

Exploring the Role of SMRs in Integrated Energy Systems: A Case Study of Industrial Heat and Hydrogen in Hungary

System value, market design and enabling conditions for non-electric nuclear applications

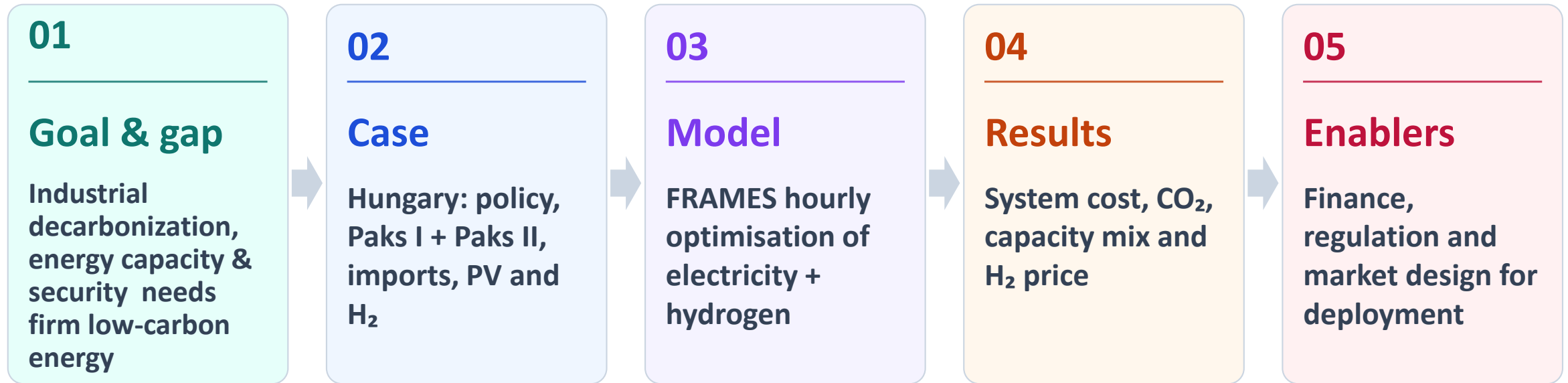


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The simulations and conclusions presented in this study are analytical and scenario-based. They draw on publicly available international sources and the author's interpretation of relevant market, policy and technology constraints. The INPRO FRAMES results should therefore be interpreted as scenario-based analytical findings intended to illustrate possible system trends and relationships, rather than as precise forecasts or investment recommendations. The views expressed are those of the author and do not necessarily reflect those of the IAEA or its Member States.

From energy system challenge to implementation pathway

Exploring SMRs in integrated energy systems: industrial heat and hydrogen in Hungary



CORE THESIS

SMR value is conditional, not self-evident. This study tests when SMRs add system value in Hungary across electricity, hydrogen and heat.

Bridging the Paris ambition and the industrial reality

From climate targets to reliable low-carbon electricity, heat and hydrogen

Paris Agreement
well below 2°C

Integrated low-carbon energy systems
⚡ Electricity | 🔥 Industrial heat | H₂ Hydrogen

Reliable low-carbon industrial energy services
Electricity
High-temperature heat
Hydrogen / feedstocks
24/7 reliability

Current NDCs: 2.3–2.5°C

SMRs as a potential bridge
value must be demonstrated

CORE TEST SMR value is not assumed – it is tested in INPRO FRAMES tool against whole-system alternatives.

EVALUATION CRITERIA

What will be compared across scenarios

Total system cost

Capacity additions

Hourly dispatch

CO₂ emissions

Electricity & fuels imports

Hydrogen cost and production technology

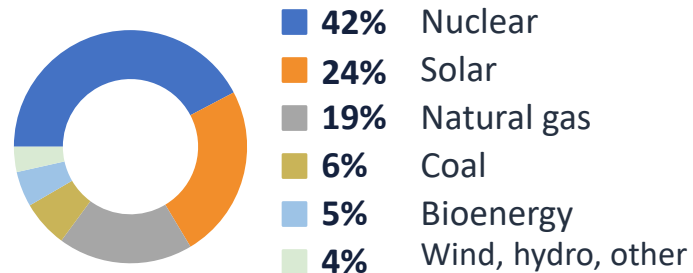
Why Hungary? A relevant case for integrated SMR systems

Electrical grid system overview & National Energy and Climate Plan (NECP) / WAM 2040 pathway



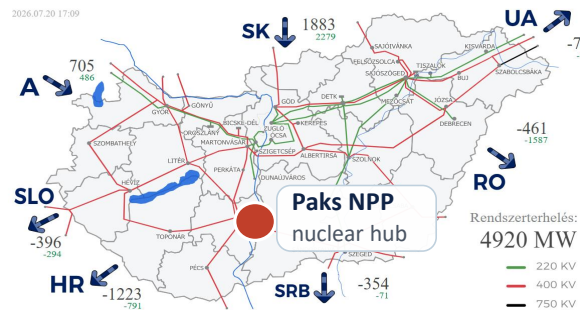
Hungary's National
Energy and Climate
Plan, 2024

2024 generation mix



38 TWh generated • $\approx 206 \text{ gCO}_2/\text{kWh}$

Cross-border power-flow



Cross-border exchanges are a regular operating feature, not a marginal backup.

What makes Hungary a useful case?

It combines mature nuclear operation, import dependence, fast solar growth and an emerging flexibility gap.

4.4 GW

Nuclear backbone

Paks I + Paks II capacity assumed from 2040 in NECP/WAM.

24%

EU Electricity market integration

24% of net electricity import dependence in 2024; interconnectivity around 42%; 49% of primary energy import dependency.

1,130

Flexibility stress signal

15-minute imbalances above 400 MW in 2024; 65% of balancing was downward; balancing costs of €359 mln in 2024.

12+2

2040 RES increase

12 GW solar and 2 GW wind; gas remains about 2.4 GW.

Case-study logic: nuclear stability + variable RES + imports + flexibility constraints

Hydrogen in Hungary: policy anchor and 2040 industrial perspective

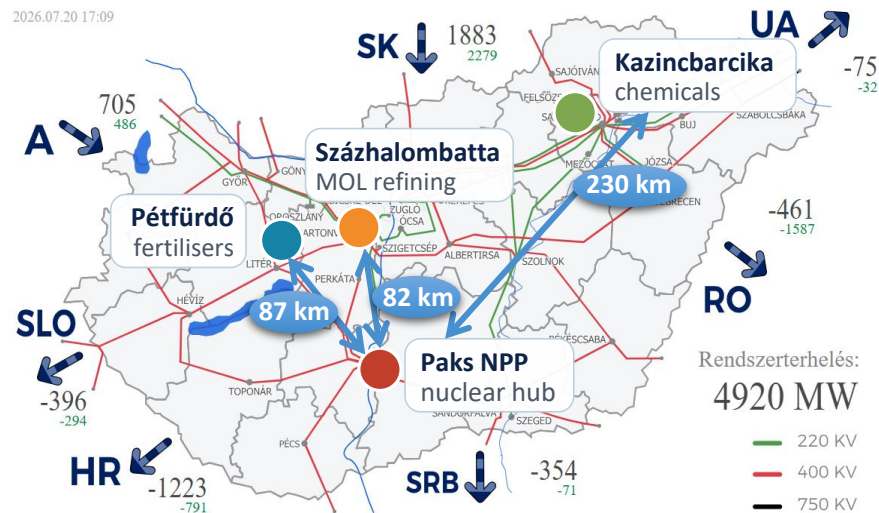
Hungarian industrial hydrogen context & Hungary's National Hydrogen Strategy



Hungary's National Hydrogen Strategy, 2021

Concentrated industrial H₂ demand clusters

Refining • fertilisers • chemicals • potential heavy transport



Where should H₂ be produced?

Policy anchor

2026

Confirmed green H₂ output

≈1.65 kt /y H₂
13 MW electrolysis

replace industrial grey hydrogen

2040

Policy target

≈145 kt /y H₂
Low-carbon and carbon-free H₂

links electricity system to industry

Current green supply covers:
≈1.1% of 2040 Strategy demand

1984 – 2014 H₂ production at Paks I NPP
≈ 2.7 t/year for the plant's own need

KEY MESSAGE

The 2040 FRAMES case tests whether integrated nuclear systems can supply it reliably and cost-effectively.

From the Hungarian context to the modelling problem

Energy security · industrial decarbonisation · technology choices · system optimisation

POLICY DRIVER

Hungary's strategic objective: reduce energy-import dependency and the share of natural gas in the energy mix

1 · ELECTRICITY & ENERGY SECURITY

Policy implication

Lower gas-import dependence requires more domestic low-carbon and flexible supply.

2 · INDUSTRIAL DEMAND

- Concentrated hydrogen users
- Potential district-heating and industrial-heat users
- Demand centres are geographically separated from some supply options

3 · STRATEGIC CHOICES

- Extend Paks I NPP
- Commission Paks II NPP
- Expand wind and solar
- Increase electrification and low-carbon hydrogen
- Assess SMRs

4 · MODELLING QUESTION

What is the least-cost 2040 technology mix that meets electricity and hydrogen demand, complies with the CO₂ constraint and reduces fossil-energy dependence?

Hungary's input data for FRAMES' optimisation case-study

2040 system represented using the historical 2024 hourly profile



IAEA TECDOC-2135
method and model
2026

2024

Historical hourly load shape



seasonality + intraday
volatility retained

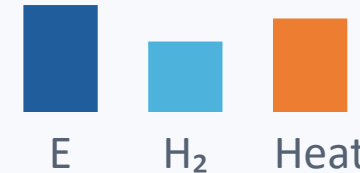
Scaling

Annual demand adjusted
hourly shape $\times$ 2040
annual demand

the profile gives timing;
scenario assumptions give scale

2040

FRAMES scenario demand



The historical profile provides the temporal shape, while annual energy demand and technology assumptions represent the 2040 scenario.

Retained

real seasonal pattern · weekday/weekend
effects · hourly volatility

Changed

annual energy demand · generation fleet constraints
for coal, gas, solar and wind · Nuclear fleet split ·
Imports proxy · H₂ demand · CO₂ limit

The adaptation changes not only input values, but also the technology structure and model constraints to represent Hungary's 2040 system more realistically.

System response to higher demand and constrained fossil capacity

Reference 2040 vs High-Demand / Low-Fossil scenario · FRAMES relaxed fleet optimisation

REFERENCE 2040

55 TWh/y

3 GW CCGT + residual coal

+9 TWh demand

fossil backup constrained



HIGH DEMAND / LOW FOSSIL

64 TWh/y

1 GW CCGT · no coal

H₂ demand unchanged

5.71 TWh · ≈145 kt/y

CAPACITY RESPONSE

LWR-SMR

0 → 1.79
~6 units
GW selected

Wind

0.55 → 2.00
GW ceiling

4-hour BESS

0 → 0.35
GWh added

Solar PV

3.9 → 3.9
GW unchanged

Main optimisation response:

firm low-carbon capacity enters, wind reaches its upper bound, and only limited battery storage is added.

DISPATCH SHIFT

TWh generated / imported

Nuclear

38.0 → 53.1 ↑

HTGR-SMR built: 0

CCGT

16.5 → 6.0 ↓

Coal

0.37 → 0 phased out

Wind

0.95 → 3.55 ↑

Imports

0.13 → 2.18 ↑

Firm low-carbon generation replaces fossil output; wind and imports provide additional balance.

SYSTEM OUTCOMES

Annual system cost

\$3.40 → \$3.83

+12.6% (demand +16.4%)

CO₂ emissions

6.07 → 2.43

Mt/y · -60%

Implicit H₂ cost

\$2.22 → \$2.08

per kg · -6.3%

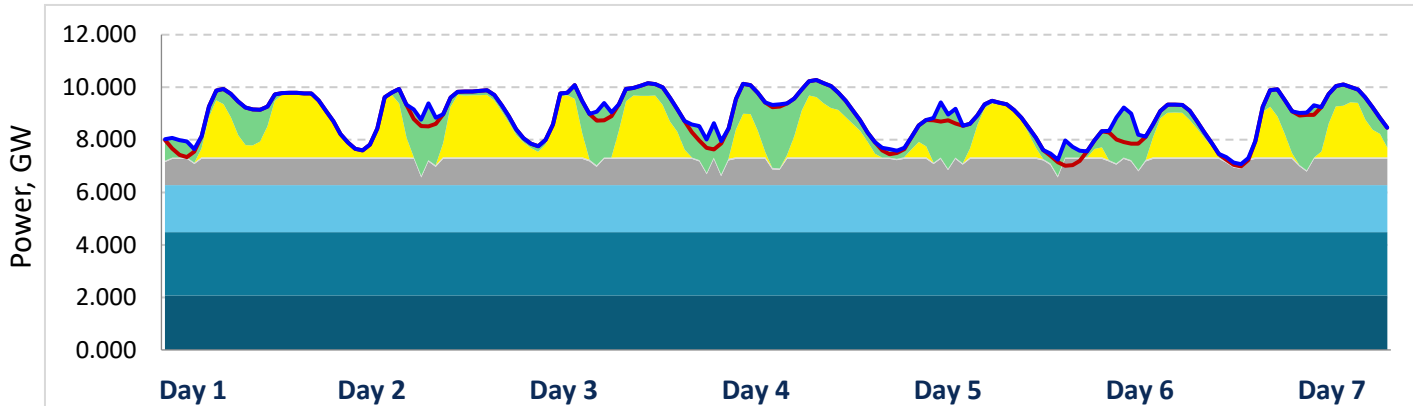
KEY MESSAGE

Under higher demand and limited fossil backup, the least-cost system adds LWR-SMR capacity, expands wind, and supplies the same H₂ demand with much lower CO₂ emissions.

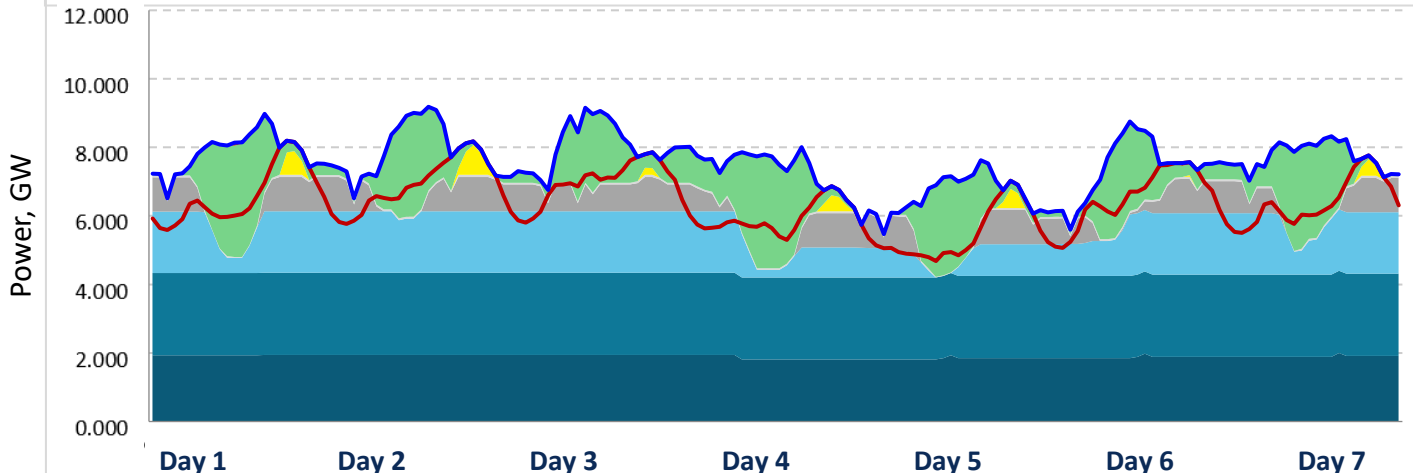
Dispatch structure: bridging demand and variability

■ Paks I ■ Paks II ■ LWR-SMR ■ CCGT ■ Import ■ RES ■ Storage discharge — Served electricity load — Demand

Winter week · Jan 09–15



Summer week · Aug 01–07



- **Firm and flexible nuclear roles**

Paks I & II provide stable baseload, while the modular LWR-SMR fleet follows residual demand.

- **Sector coupling & H2 production**

The difference between Load & Demand lines indicates electricity-to-hydrogen production and storage charging which helps maintain the hourly balance

- **Winter peaks**

CCGT and imports cover the residual peaks

- **Summer flexibility**

High solar output reduces residual demand; CCGT and imports decline first, followed by LWR-SMR load reduction and brief shutdowns.

Low-carbon capacity links variable RES with 24/7 electricity + H₂ demand + storage charging.

A three-layer bankability architecture for Hungarian hydrogen

Use regulated infrastructure, revenue stabilisation and industrial off-take to convert system value into bankable projects

WHY THIS IS NEEDED

FRAMES shows system value, but investors need a revenue model.

- Construction-period cash flow
- Predictable H₂ revenue
- Committed industrial demand
- Clear risk allocation

THREE-LAYER STRUCTURE

Each layer stabilises a different risk before private capital and industrial users commit.

1

RAB / CWIP-like mechanism

Annex

Reduce construction financing cost

shared connection

compression

storage

pipelines

2

Hydrogen CfD

Annex

Stabilise low-carbon H₂ price after Commercial Operation Date (COD)

strike price

reference price

claw-back

budget control

3

Industrial off-take consortium (~Exeltium) or SPV (~Mankala)

Stabilise demand and allocate volume risk (take-or-pay)

refinery

fertilisers

chemicals

petro-chemicals

TARGET OUTCOME

Bankable low-carbon H₂ market

Construction risk managed by RAB/CWIP

Price risk managed by H₂ CfD

Volume risk managed by off-take

Private users commit when they receive price certainty, supply security and capped exposure to construction risk.

CORE IDEA RAB/CWIP for infrastructure, CfD for price risk, and industrial take-or-pay contracts for volume risk.

Regulatory Development Needs for an SMR–H₂ CfD/RAB Scheme

The challenge is fragmented regimes and missing enabling rules for the coupled system

CURRENT REGIMES

Nuclear safety
Law + HAEA
Code (NSC)

EU hydrogen market
Dir. 2024/1788 · Reg.
2024/1789

Industrial safety
H₂, pressure,
Seveso

State aid /
support
CEEAG · CISAF

Low-carbon H₂
Delegated Reg.
2025/2359

A coupled SMR–H₂ project crosses all five regimes at once.

WHAT TO DEVELOP

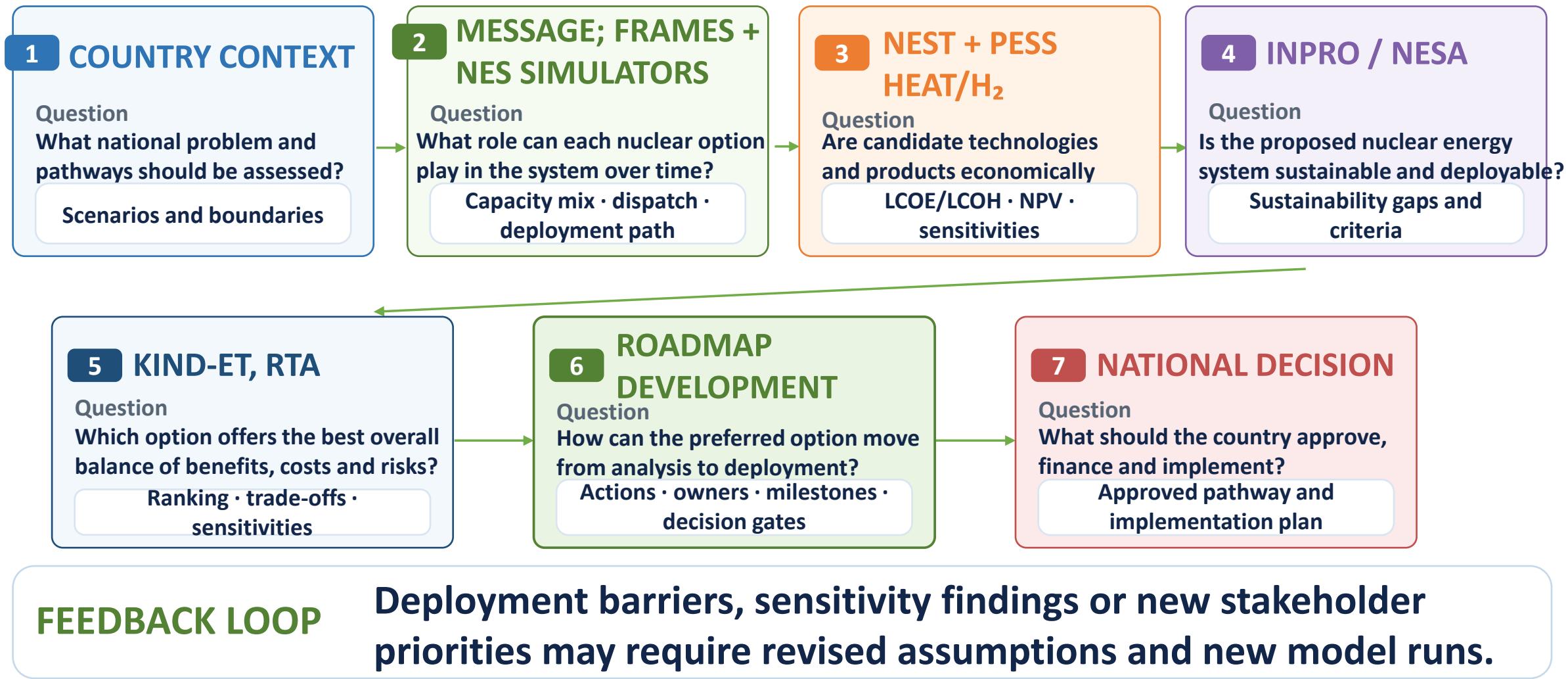
- Government act establishing a public H₂ CfD counterparty or designated support fund.
- Legal basis for H₂ CfD payments.
- National transposition of EU hydrogen market rules.
- Low-carbon H₂ certification pathway for nuclear electricity.
- Enhanced guidance for SMRs, multi-module sites and nuclear–H₂ external hazards.

FINAL MESSAGE

Development priority: integrated licensing roadmap + statutory CfD counterparty + low-carbon H₂ certification + SMR-specific nuclear regulator (HAEA) interface guidance.

From Complementary IAEA/INPRO Tools to Deployment

Outputs from one analytical layer become inputs to the next – from system assessment to an actionable roadmap



Takeaways for deployment of SMRs for hydrogen and heat

From system value to implementation conditions

1 System value is conditional

2 Hydrogen adds sector-coupling value

3 Technology availability ≠ economic selection

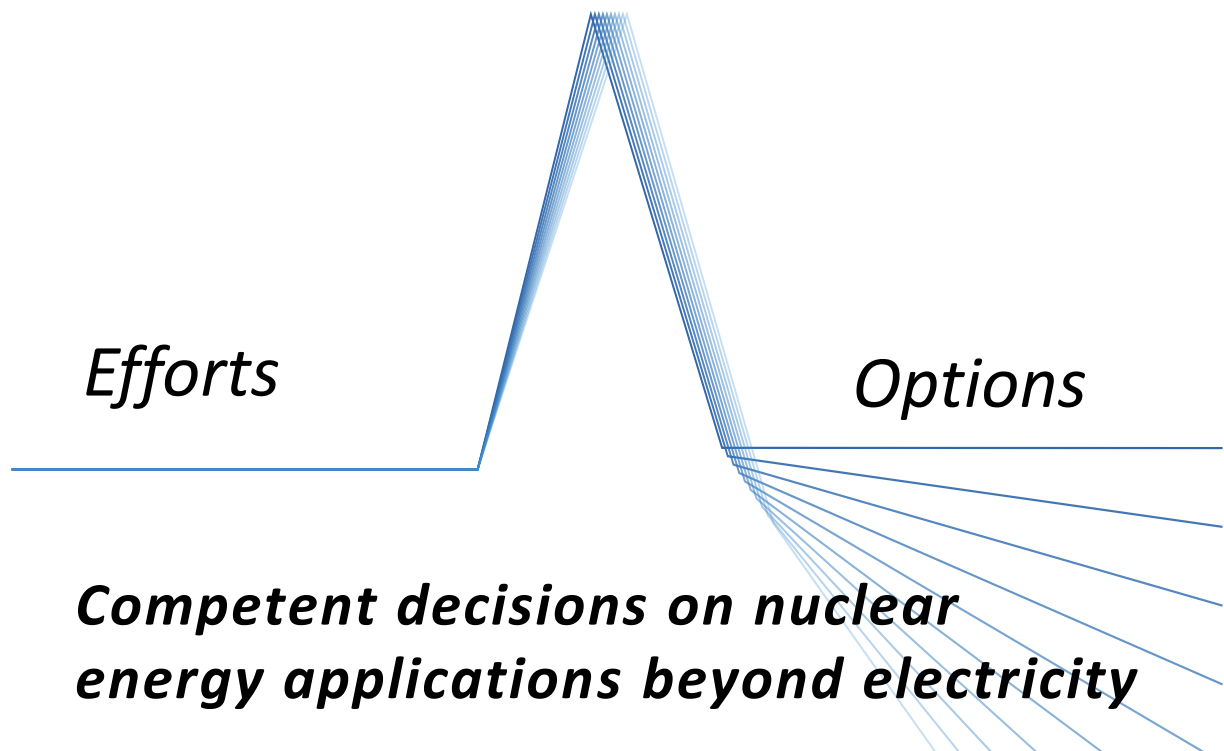
4 System optimisation does not create bankability

5 Deployment depends on state support, regulatory coordination and a roadmap

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SMRs for hydrogen and industrial heat should be assessed as part of an integrated energy-system pathway:

- first demonstrate conditional system value,
- then create bankable demand,
- coordinated regulation and an implementation roadmap.



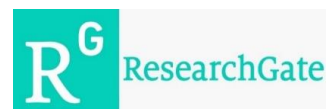
Thank you for your attention!

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https://paks2training.tilda.ws/paks_en



<https://www.researchgate.net/profile/Yulia-Chernyakhovskaya>



Annex. A Hydrogen Regulated Asset Base (RAB): what should be regulated?

Recover construction-period costs only for shared infrastructure – with clear cost caps and industrial demand commitments

DESIGN RULE

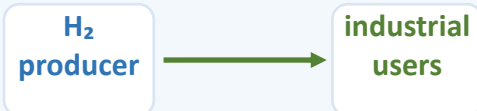
Annex 1

Regulate monopoly-like hydrogen infrastructure, not an unlimited technology cost.

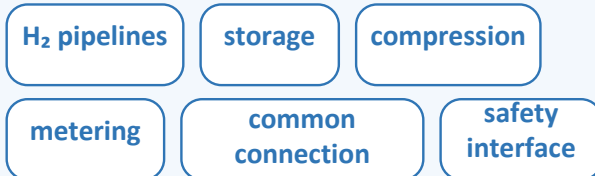
Industrial users pay for reserved capacity; the state pays only for clearly identified public benefits.

1 · ASSET PERIMETER

Core regulated asset



What belongs in the RAB



Conditional inclusion only after a public-interest test

- nuclear–hydrogen interface
- shared electrolyser balance-of-plant

Not the full SMR cost or industrial plant retrofit

2 · COST RECOVERY

Construction-period revenue

Industrial capacity-reservation charge

€/kg of contracted annual H₂ capacity or €/MW of reserved electrolyser capacity

Who pays for what?

Industrial off-takers

reserved capacity
priority supply
price certainty

State / public budget

first infrastructure
energy security
gas-import reduction

- Pre-COD payments are credited against future H₂ network charges
- Users receive a clear price corridor and priority access in return

3 · CONSUMER PROTECTION

Regulated Asset Base (RAB) only works if investors and users trust the rules.

Independent cost review

Approved cost cap

Milestone-based recovery

No automatic pass-through of overruns

Availability and non-delivery rules

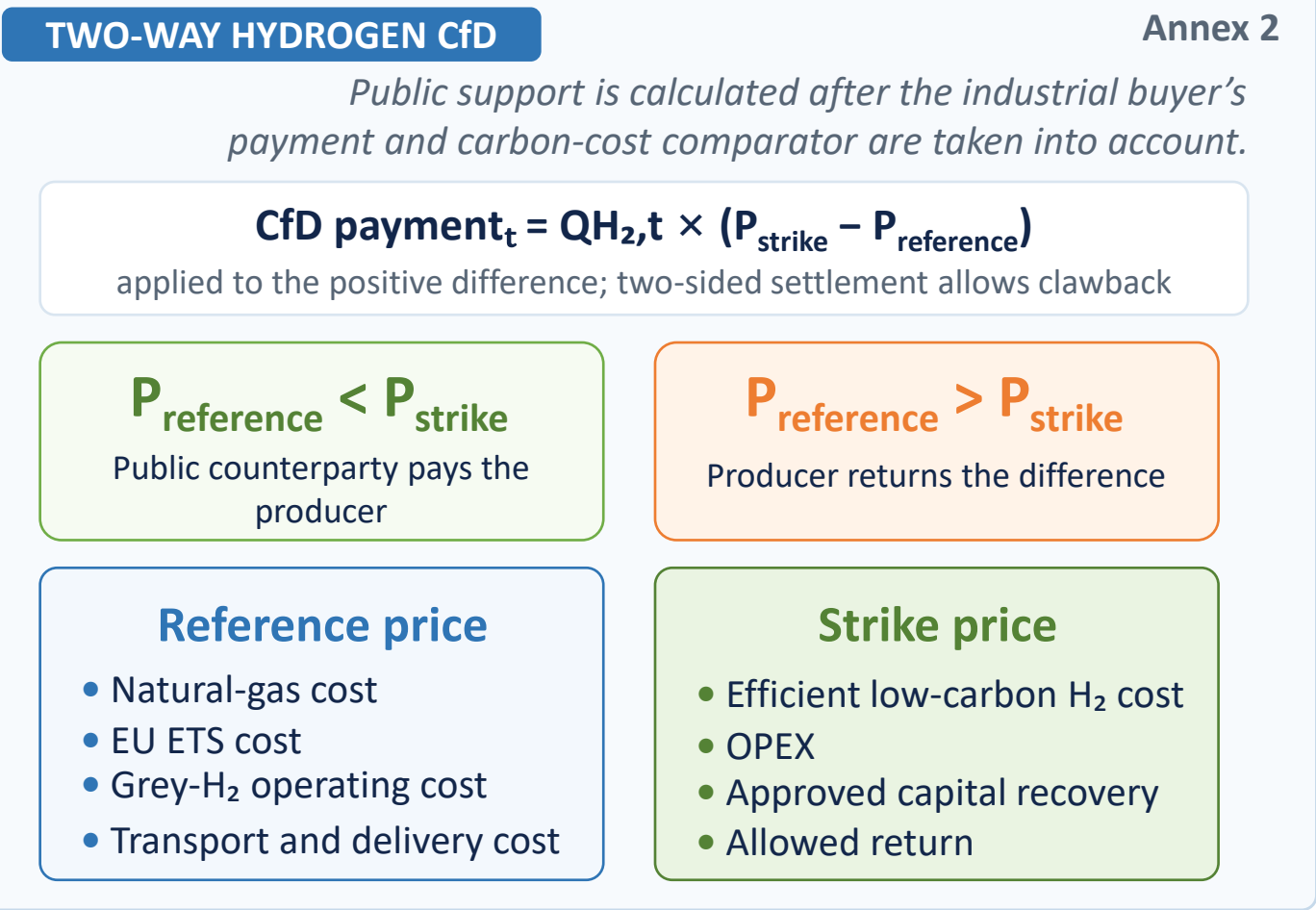
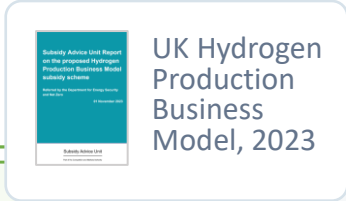
Transparent tariff formula

CORE IDEA

A Hydrogen RAB should reduce financing cost for shared infrastructure while preserving industrial-user responsibility for volume and technology-choice risk.

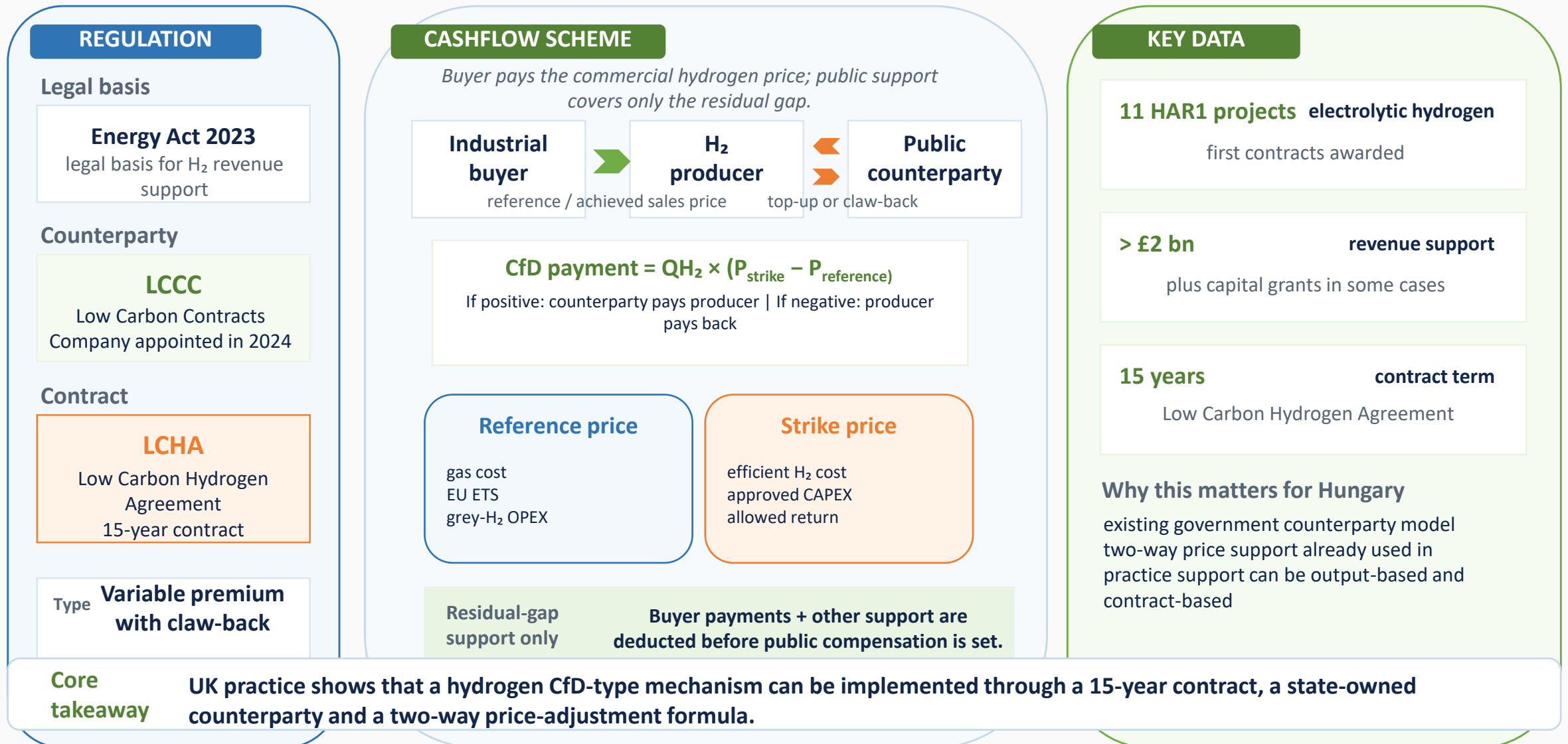
Annex. Hydrogen CfD: Covering the Residual Price Gap

The industrial buyer pays the market-based reference price; public support covers only the remaining gap



Annex. UK practice: Hydrogen Production Business Model

Regulation and contract practice for a hydrogen CfD-type mechanism



Annex. Track record of H₂ production at Paks I NPP

On-site hydrogen for turbine-generator cooling · operational lessons for non-electric applications

≈1984 / 87 –
2014

2 units of on-site H₂
production

20 Nm³/h

SZEU-20 capacity

≈2.7 t/y H₂

auxiliary annual
consumption

8 generators

rotor cooling



Hydrogen production
building



SZEU-20 electrolyser
cell stack



Gas separation &
pressure control



Hydrogen unloading
station



Hydrogen storage
area (15 receivers)

From production → conditioning → unloading → storage

Technical track record

- SZEU-20 water electrolysis
- 20 Nm³/h; ≈30,000 Nm³/y
- H₂ for 8 generator rotors

Operational difficulties

- High production cost
- Maintenance-intensive cells
- Low utilisation; asbestos diaphragms

Final solution in 2014

- On-site production replaced by purchased H₂ (1/4 of cost)
- New unloading / receiving station
- External supply: since 2006

KEY MESSAGE

Paks I demonstrates proven nuclear-site H₂ production and handling experience – at auxiliary scale, not industrial-scale hydrogen supply.