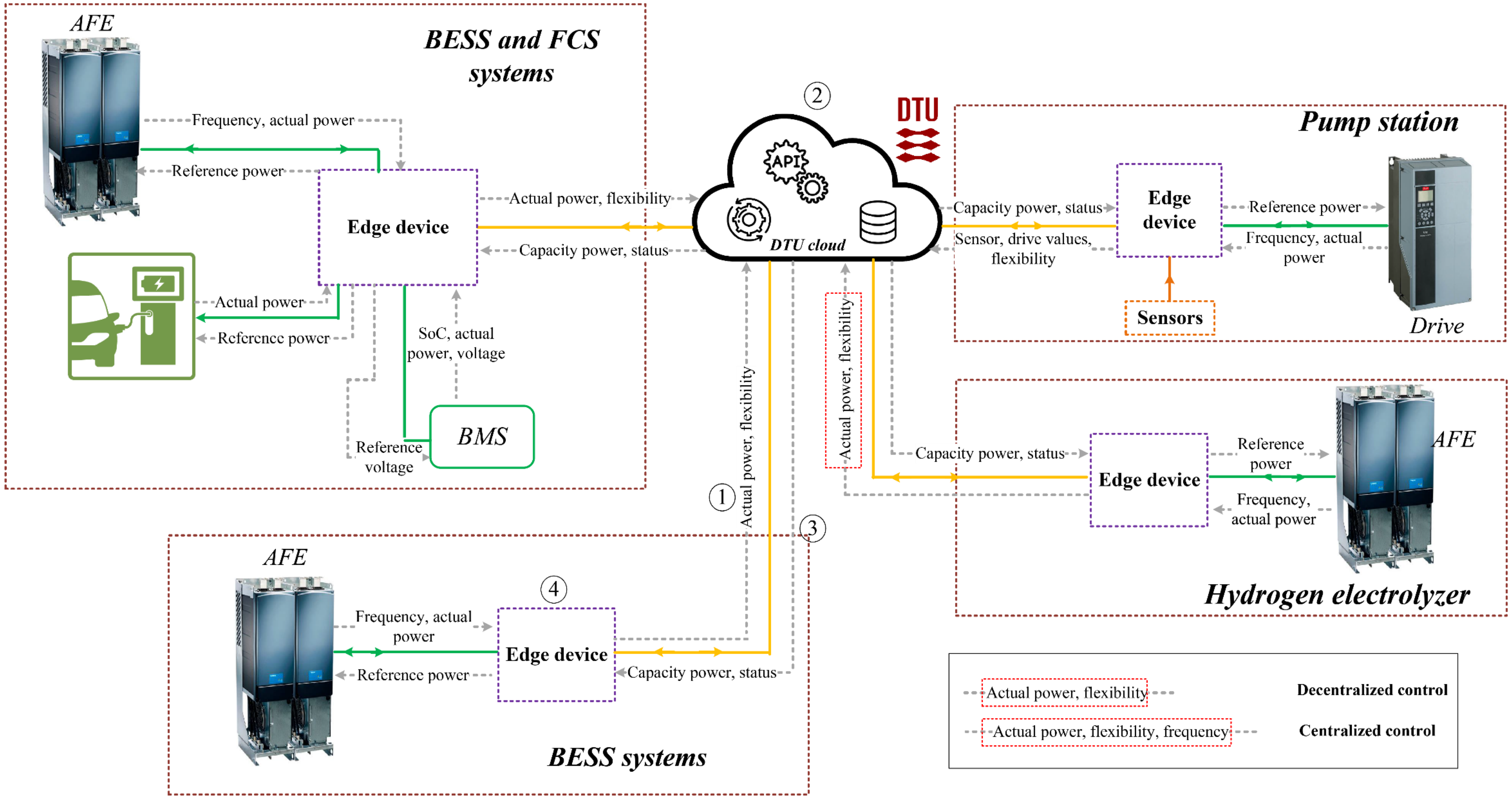
DC source emulates a generator or storage unit.

- Load imbalances are created at t_1, t_2 and t_3.
- GMU registers currents, phase-shifts, and power factor.
- IoT Hub is used to send data every 15s.
- Rpi used as intermediate with Cloud and dSPACE.
- Negative sequence reference updates the controller every 30s.
- The unbalanced voltage is compensated by injecting the negative sequence of the grid current through the converter.

Dev 6: Frequency regulation Market Bidding



Dev 7: The operation of Virtual Power Plants



Simulation:

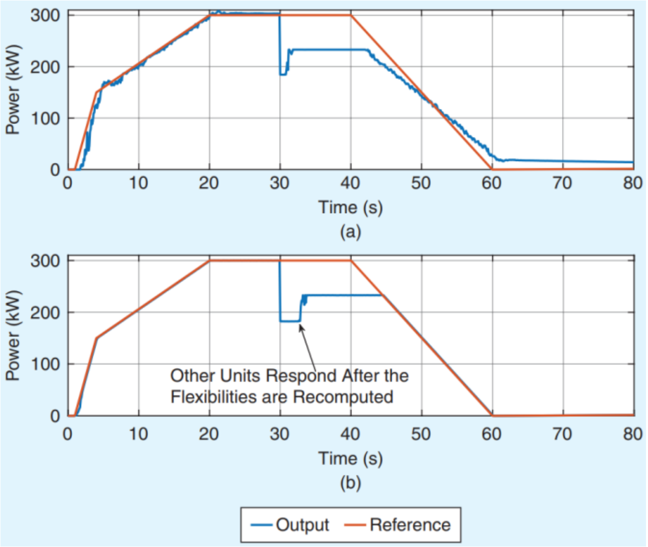
The total agreed power delivery with the TSO is 300kW.

The time step of updating the available flexibilities is 2s.

5 units of P={50,100,33,50,150}kW

FCR-D on each unit.

At t=30, unit 5 experiences malfunction.



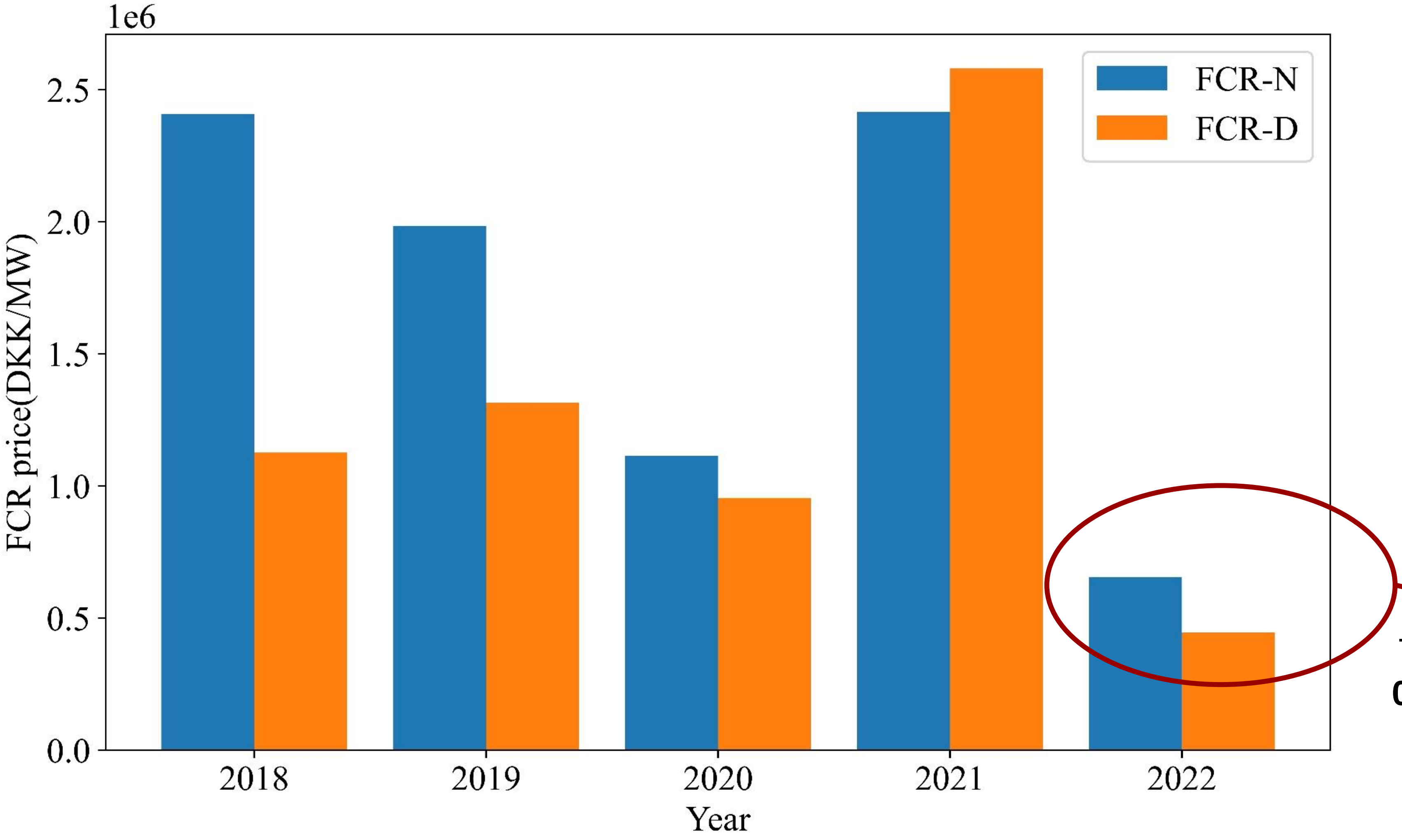
Thanks for your attention!

Frequency Reserve Market

Frequency Regulation

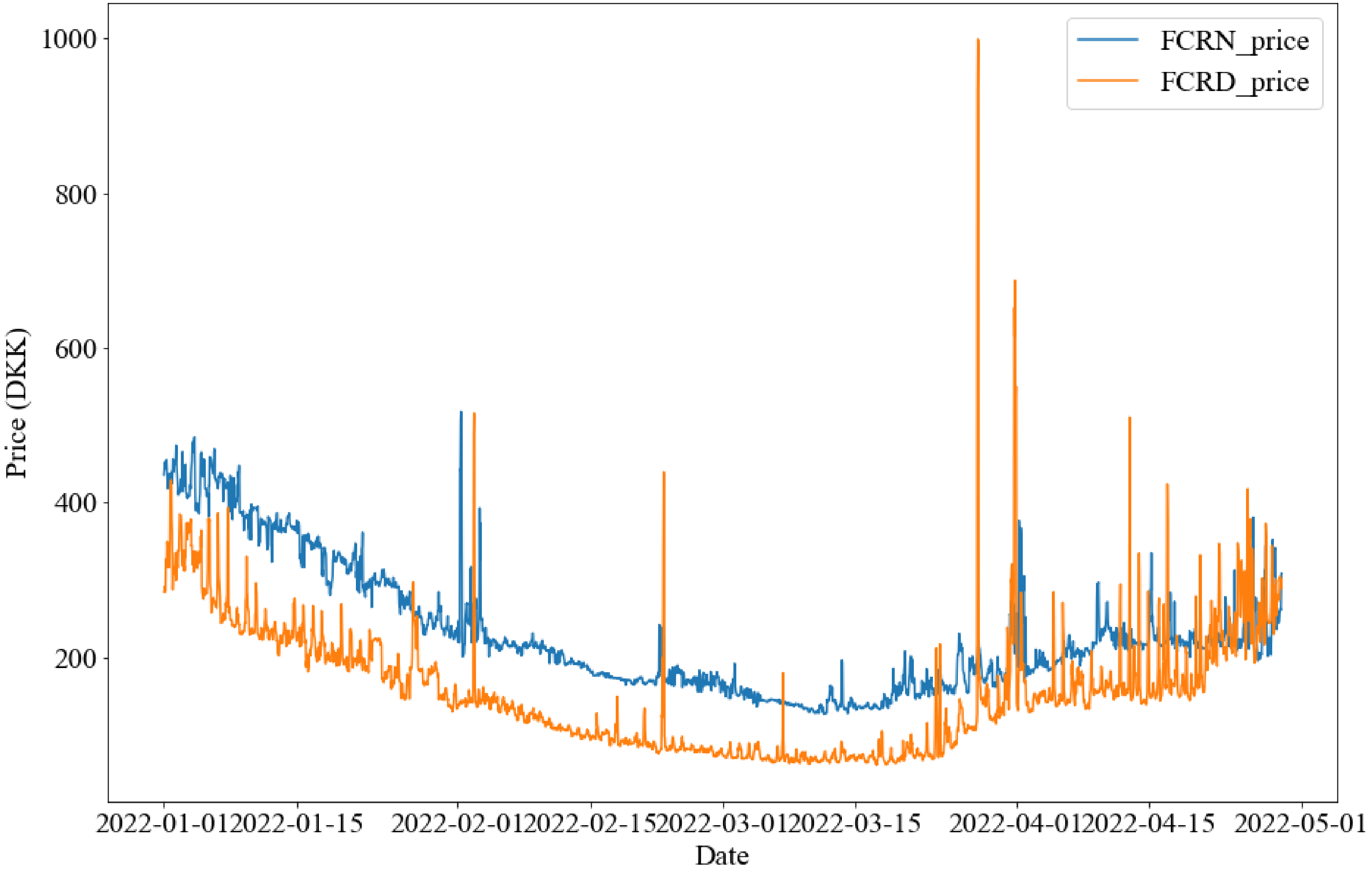
- Primary Control
  - Frequency containment reserve (FCR)
    - FCR Normal (FCR-N)
    - FCR Disturbance (FCR-D)
  - Fast Frequency Reserve (FFR)
- Secondary Control
  - Automatic frequency restoration reserve (aFRR)
- Tertiary Control
  - Manual frequency restoration reserve (mFRR)

FCR price in DK2

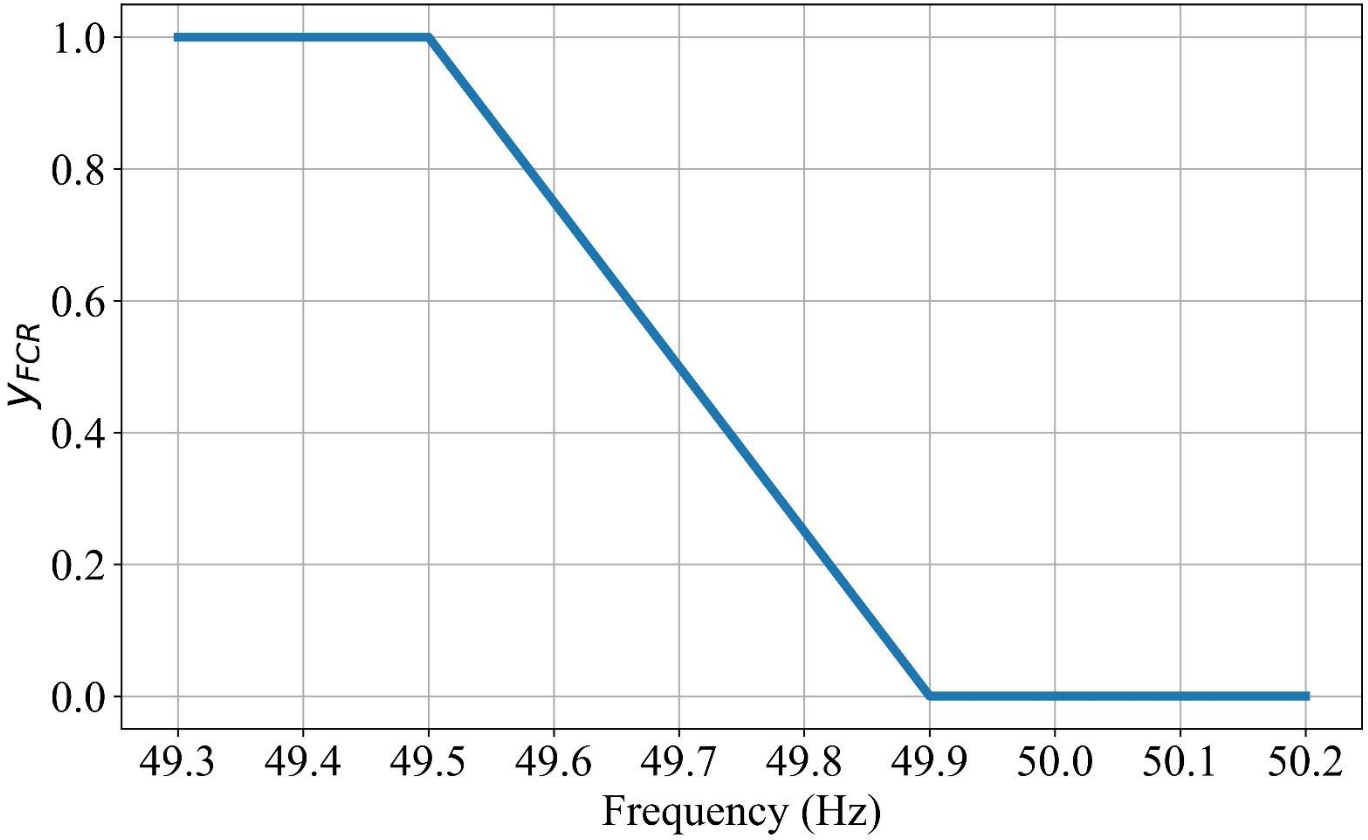


The price was taken from **01-01-2022** to **28-04-2022**

FCR price in DK2 (2022)



Frequency Containment Reserve Disturbance (FCR-D)



- Upward regulation, activated when the frequency < 49.9 Hz
- The capacity given is a function of frequency, formulated as

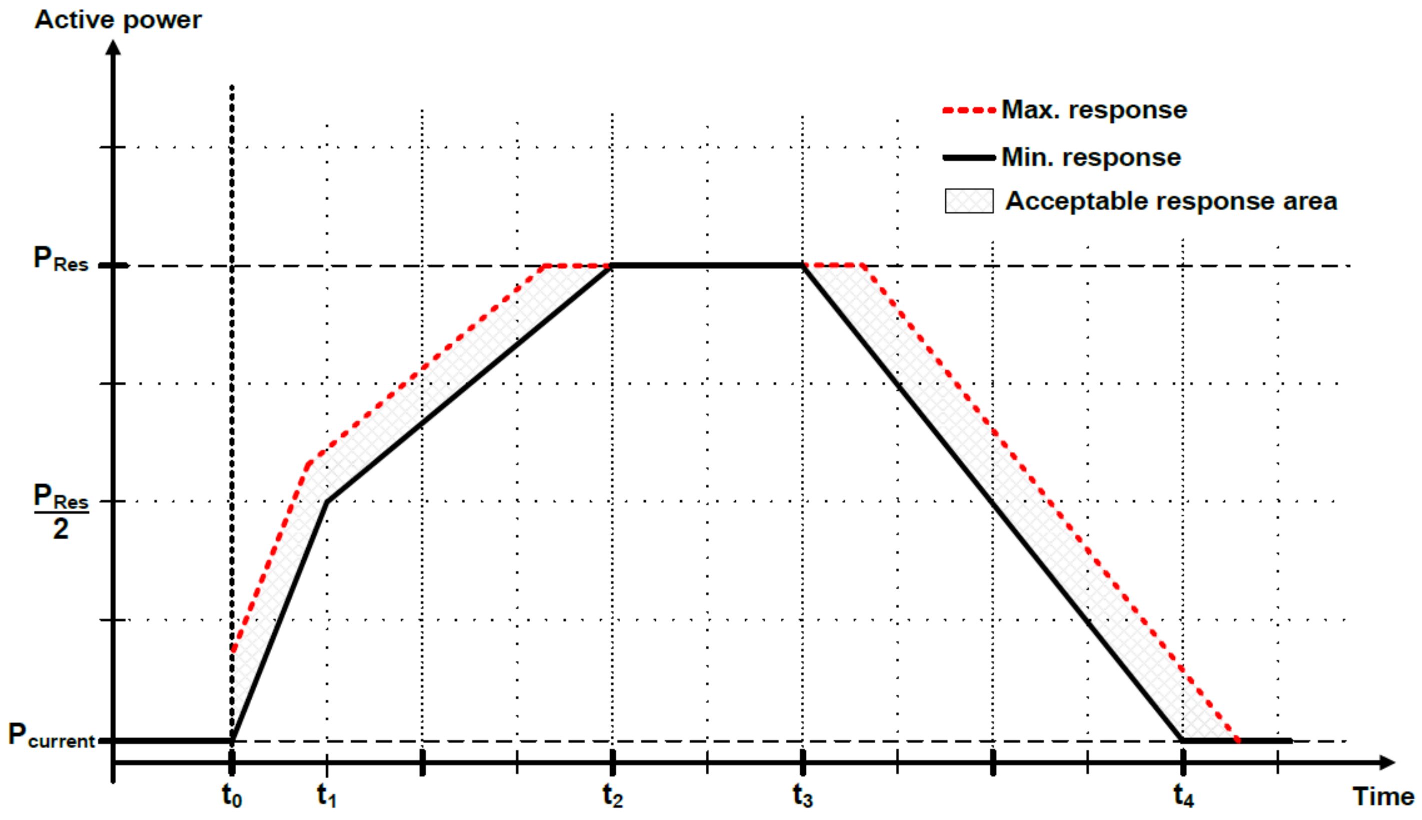
$$y_{FCR} = \begin{cases} 1 & f < 49.5Hz \\ \dfrac{49.9 - f}{0.4} & 49.5 \leq f \leq 49.9 \\ 0 & f > 49.9Hz \end{cases}$$

$$P_{FCR\_D} = y_{FCR} P_{cap}$$

Measurement requirements:

- Minimum measurement accuracy is 10mHz
- Minimum measurement sensitivity is 10mHz
- Minimum resolution (time step) is 1 second

Frequency Containment Reserve Disturbance (FCR-D)



Response and Response Time:

- 50% of capacity within 5 seconds
- The remaining 50% capacity within an additional 25 seconds

Re-establishment period:

- If full capacity has been delivered for minimum 15 mins, the units are allowed to re-establish for maximum 15 mins.

$$R = \frac{1}{15 \cdot 60} \sum_{t=1}^{\min(n,3600)} y_t$$

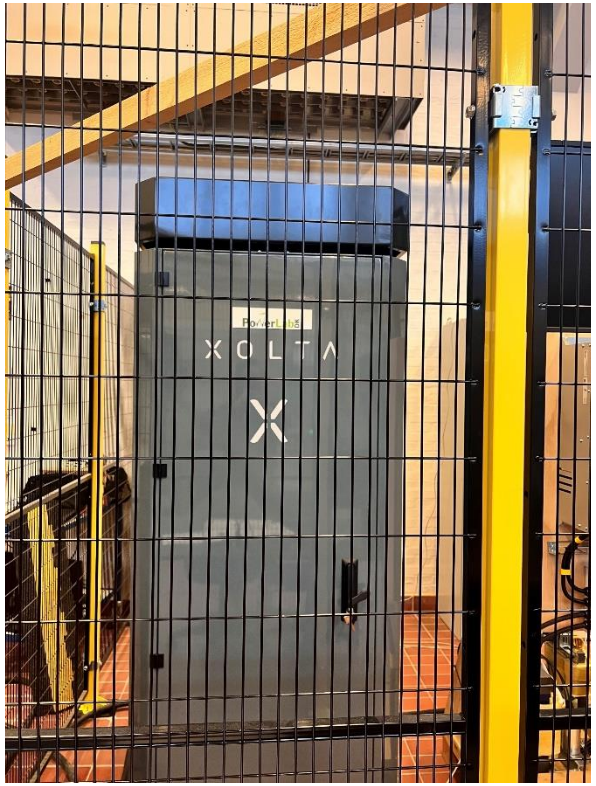
If **R = 1**, then we allow to re-establish for maximum 15 mins, then **R=0**

Minimum bid size:

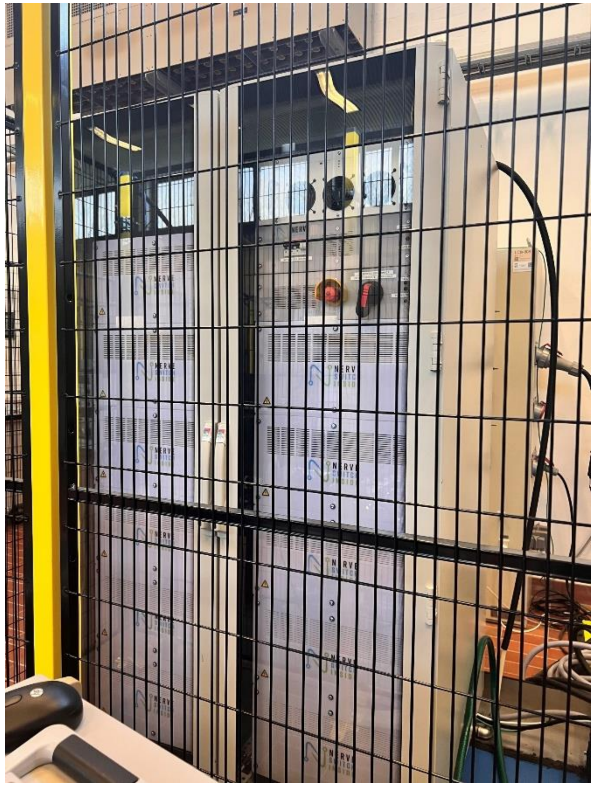
- 0.3 MW

Frequency Containment Reserve Disturbance (FCR-D)

Potential assets:

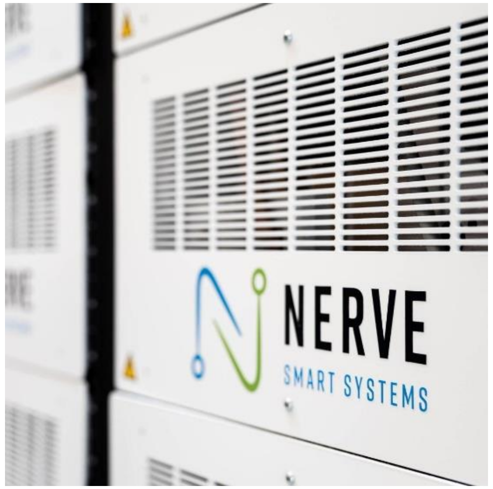


79 kW



33 kW

30 kW



30 kW

Frequency Containment Reserve Disturbance (FCR-D)