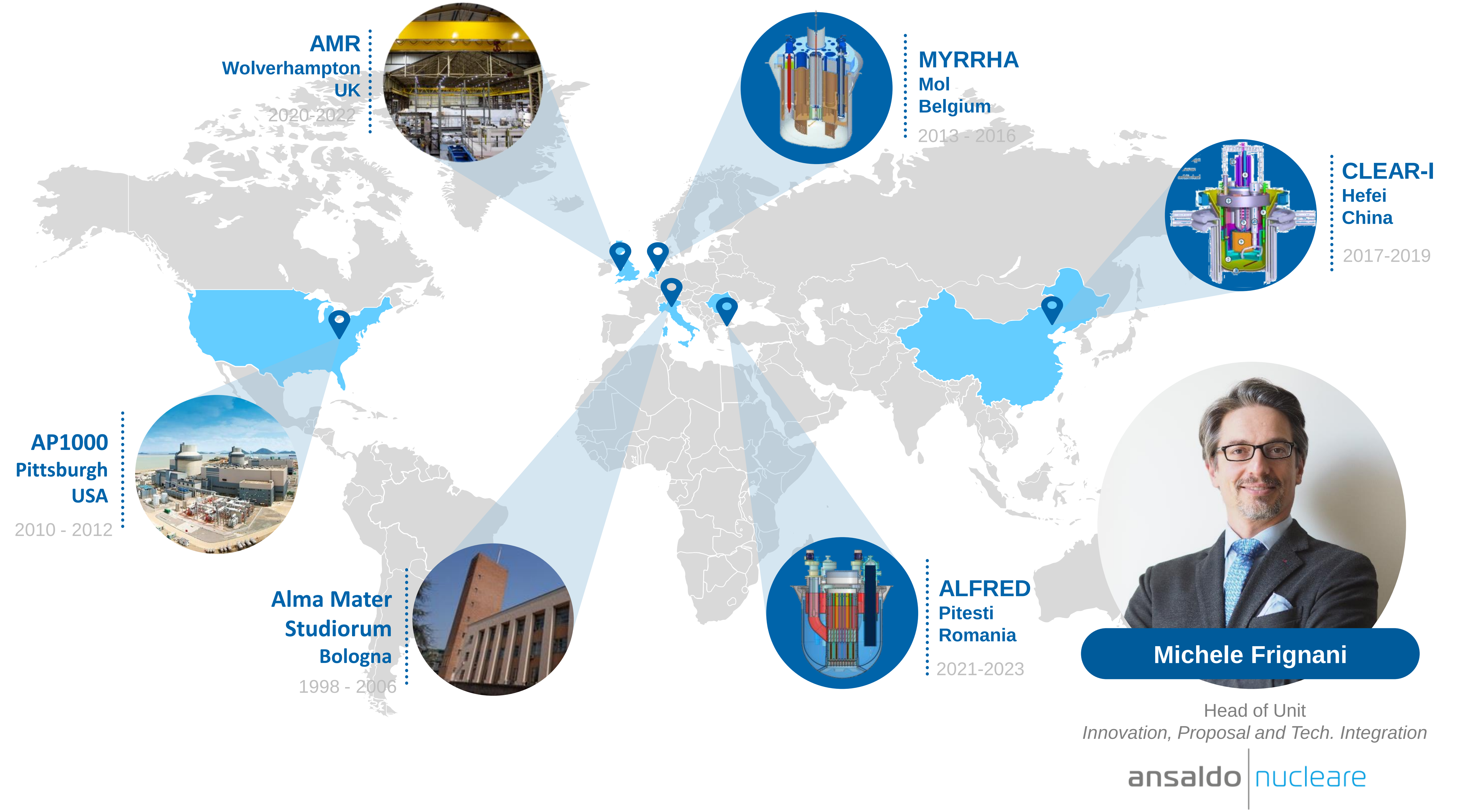
Industrial interest on SMR and NHSE

M. Frignani
Nuclear Technologies and Product Development


AMR
Wolverhampton
UK
2020-2022
MYRRHA
Mol
Belgium
2013 - 2016
CLEAR-I
Hefei
China
2017-2019
AP1000
Pittsburgh
USA
2010 - 2012
Alma Mater
Studiorum
Bologna
1998 - 2006
ALFRED
Pitesti
Romania
2021-2023
Michele Frignani
Head of Unit
Innovation, Proposal and Tech. Integration
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Outline

- Ansaldo Nucleare: investing to meet sustainability goals
- Opportunities and challenges of SMRs and AMRs
- Peculiarities of LFRs among the AMRs
- SMRs and AMRs in the future hybrid energy systems

Ansaldo Industrial Plan

PRESS RELEASE

Genoa, 31st March 2023

Ansaldo Energia approves its new Industrial Plan up to 2027, giving the go-ahead for reinforcement of the company's capital

Transition ready

- Sale of power generation machinery
- Special focus on international markets
- Increased contribution by its Service Business Unit

Green diversification

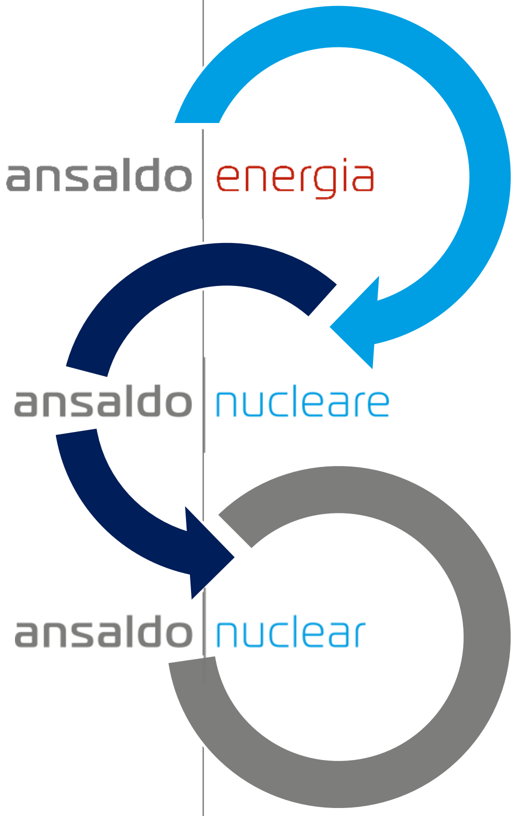
- Diversification of the company's business in the context of the energy transition
- Initiatives concerned with storage systems (utility scale)
- Electrolysers for hydrogen production.

Nuclear

- Fusion (with construction of the experimental Iter plant in France)
- Fission (with projects such as those underway in Romania and Slovenia)
- Decommissioning, with a number of projects in Italy and the UK

The new Plan aims to make the most of the company's legacy of technology and know-how in the conventional gas turbine and nuclear power industries, leveraging diversification of its business in the context of the energy transition.

Ansaldo Nucleare in a snapshot



Since 1966, Ansaldo Nucleare (formerly Ansaldo Meccanico Nucleare) is responsible for the nuclear business in the Ansaldo Energia group.

406
Employees

70 € million
2022 Revenue

132 € million
2022 Backlog

10
R&D&I Projects

42
In-house skills

9000 sqm
Workshops (UK)

Major Nuclear Projects in our Portfolio

Nuclear New Builds

Cernavoda (Romania)

Units 1 & 2 Completion

Sanmen Unit 1 AP1000 (China)

Steel Containment Vessel - Passive Residual Heat Removal

ESS (Sweden)

Shield Doors

Decommissioning & Radioactive Waste Manag.

Sellafield (UK)

Silo Emptying Mobile Caves (MSSS) Machines

SRP Gloveboxes (UK)

2 manufacturing lines of gloveboxes for encapsulation of Pu

Caorso (Italy)

Drum Retrieval Machine

Services for Nuclear Power Plants

Embalse (Argentina)

PLEX & Diesel Station Refurbishment

Cernavoda (Romania)

Component Cooling Upgrade and Post Fukushima Evaluations

Krsko NPP

Safety Upgrade Program Bunkered Building 2 Project

Fusion

ITER (France)

Tokamak Assembly – TAC2

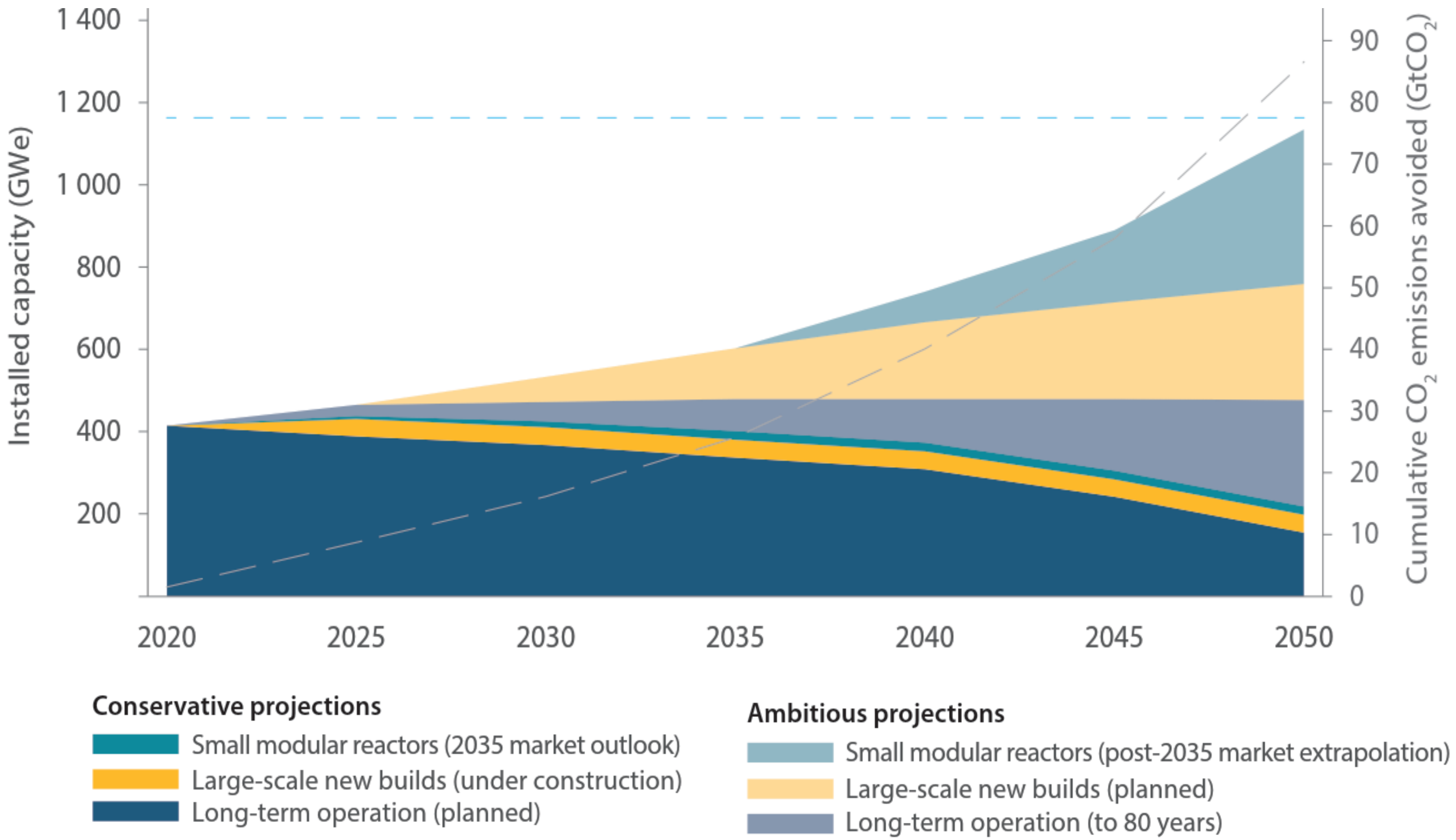
ITER (France)

Steady state electrical network – TB13

DTT (Italy)

Engineering (plant, systems, components)

Powering the present and shaping the future



Source: NEA, 2022.

Vision driven Innovation

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Short-term
Timely and efficient solutions for the safety upgrade, life extension and dismantling of old plants, accelerating the return to green-field of nuclear sites

Medium-term
Integrate new flexible and more sustainable nuclear power plants, to make the energy transition smoother and cheaper

Long-term
Make fusion available to future energy needs, with the highest sustainability standards for a new source of clean energy

Ansaldo Nucleare’s main commitment is to innovate nuclear solutions to protect the planet and power our future

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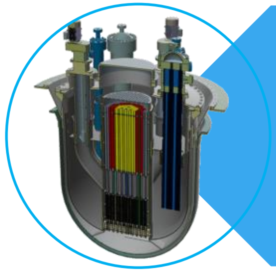
Ansaldo Nucleare’s goals

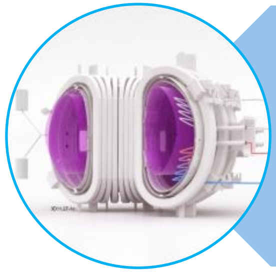
Contribute to the first SMRs which will be built in Europe by 2030

- Likely based on LWR technology, as the most mature
- Will pave the way towards cooperation schemes among national authorities for transnational approval process
- Wil favour new aggregations of Supply Chains, then influencing single supplier’s investment plans



Accelerate the development and the deployment of Lead Fast Reactors

- Most mature Gen-IV technology able to minimize wastes and close the fuel cycle
- Adequate to cope with industrial heat needs up to 400-500°C
- Relying on extensive EU knowledge and on testing facilities under construction in Romania and UK
- Licensing is the critical factor to reach commercial maturity in a reasonable time-frame



To be at the forefront of fusion technology industry

- Our experience at ITER is giving us significant return in terms of advanced technology processes
- The step from ITER up to a commercially viable fusion plant is huge and will require further technology breakthroughs in various areas, but…
- **We do know that nnovation in nuclear requires longranging view and collaborative approach**

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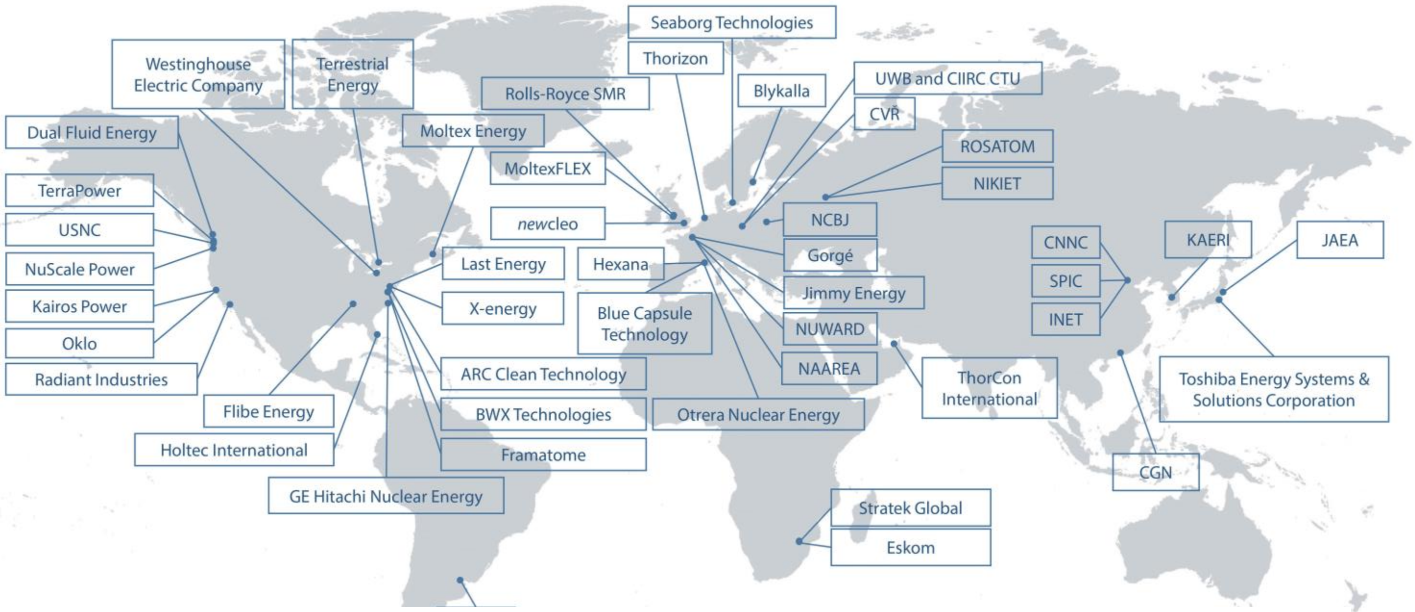
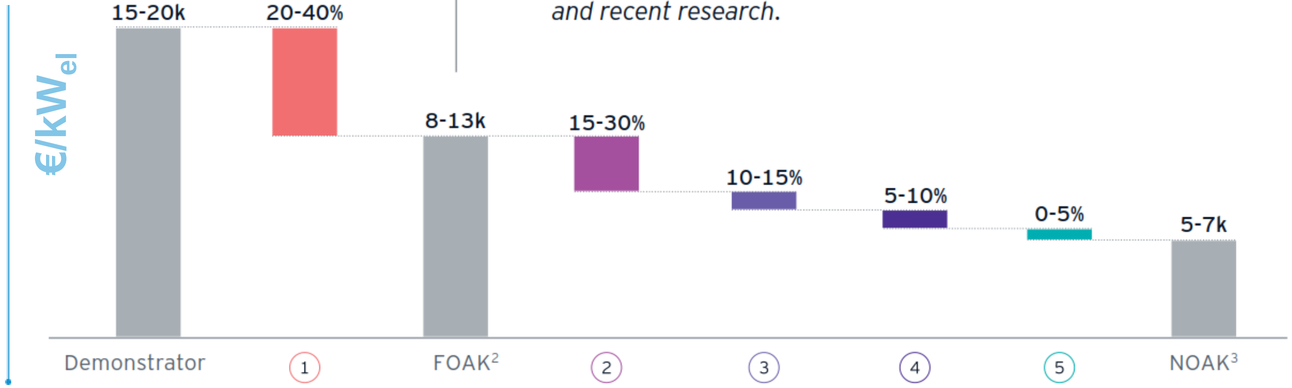
SMR & AMR – What are the challenges and the opportunities?

Challenge	Opportunity
Cost and Construction time	Simple design and standardization
	Modularization
	Co-siting
Network integration	Size
Nuclear safety	Integrated design
	Passive safety
Nuclear waste	Fuel cycle closing

Gen. III/III+



Based on manufacturers' announcements, readjusted from early SMR feedback, recent costs observed on large NPP FOAKs, and recent research.



1 First industrialization

2 Modularization

3 Co-siting

4 Learning

5 Standardization

IAEA - Advances in SMR Technology Developments 2022, NEA - The NEA SMR Dashboard 2023, Expert interviews, Desk research, EY-Parthenon analysis

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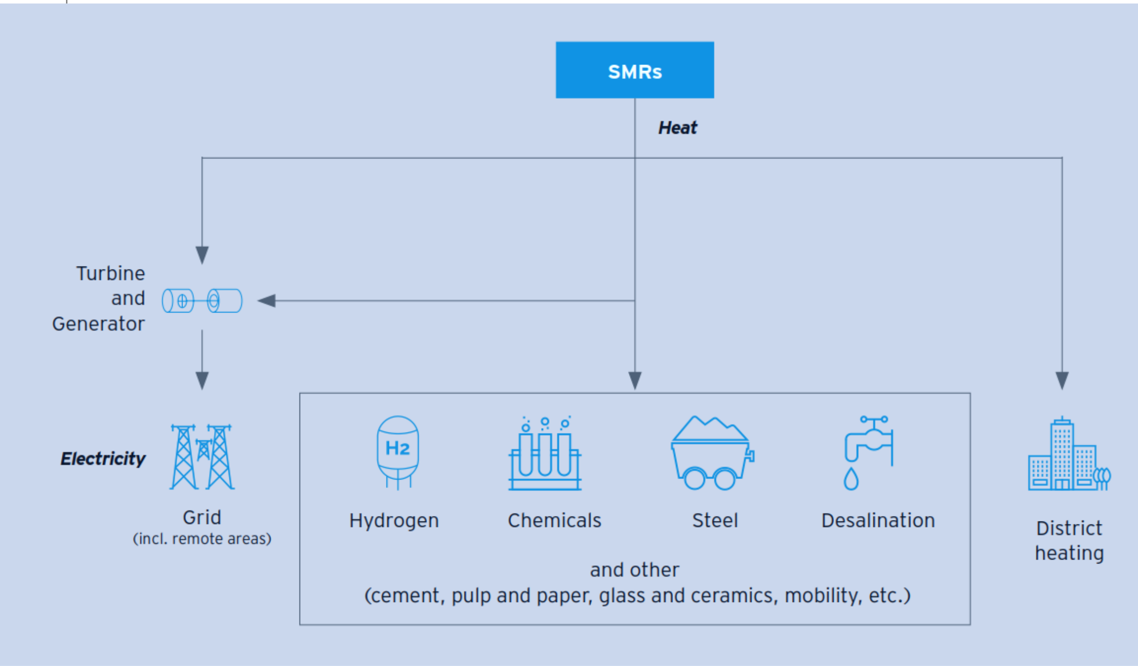
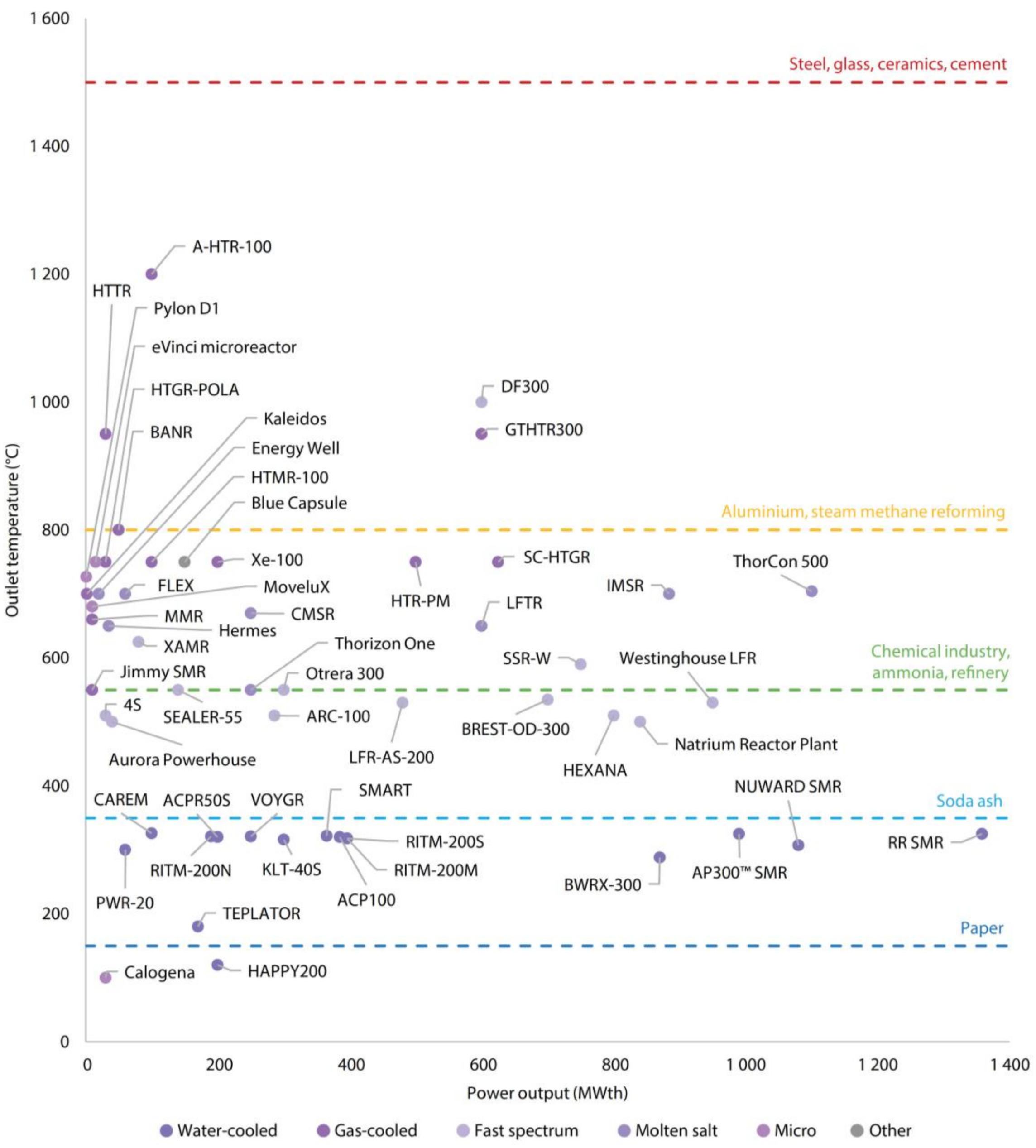
Electricity and beyond



Hybrid coupling allows reheat through synergistic features (electricity, heat, …)



IAEA - Advances in SMR Technology Developments 2022, NEA - The NEA SMR Dashboard 2023, Expert interviews, Desk research, EY-Parthenon analysis

Small Modular Reactors development

- Small size facilitates siting (e.g., possible reuse of coal-fired power plant sites)
- Mass workshop construction allows better control of time and cost
- Lower capital cost due to smaller size facilitates finance-ability

Water-cooled SMR

The first SMRs, based on water reactor technology (LW-SMR) will be deployable by the end of the decade

NUWARD (EDF)

PROs

Cost reduction by innovative design

Joint licensing at the EU level

Engagement of industrial shareholder (Advisory Board)

Product developed for the European market

Potential collaboration extended to EPR2

RR-SMR (Rolls Royce)

PROs

Cost reduction through factory built

Schedule reduction through modularization

Minimum innovation (reduced licensing risks)

Licensing application started

Financial support by national government and private investors

BWRX-300 (GEH)

PROs

Scaled-down version of licensed BWR (with minimum innovative features)

Strong stakeholder engagement (notably in Canada)

Minimum time-to-marked (potentially first on the market)

Appealing for the supply of specifica mechanical components

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Advanced Modular Reactors and LFR

Lead Fast Reactors

Construction of SMRs based on Generation IV technologies (requiring demonstration prototypes) will be possible in the late 1930s.

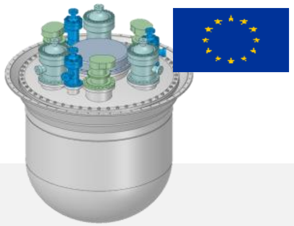
Advanced Modular Reactors (AMRs) will enable waste minimization and better utilization of natural resources

Simplified, robust and modular solutions enhanced by proven passive safety features

Advanced technology for the closure of fuel cycle using existing reprocessing technology

Meet decarbonization targets through competitive electricity and high temperature heat

Adaptability to wide range of customers and sites



ALFRED (FALCON)

PROs

Demonstration role with enhanced passive safety

Closure of the fuel cycle for waste minimization

EU framework of collaboration and RO committment

20+ years of experimental activties and 40+ dedicated facilities

EU-LFR-SMR

PROs

Innovative design features (including passive safety Cat. B)

Steam temperature compatible with industrial uses

High competitiveness (simplification and modularization)

Ongoing experimental program and safety authority engagement in UK, BE, RO

Levelized Cost Of Electricity

$$\frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t (including financing)
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Electricity generation in year t
r = Discount rate
n = Life of the system

- What does it mean?
- LCOE is a measure of the average net present cost of electricity generation for a generating plant over its lifetime.
- But what does it really mean?
- LCOE is the minimum constant price at which electricity must be sold to break even over the lifetime of the project
- Is it meaningful?
- It requires assumptions and projections.
- Sustainability and environmental typically impact not factored in.
- It does not take into account a dispatchability premium (better looking at Levelized Avoided Cost of Energy -LACE- or Value-Adjusted Levelized Cost Of Electricity -VALCOE-)
- It is not fully effective for comparing different sources, unless considering all elements

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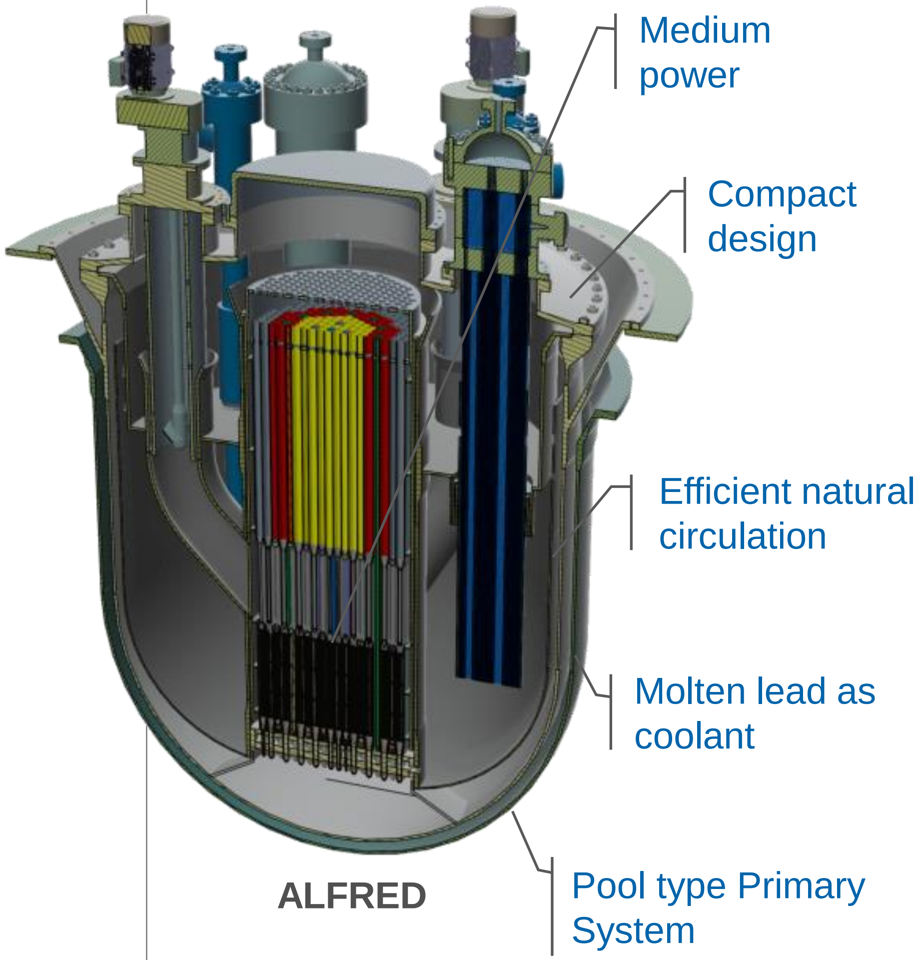
LFR Technology Development in Romania



FALCON: a long-term commitment, in collaboration with Italian research centers, universities and suppliers, to promote LFR Gen-IV technology at European level and beyond.

ALFRED: An international program to support the development of a technology park in Romania, aimed at accelerating the implementation of LFR.

The Romanian government's commitment to support the initiative by investing more than €120 million in the construction and operation of experimental facilities as a strategic asset for the country.

ATHENA: the most powerful facility in Europe and the only one in the world for performance testing and licensing support on LFR technology (worth €22 million investment).

CESINA Partnership

SMR Industrial Alliance

- Meet decarbonization targets through high temperature heat
- Advanced technology for the closure of fuel cycle
- Proven passive safety features
- Adaptability to wide range of customers
- Competitive economics

Reference design

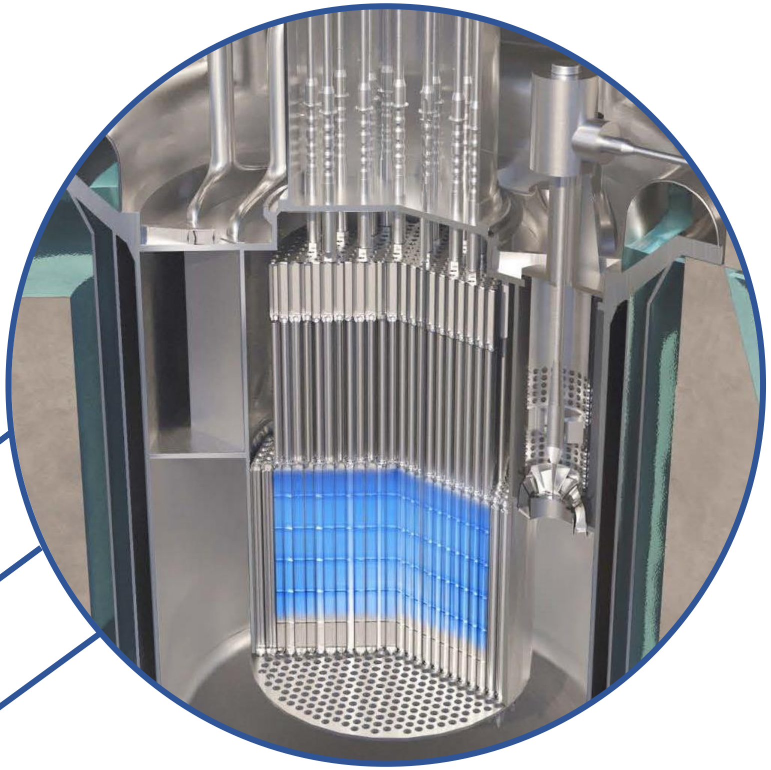
Simplified, robust, modular

Candidate sites

Mol-Belgium and Pitesti-Romania

Shared roadmap

Commercial deployment by 2040



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ENEA
Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

RATEN
REGIA AUTONOMĂ
TEHNOLOGII pentru ENERGIA NUCLEARĂ

sck cen
Belgian Nuclear Research Centre

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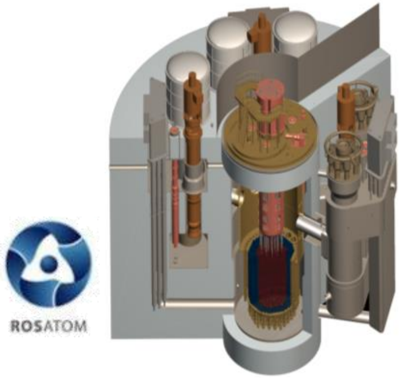
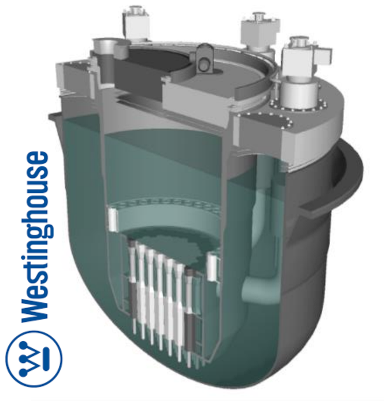
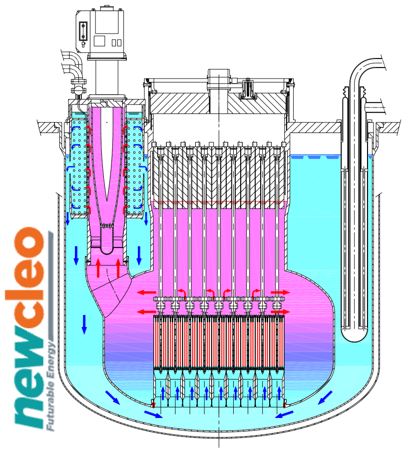
Nuclear vendors and new-comers in the LFR panorama



BREST-OD-300
300 Mwe, Russia
Under construction

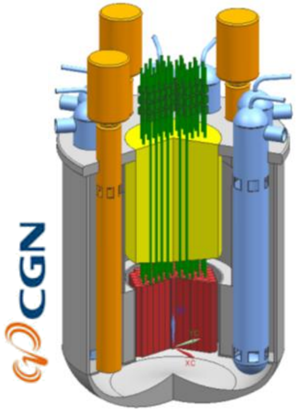


Westinghouse LFR
450 MWe, USA
Under design

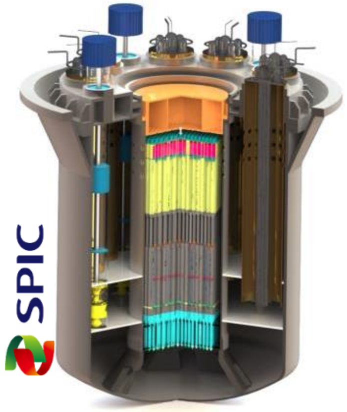


NewCleo AS-200
200 MWe, USA
Under design

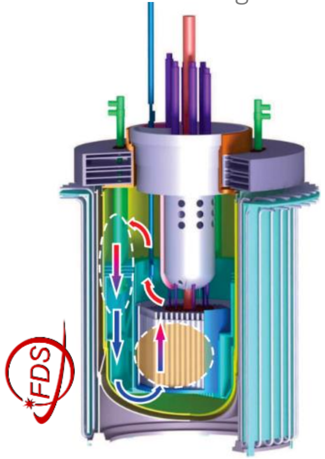
LeadCold SEALER
1-10 MWe, Sweden
Under design



CLFR-300 and CLFR-10
300/10 Mwe, China
Under design



BLESS
100 Mwe, China
Under design



CLEAR-1
10 MWth, China
Under design

Micro-Uranus
60 MWth, Korea
Under design

Opportunities and Challenges of using Lead as a coolant

Opportunities = Innovation in design approach

- Enhanced natural circulation
- Negative reactivity feedback
- Favourable breeding/transmutation
- Reduced pump head requirements
- No intermediate circuit
- Minimum stored energy in the system
- Fission products retention
- Simplified layout

Challenges = Innovation in design provisions

- Protective measures against corrosion
- Coolant chemistry and filtration
- Self-regulating and anti-freezing DHR passive system
- Avoidance of steam drag into the core
- Passive shutdown systems
- Limited plant size
- Maintenance, inspection and repair strategy

Lead-cooled Fast Reactors offer improved capabilities in terms of **passive safety** and **sustainability** that make them one of the most interesting candidates for the **Advanced Modular Reactor** segment.

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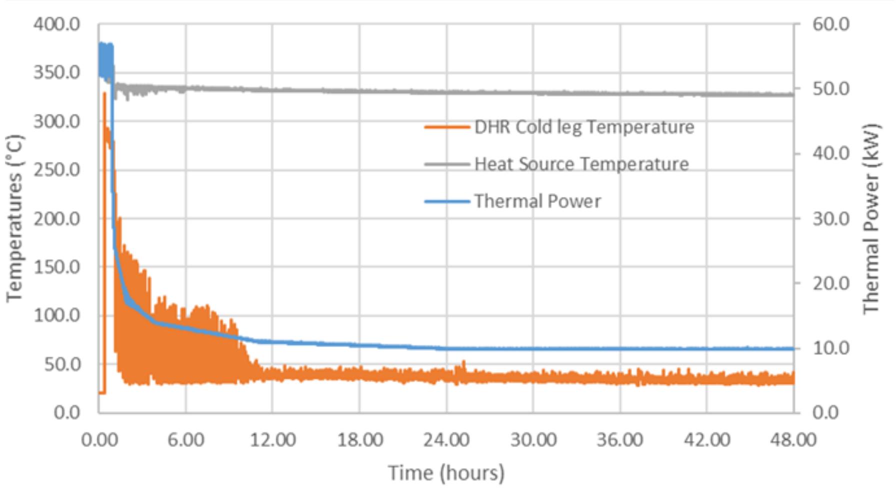
ALFRED Decay Heat Removal System

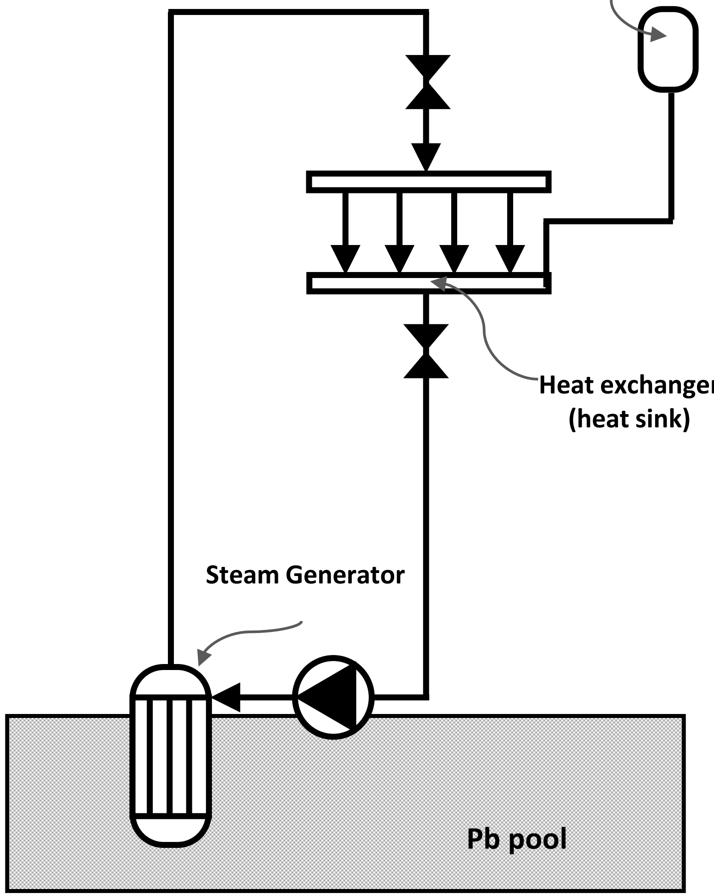
Requirement: to remove decay heat passively

Challenge: lead freezes @ 327°C

Idea: self-regulating system

Solution: non-condensable gases





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(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
30 April 2015 (30.04.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/059672 A1

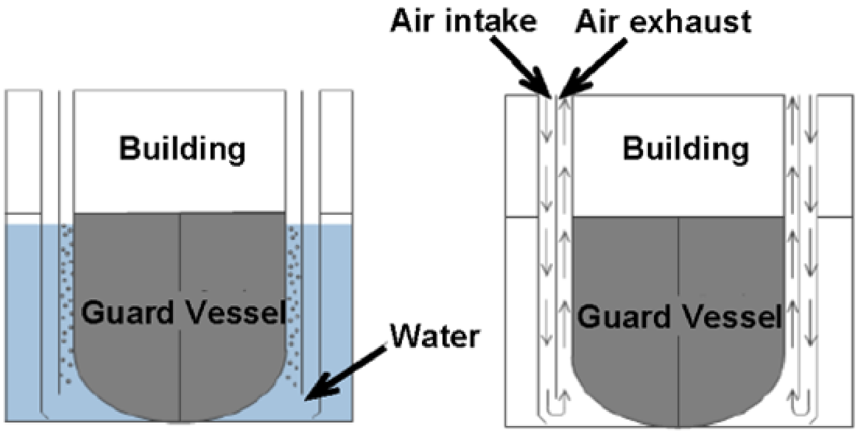
W-LFR Decay Heat Removal System

Requirement: remove decay heat passively

Challenge: lead freezes @ 327°C

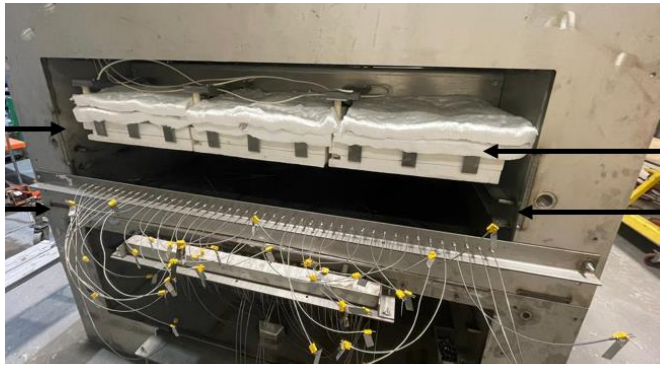
Idea: Rely on thermal radiation

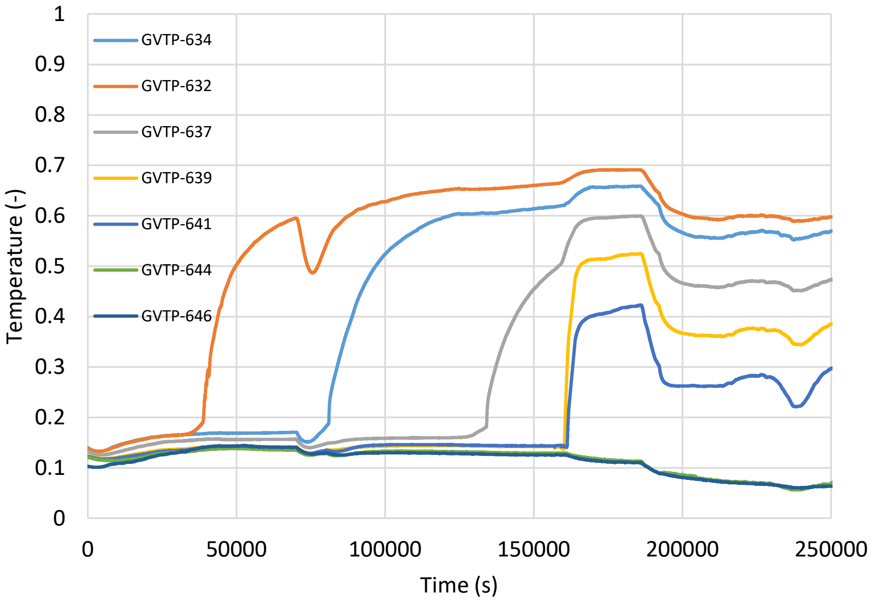
Solution: External system



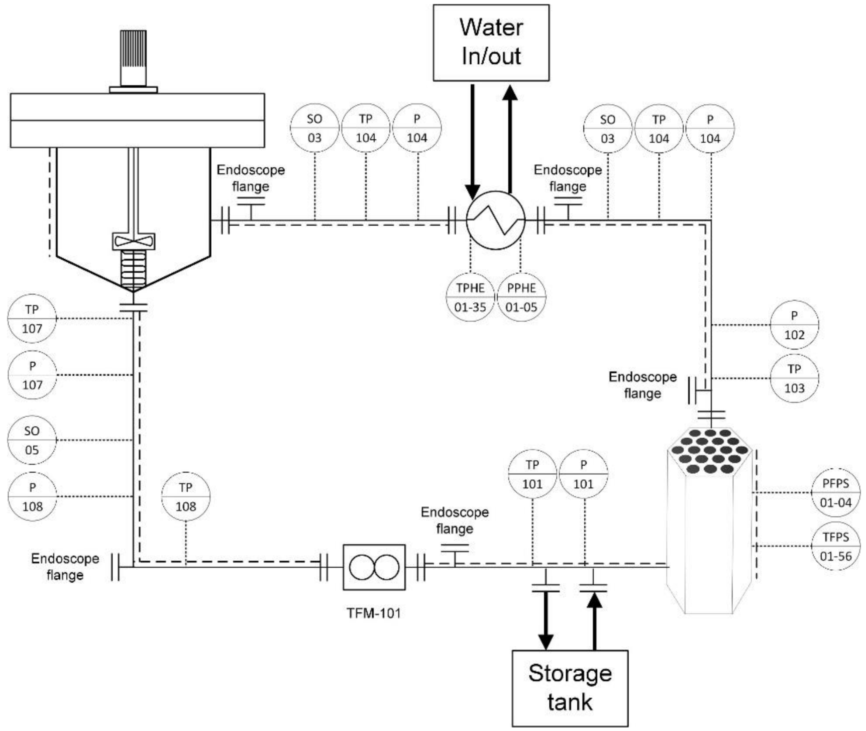
Water-cooling mode (notional)

Air-cooling mode (notional)

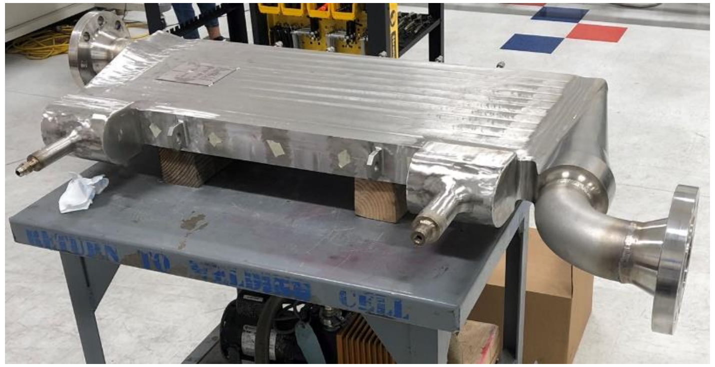




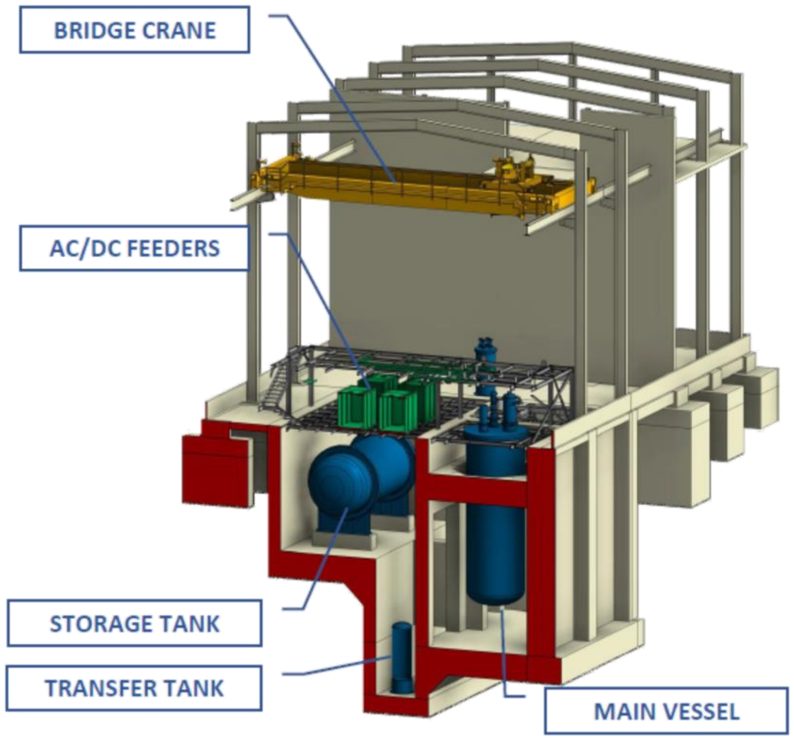
Testing Innovative components for lead application - VLF



Power (kW)	500	**Sec. loop**	sH_2O
Lead inventory	3.5 tons	**Core**	19 pins
Lead cycle (°C)	390 – 530	**HX**	Microchannel
Mass flow (kg/s)	25.0	**Budget**	2 M£



Testing Innovative components for lead application - ATHENA

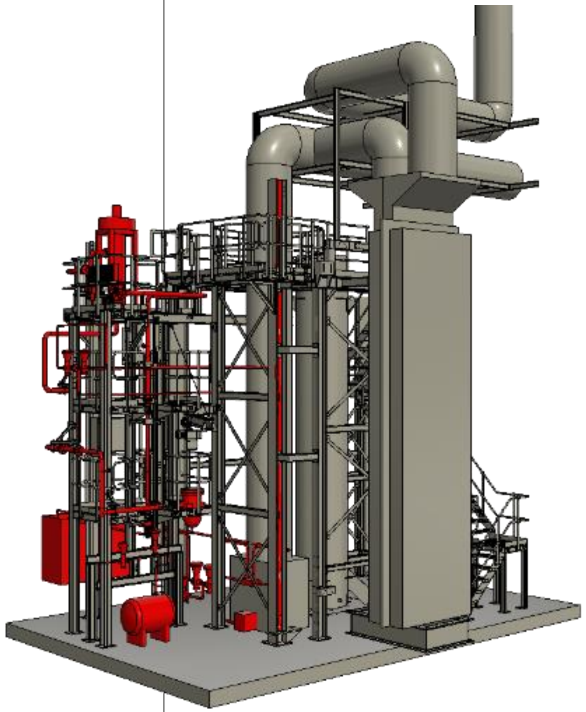


Power (kW)	2200	**Sec. loop**	H_2O
Lead inventory	800 tons	**Core**	127 pins
Lead cycle (°C)	400 – 520	**HX**	Bayonet
Mass flow (kg/s)	250,0	**Budget**	20 M€

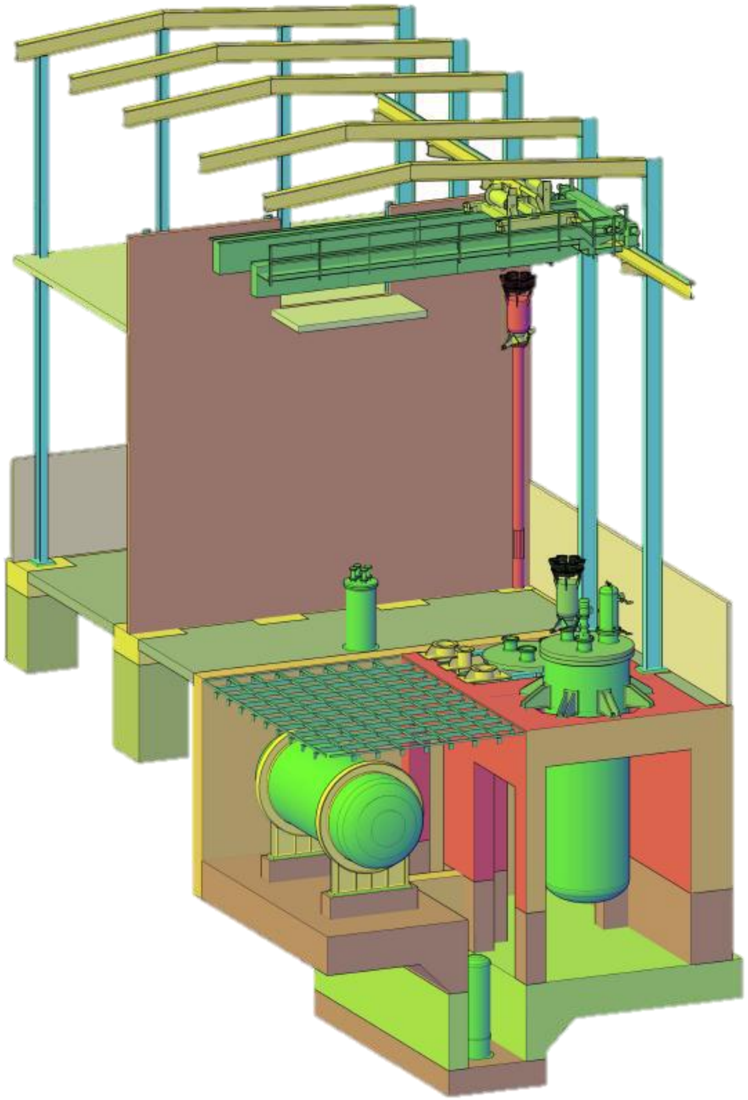
ATHENA is the largest pool-type facility ever built and the first and unique pure lead pool-type facility worldwide

More than 50% of the equipment for the technological part are supplied by Italian companies

ATHENA Facility
(compared with VLF facility in the UK)



VLF under construction in the UK		ATHENA under construction in Romania
500	**Power (kW)**	2200
Loop	**Type**	Pool
3.5 tons	**Lead inventory**	800 tons
390 – 530	**Lead cycle (°C)**	400 – 520
25.0	**Mass flow (kg/s)**	250.0
No	**Accident testing**	Yes
sH_2O	**Sec. loop**	H_2O
19 pins	**Core**	127 pins
Microchannel	**Heat exchanger**	Bayonet
2 M€	**Budget**	20 M€



Why baseload is preferable?

$$\frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t (including financing)

M_t = Operations and maintenance expenditures in year t

F_t = Fuel expenditures in year t

E_t = Electricity generation in year t

r = Discount rate

n = Life of the system

- Is it a safety concern?
- Not really. In PWR, power can be safely changed by regulating
    - position of control rods,
    - the concentration of boric acid in the RCS
    - core inlet temperature
- Is it a flexibility issue?
- According to EUR, NPPs are capable of daily load cycling operation between 50% and 100 % of nominal power, with a rate of change of the electric output of 3-5% of rated power per minute.
- Let’s look back at LCOE.

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Impact of fuel costs on LCOE

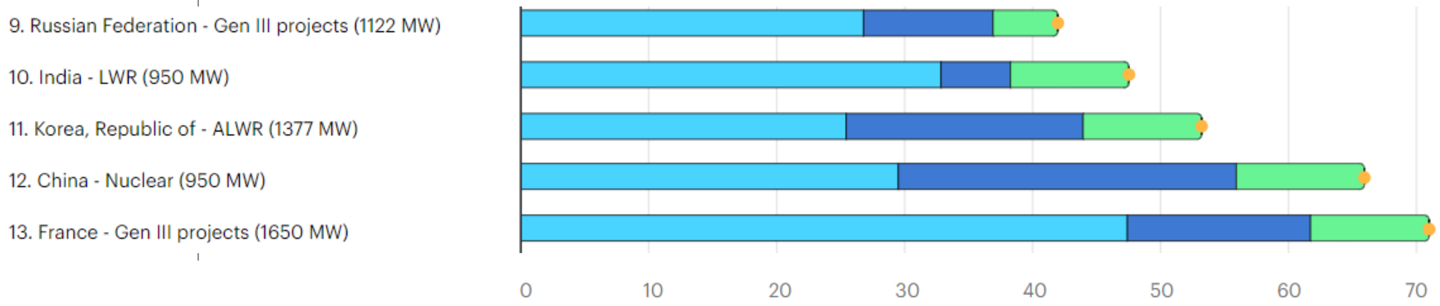
Discount rate
7%
Central case

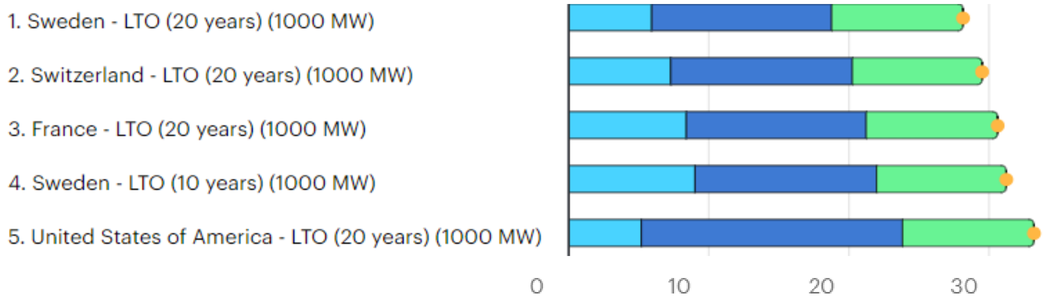
Carbon price
30.00 USD/ton
Default assumption

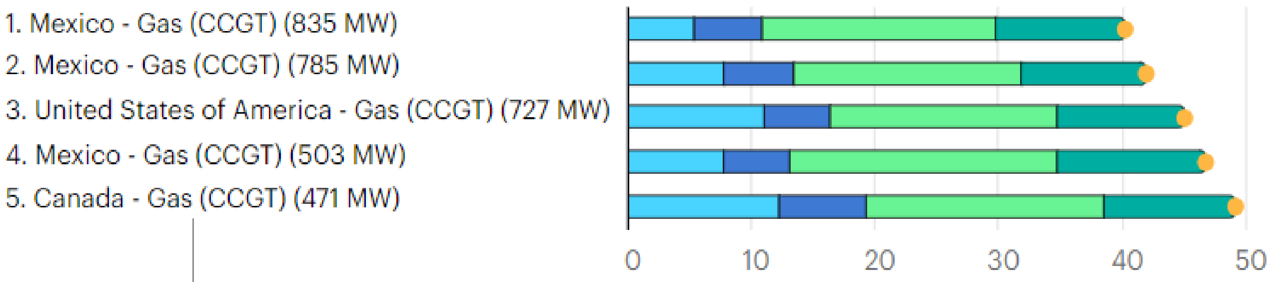
Heat price
37.06 USD/MWh
Default assumption

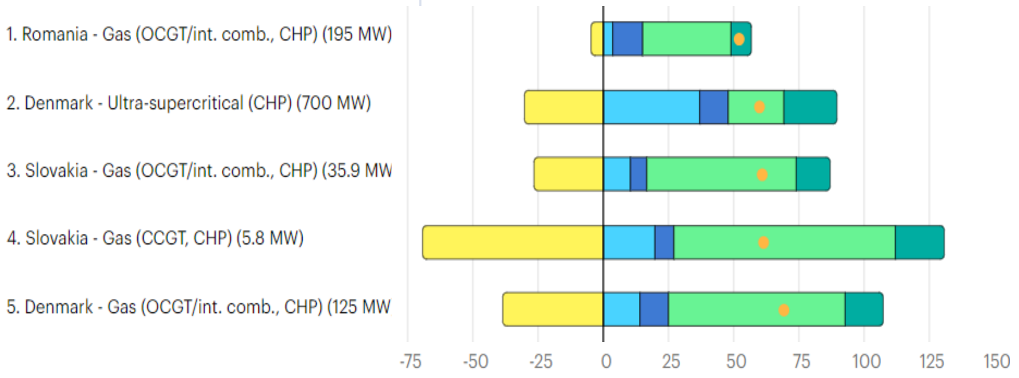
Coal price
100%
Default assumption

Gas price
100%
Default assumption









Construction, refurbishment & decommissioning **O&M** **Fuel** **Carbon emissions** **Heat** **Total**

https://www.iea.org/data-and-statistics/data-tools/levelised-cost-of-electricity-calculator

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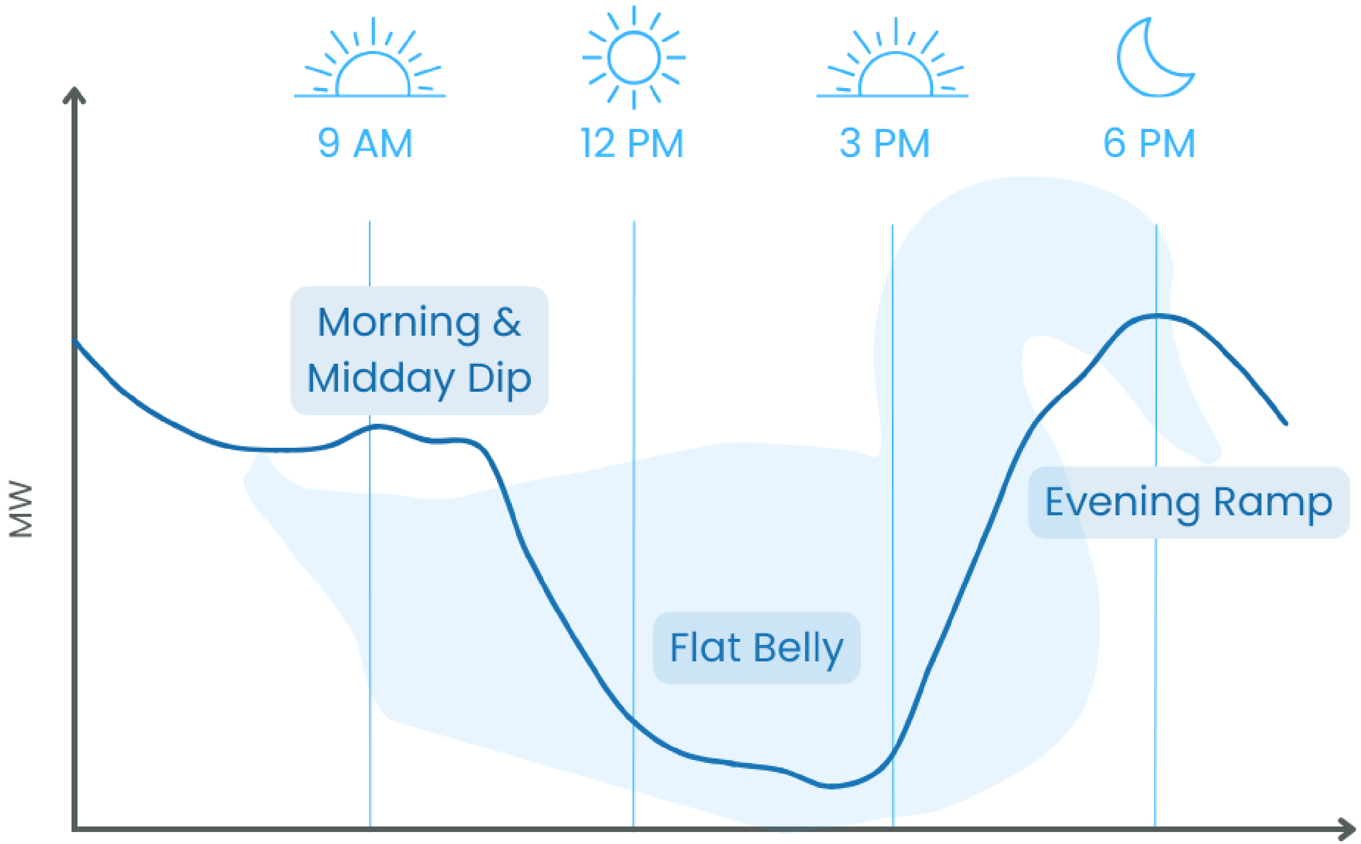
Understanding the duck curve in energy demand



- Challenge in balancing electricity supply and demand when intermittent, non-dispatchable, weather-dependent renewable energy sources weather-dependent are a significant part of the energy mix.

- Solutions?
- Adapt with added systems costs (energy storage at utility scale!)
- Follow an offer/demand law and provide a premium to the dispatchable sources (negative energy prices are already a reality!)

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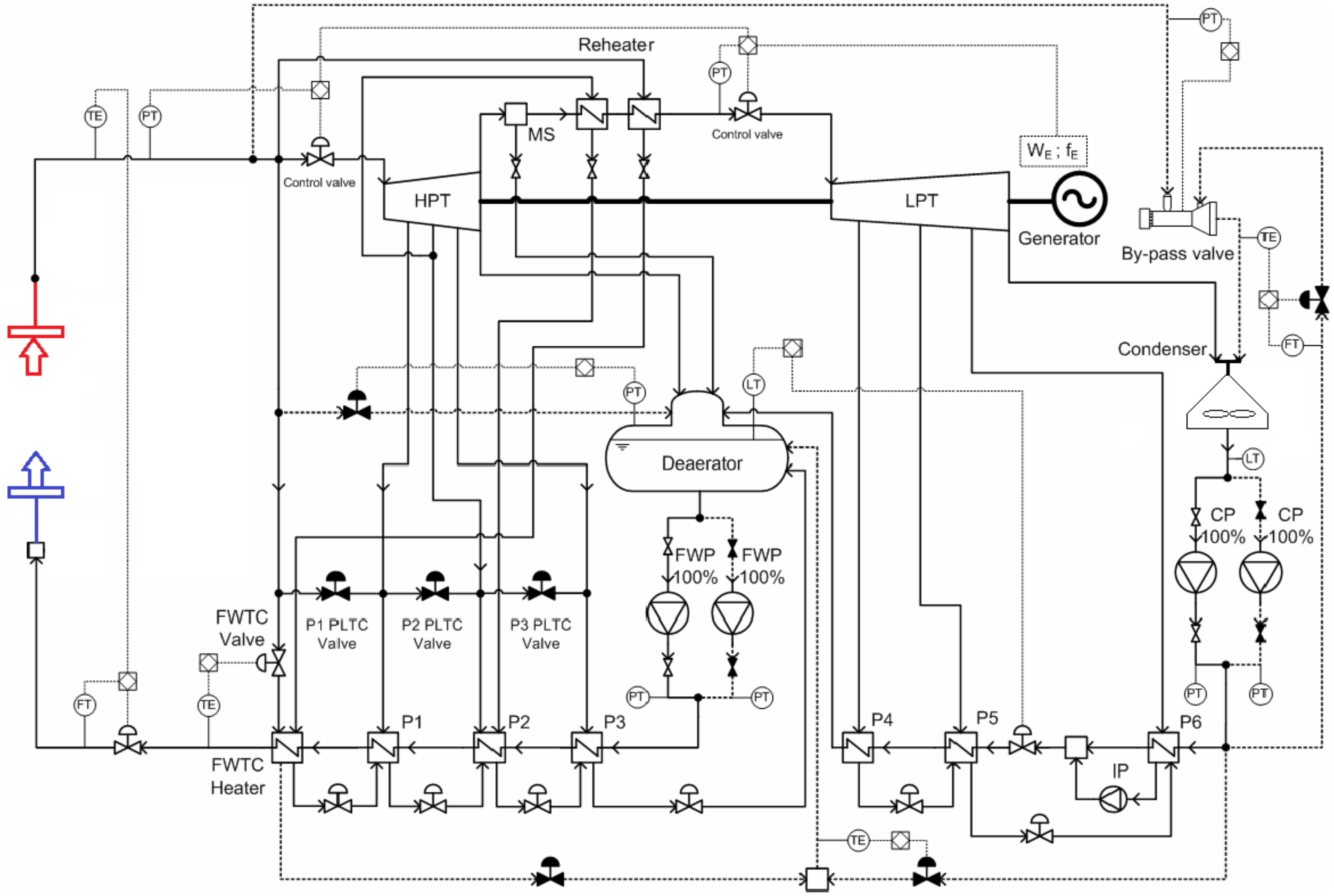
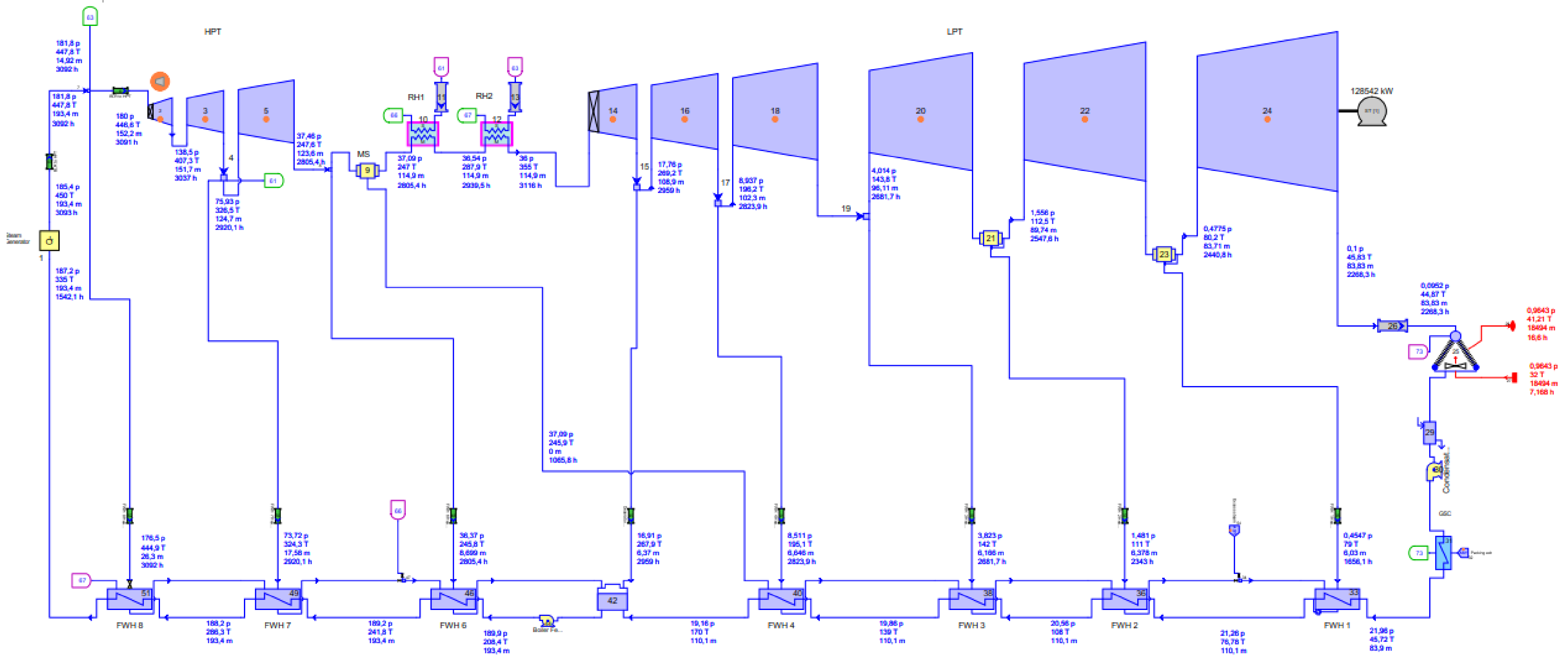
Balance of Plant Architecture



Balance of Plant Architecture



Energy storage technologies and their integration in Hybrid Energy Systems

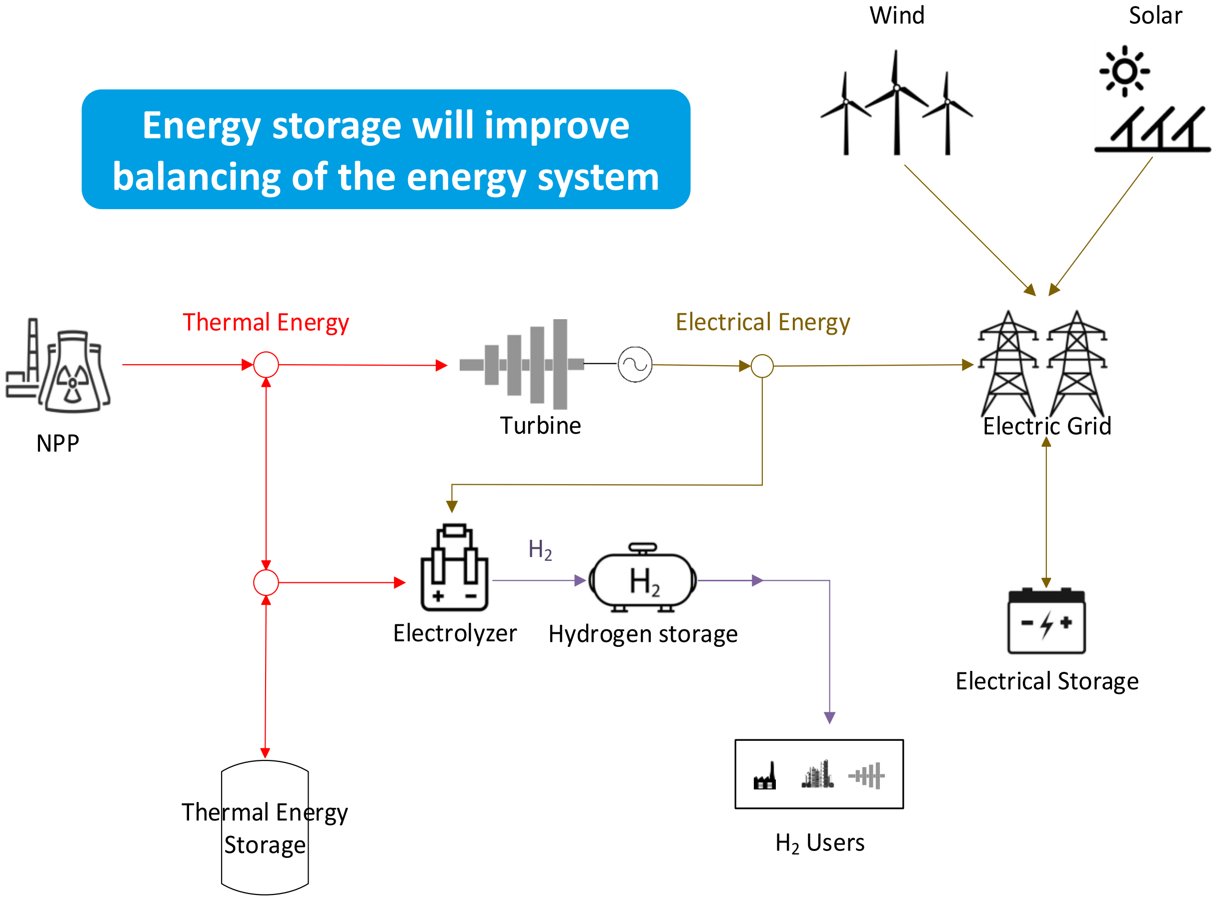
Technology	Thermodyn. Conditions	Storage Time	Efficiency	Cost	Techn. Status
Steam Accumulator	Main Steam Conditions	Hours	95% (T2T)	Very High	Commercial for CSP
Molten Nitrate Salts	290-565 ºC	Hours to Days	98% (T2T)	High	Commercial for CSP
Solid materials (e.g. concrete)	400ºC	Hours to Days	98% (T2T)	Low	Laboratory
FIRES[1][2]: NACC / NARC	550-700 ºC	Hours to Days	98% (E2T) <40% (T2E)	High	Laboratory
Hydrogen[1]: Electrolysis – Fuel Cells	-	Days	<80% (E2T) <60% (T2E)	High	Few Utility-Scale Projects - Laboratory
Hydrogen: NACC / NARC	550-700 ºC	Hours to Days	80% (E2T) 30% (T2E)	High	Laboratory
Electric Batteries	-	Days	90% (E2E)	Very High	Few Utility-Scale Projects

https://www.osti.gov/servlets/purl/1575201

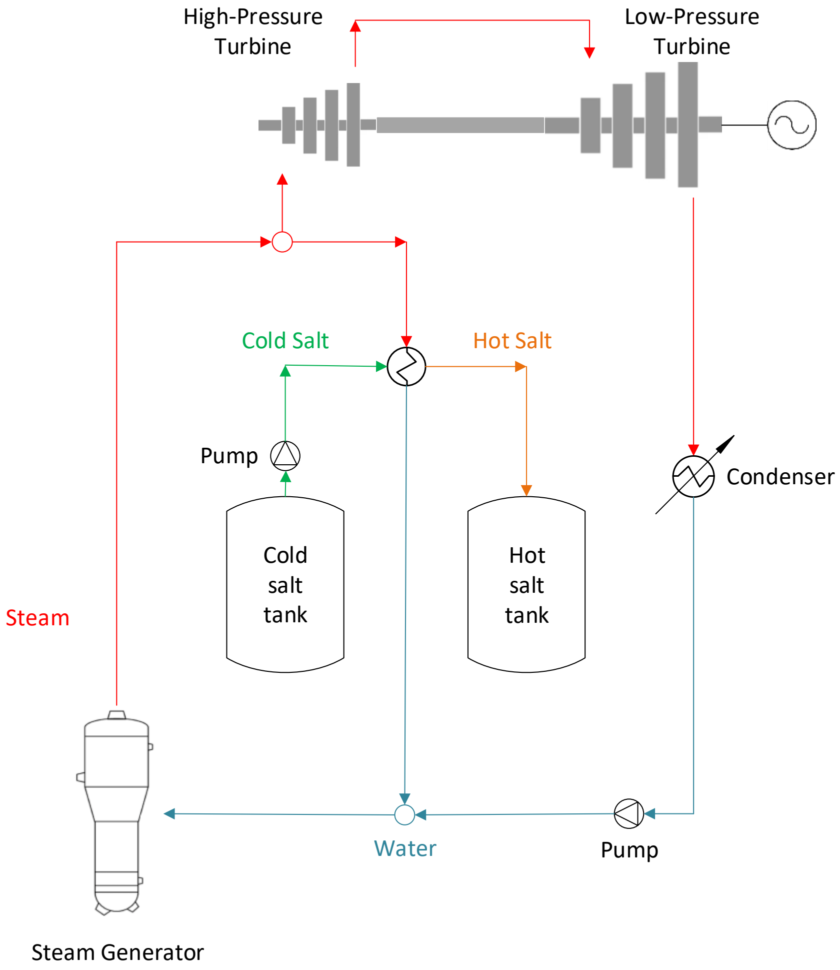
https://www.tandfonline.com/doi/full/

E2E – Electric to Electric
E2T – Electric to Thermal
T2T – Thermal to Thermal

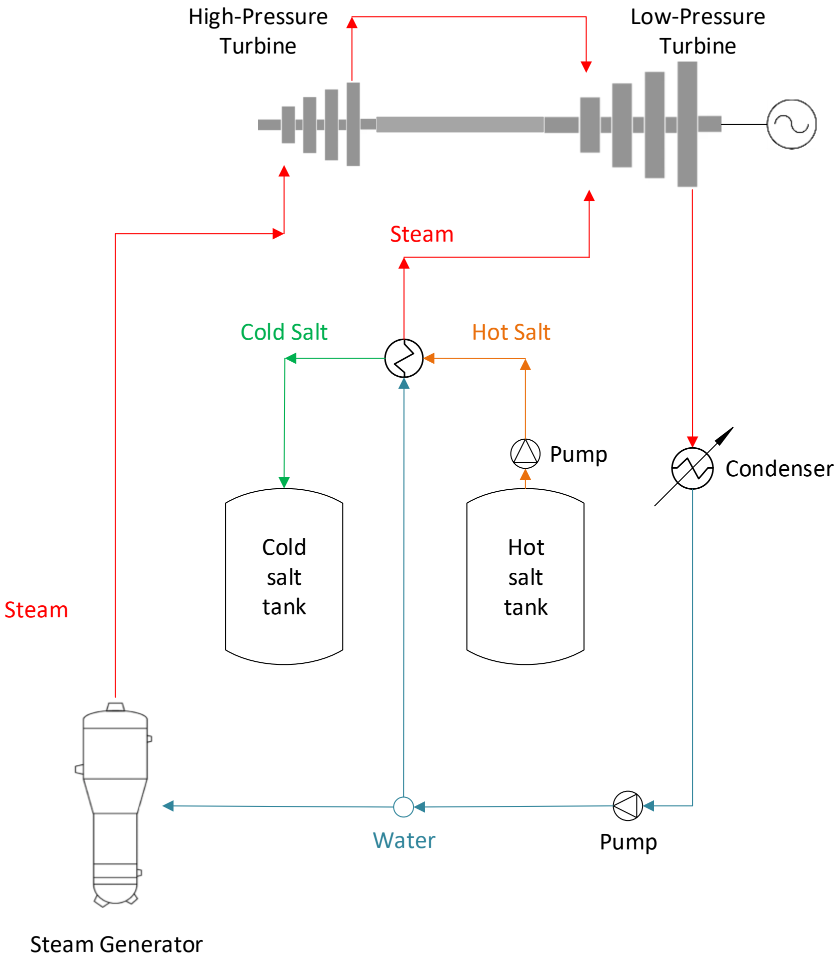
Energy storage will improve balancing of the energy system



Coupling with thermal energy storage

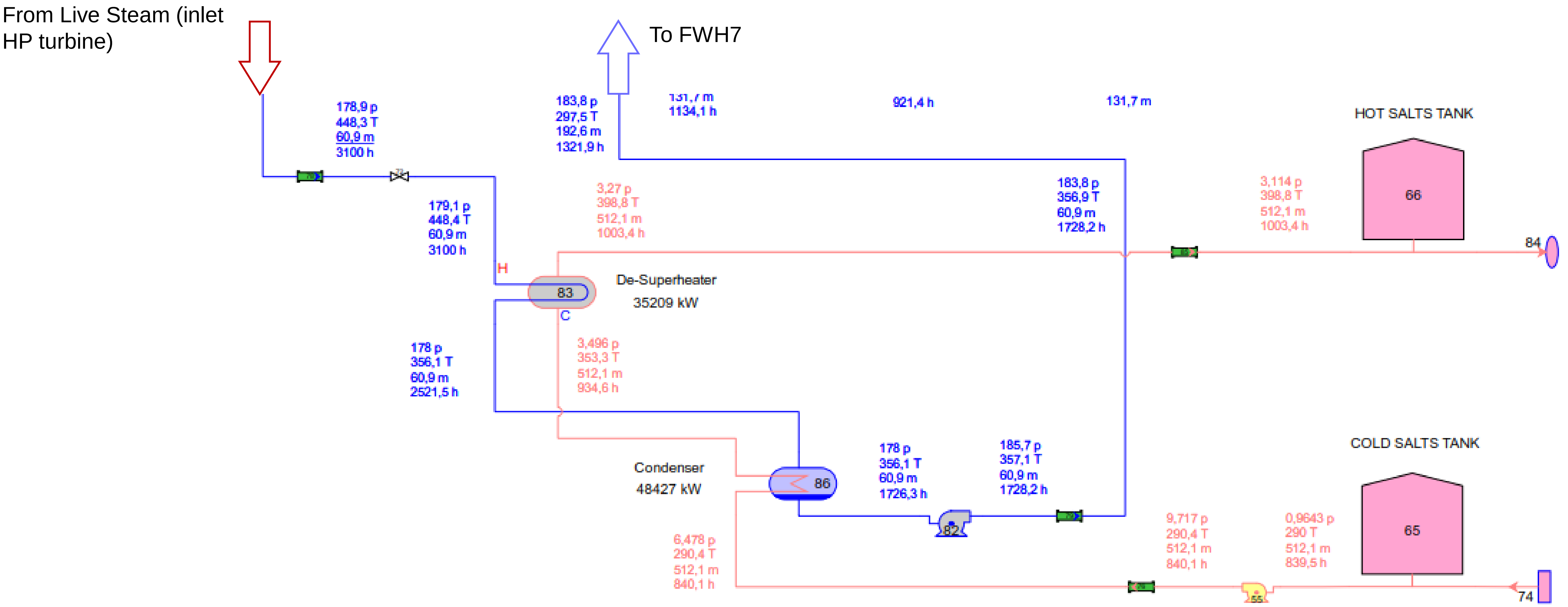


Loading Operating Mode Schematic



Unloading Operating Mode Schematic

Molten Salt TES – Loading phase



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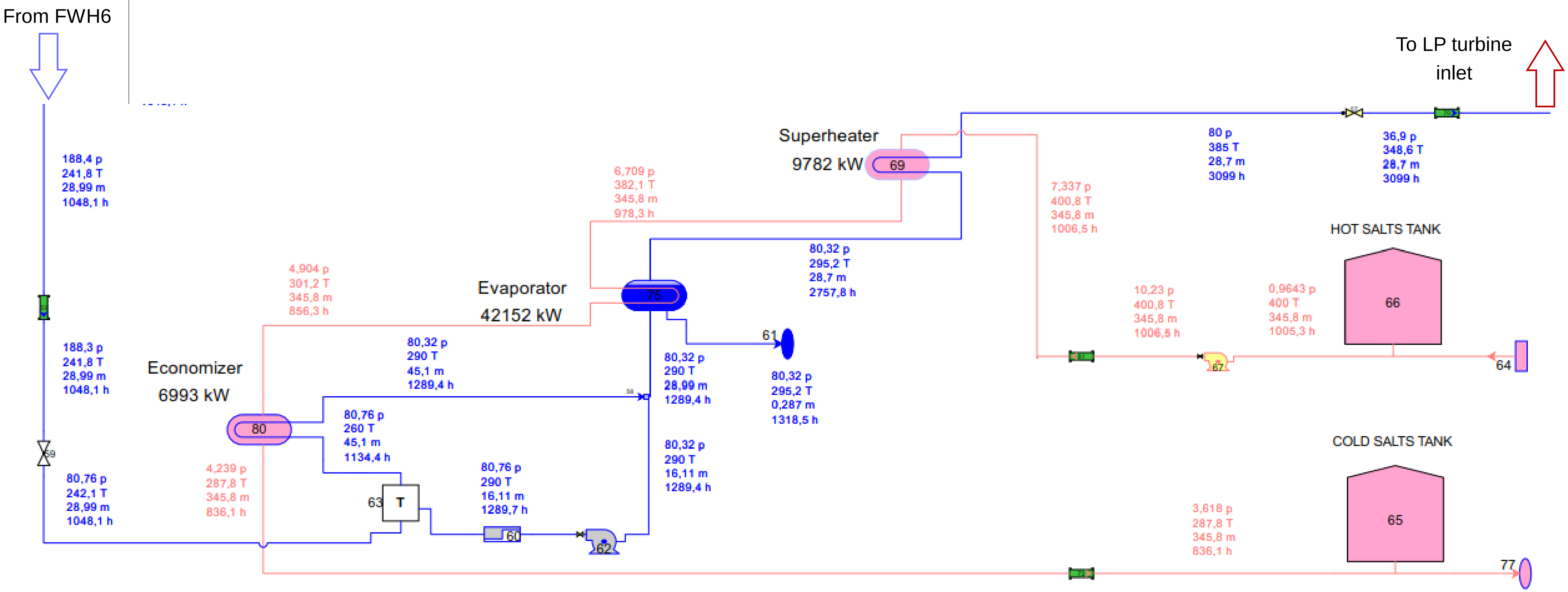
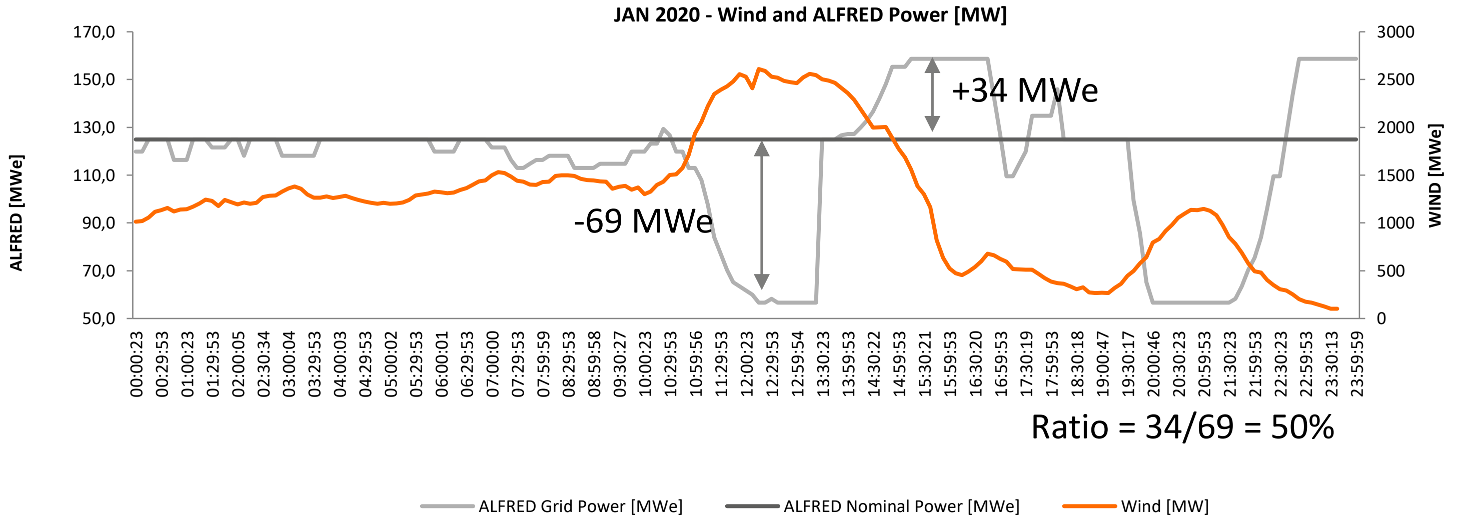
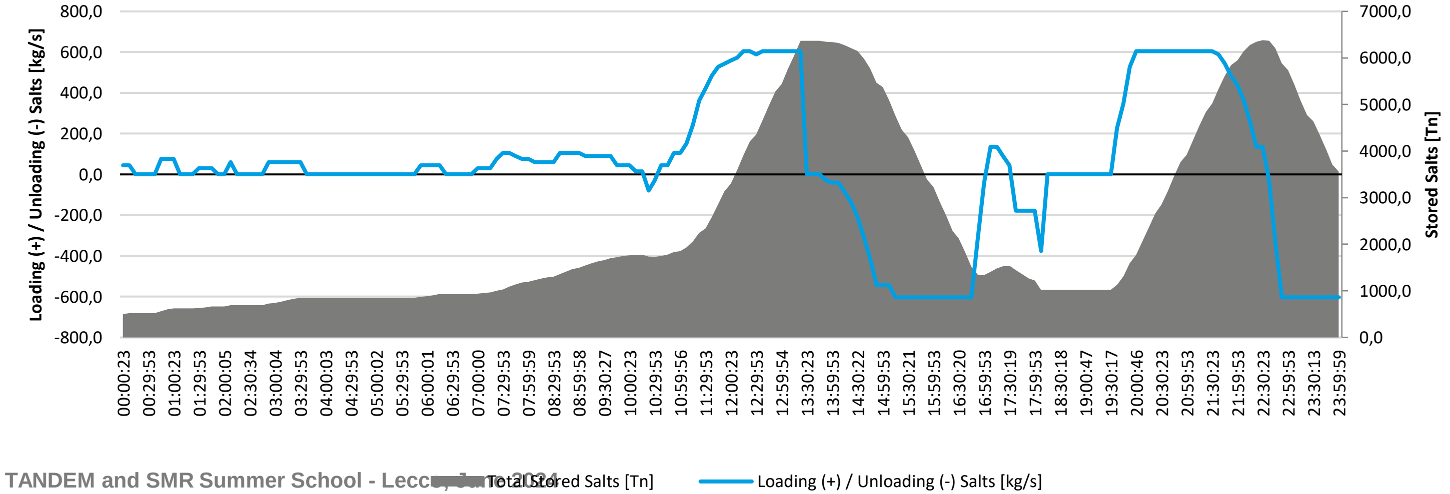
Molten Salt TES – Unloading phase

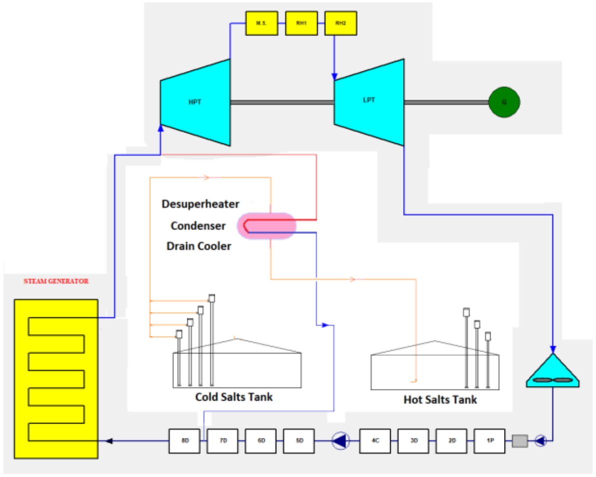


Load Following with TES (molten salts)

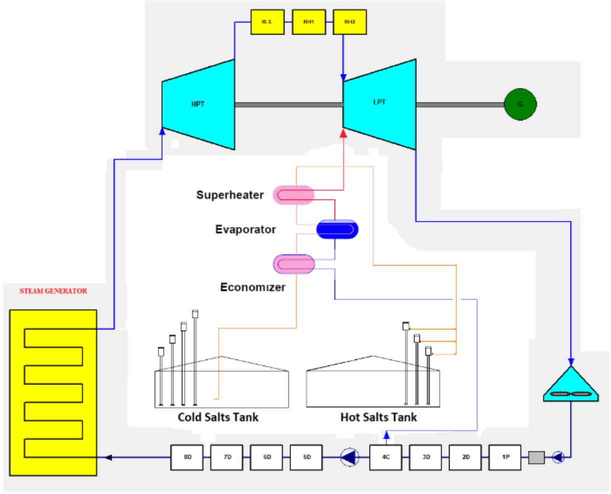




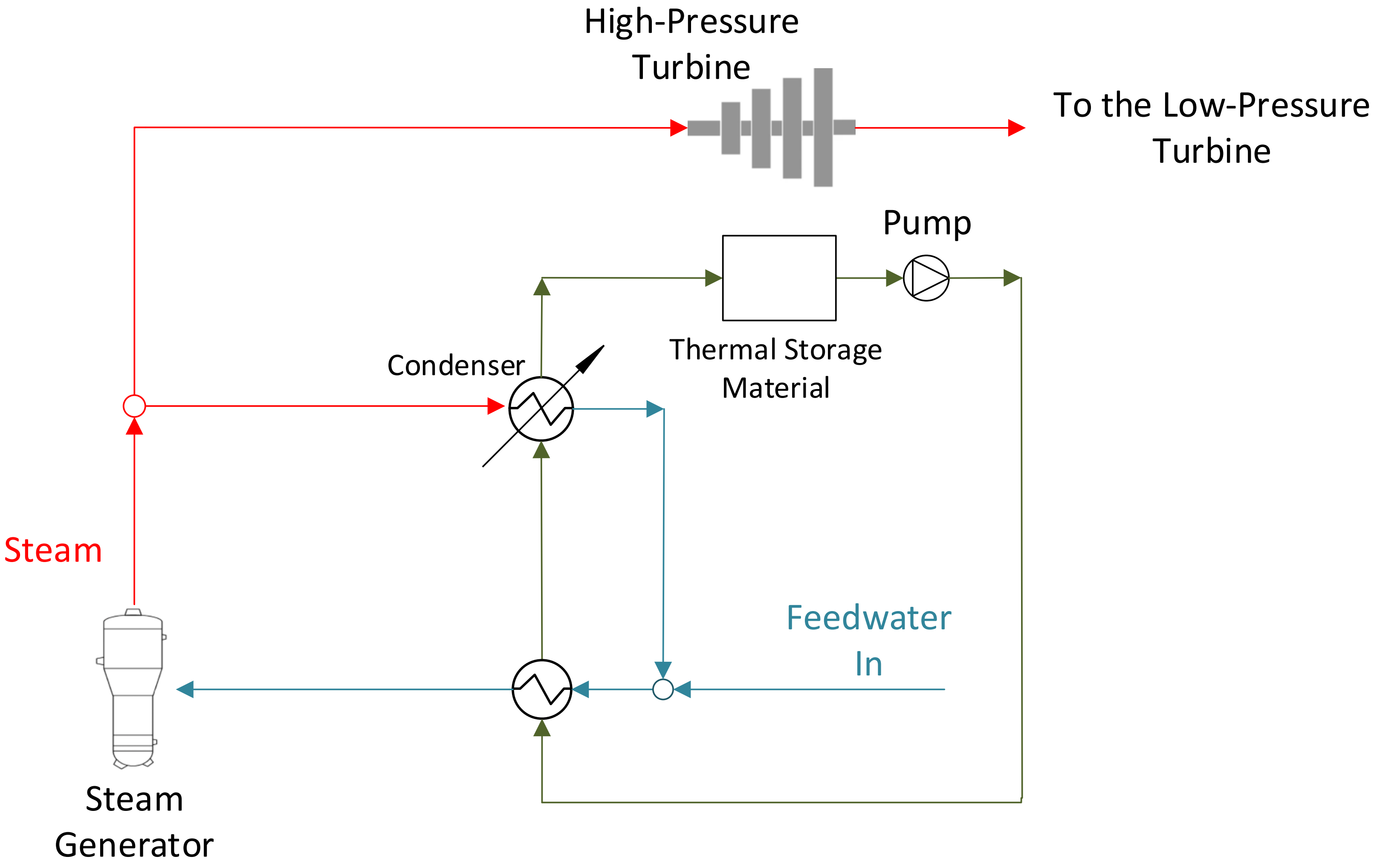
Loading



Unloading



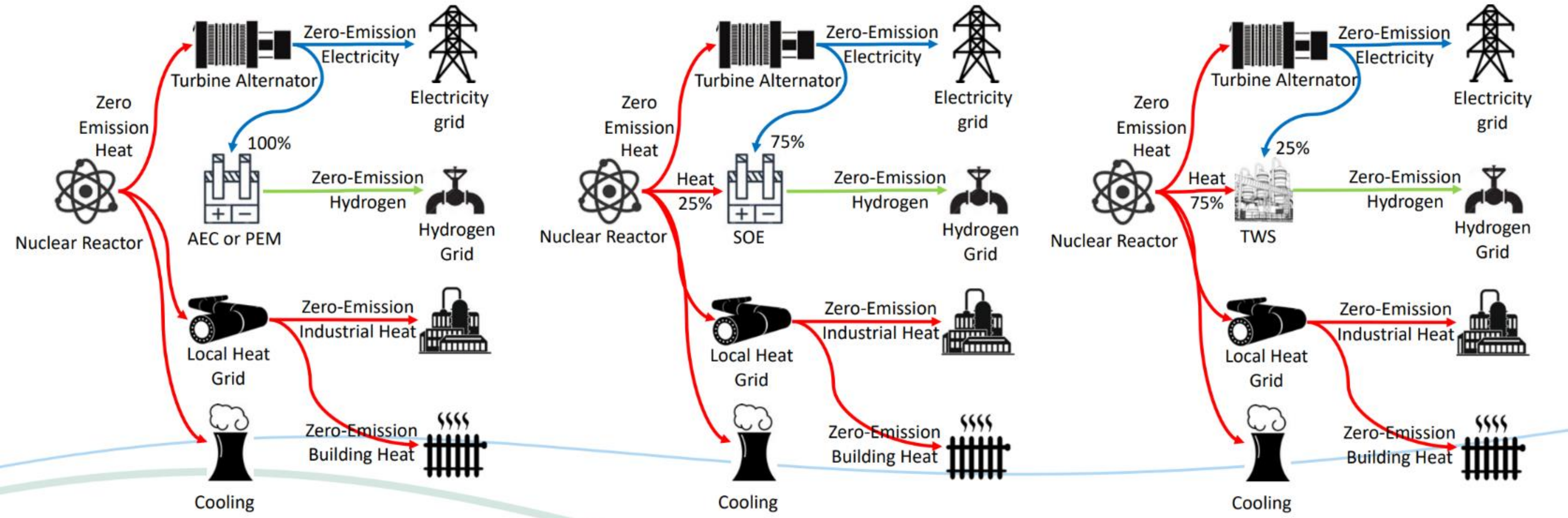
Coupling with energy storage (lower temperature solution)



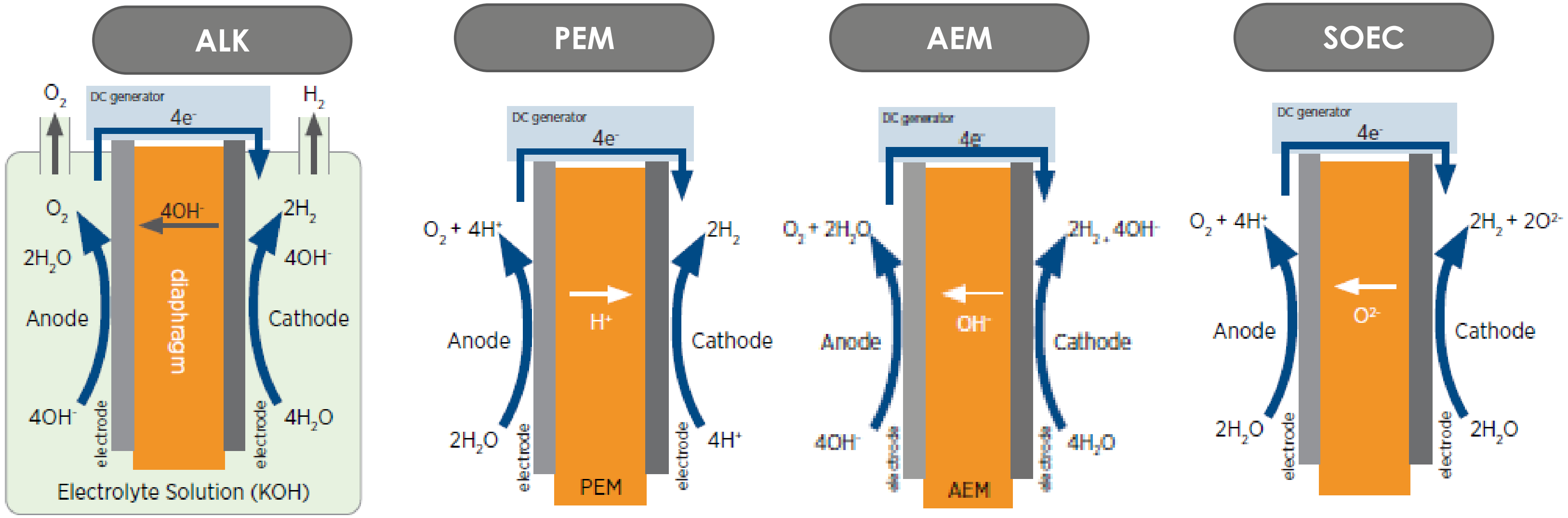
Alkaline Electrolysis (AE) Protone Exchange Membrane (PEM)

Solid Oxide Electrolysis (SOE)

Thermochemical Water Splitting (TWS)



General overview of electrolyser technologies



Maturity level	Mature	Early	Pilot	Pilot
Operating Temperature [°C]	70-90	50-80	40-60	600-850
Operating Pressure [bar]	1-30	1-70	1-35	1
Load Range	15%-100%	5%-120%	5%-100%	30-125%
System specific consumption [kWh/kg H2]	52-60	52-60	52-60	40 - 50
Efficiency LHV [%]	64 - 56	64 - 56	64 - 56	83 - 67
Lifetime [khrs]	60-90	50-80	5-35	20-45
Cold start-up [minutes]	<50	<20	<20	>600

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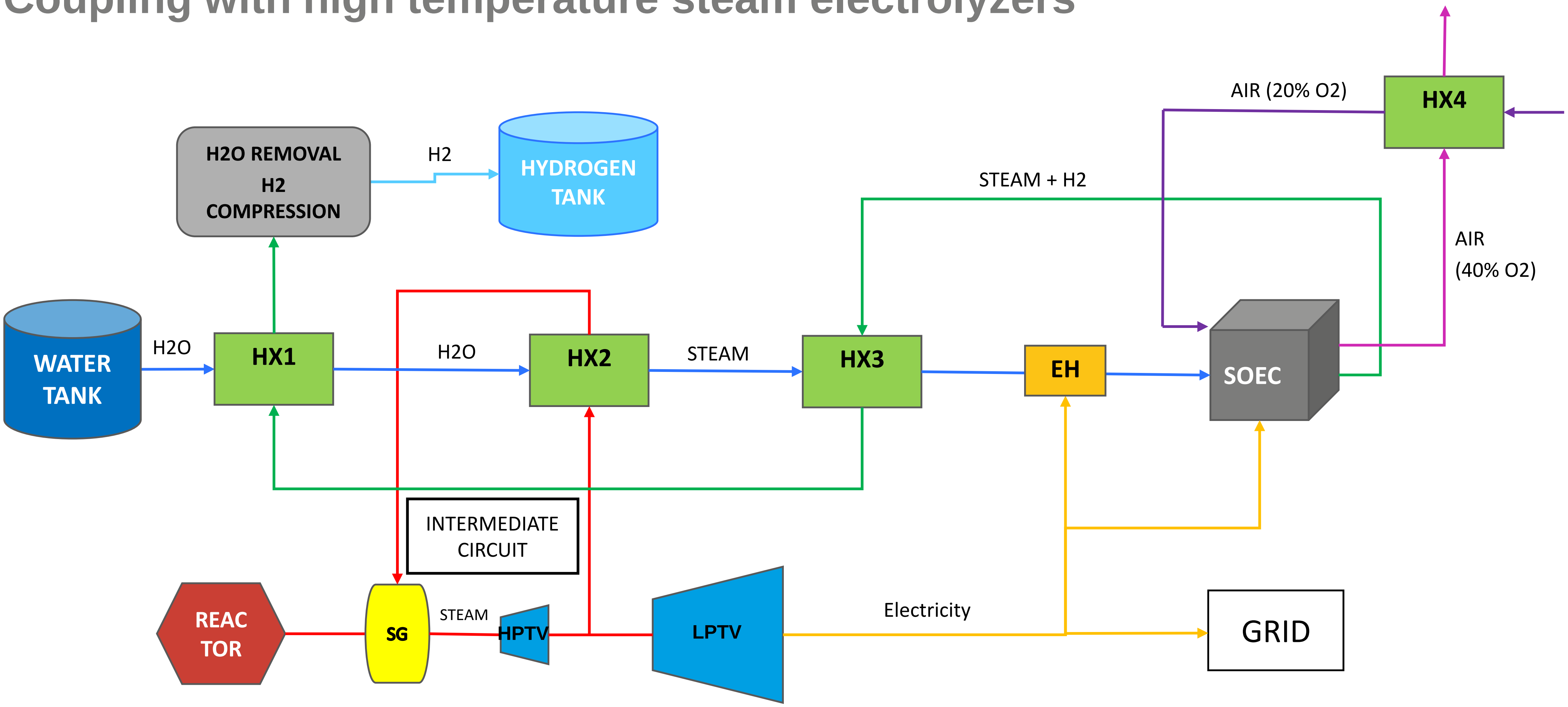
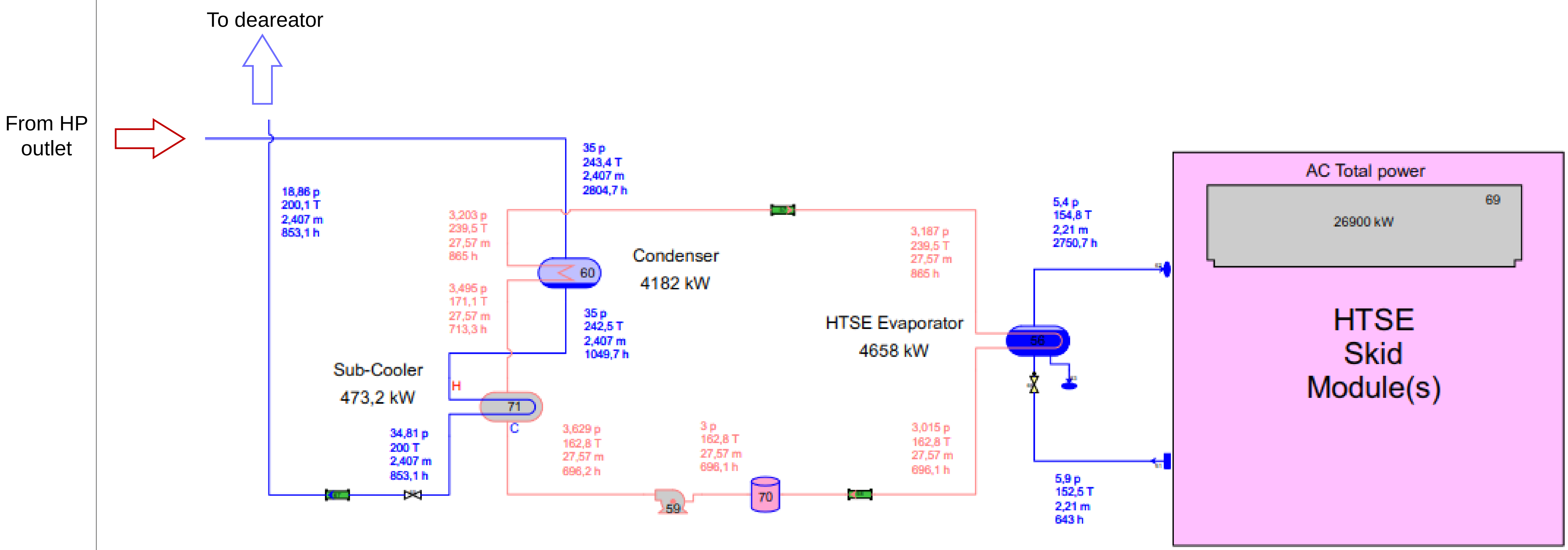
Hydrogen production is the most effective means to decarbonize hard-to-abate sector

Coupling with high temperature steam electrolyzers



Molten Salt TES – Unloading phase



Our vision for new builds

Simplification

- **Financing** of large NPPs is very different from other power plants, because of the **size** of the investment and the long construction schedule, with associated **risks**.
- This is even more true for **First-of-a-Kind** new reactor designs.
- **Simplification** is crucial towards reduction of construction costs and timing, then making the **financing** less cumbersome.

Social acceptability

- When looking to new-comers or densely **populated areas** as an integrated market, a high level of **safety** shall be granted and perceived.
- Innovation based on **passive safety** features offers a better acceptability and **lower perceived risk**.
- Similarly, **waste minimization** is an issue to address, when looking for an increasing nuclear production.
- New plants able **to close the fuel cycle**. i.e. Generation IV designs, will have a place in the future markets.

Transnational Synergies

- New Nuclear needs to be **standardized**, particularly wherever the regional markets are too small to allow for **series effect** benefits.
- **Development costs** of New Nuclear are significant: **cooperation** is the key to accelerate.
- The global supply chain in western countries has been suffering the lack of New Builds in the past decades.
- **Cooperation** among national supply chains can allow for less **investment costs**, while ensuring larger and more stable markets to everybody.

The SMR business model looks to us an approach of interest to develop and deploy a New Nuclear in regional markets

Key takeaways

- **Ansaldo Nucleare's vision**: our vision considers nuclear as having the lowest environmental impact, the highest resilience and the lowest system costs. We've been investing in LFR as the most promising Gen-IV technology to meet the sustainability goals.
- **Using lead as a reactor coolant**: lead as a coolant is changing the paradigm in nuclear plant design, offering opportunities and challenges for the development of new ideas and concepts, while offering opportunities for simplification and cost reduction.
- **Experimental facilities**: licensing challenges require investment, but also generate new opportunities for students and researchers in support to the performance validation of SMR and AMR technologies.
- **Advantages of high temperature**: SMRs and AMRs have the key features to be fully integrated in energy systems with high penetration of renewables, offering new methods for load following through energy storage and cogeneration.

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Thank you for your attention
Grazie!