2017 The 17th IERE General meeting and Canada Forum

Session 2: Advances in energy storage and conversion technologies

ENERGY STORAGE FOR GRID SCALE APPLICATIONS COMBINED WITH CONVENTIONAL POWER PLANTS – INNOVATIVE CONCEPTS FOR SUSTAINABLE ENERGY CONVERSION AND USE

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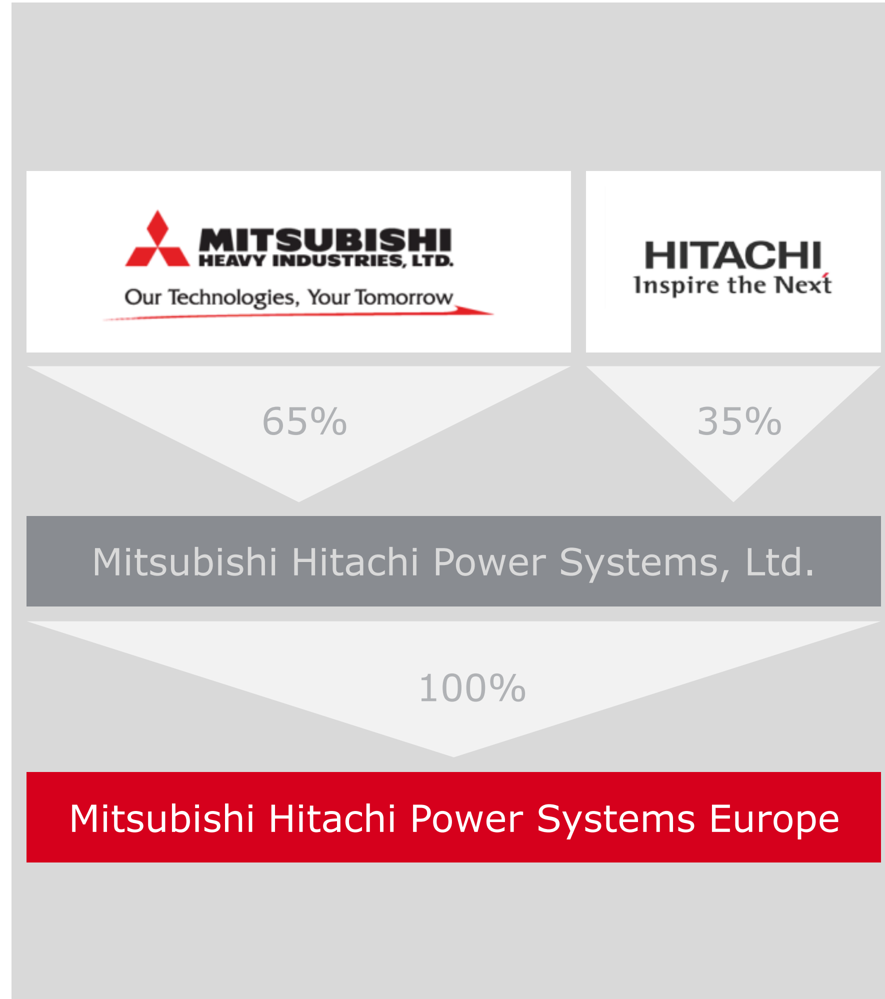
Mitsubishi Hitachi Power Systems, Ltd. (MHPS)

- Start of Joint Venture: 1 February 2014
  Mitsubishi Hitachi Power Systems, Ltd. (MHPS)
- HQ Location: Yokohama, Japan
- Number of MHPS Group companies: 58
  (8 in Japan, 50 overseas)
- Total workforce: approx. 20,500 (consolidated)
- Major operations/ businesses:
  - Thermal Power Generation Systems
  - Geothermal Power Generation Systems
  - Environmental Systems
  - Fuel Cells
- Capital: 100 billion Yen / 1.05 billion USD

  (USD/JPY: 95)



MHPS – Business Activities/ Products

Gas Turbine Combined Cycle (GTCC) Power Plants

Boilers

Integrated Coal Gasification Combined Cycle (IGCC) Power Plants

Environmental Plants SCR ($DeNO_x$) Systems / Flue Gas desulfurization

Gas Turbines

Generators

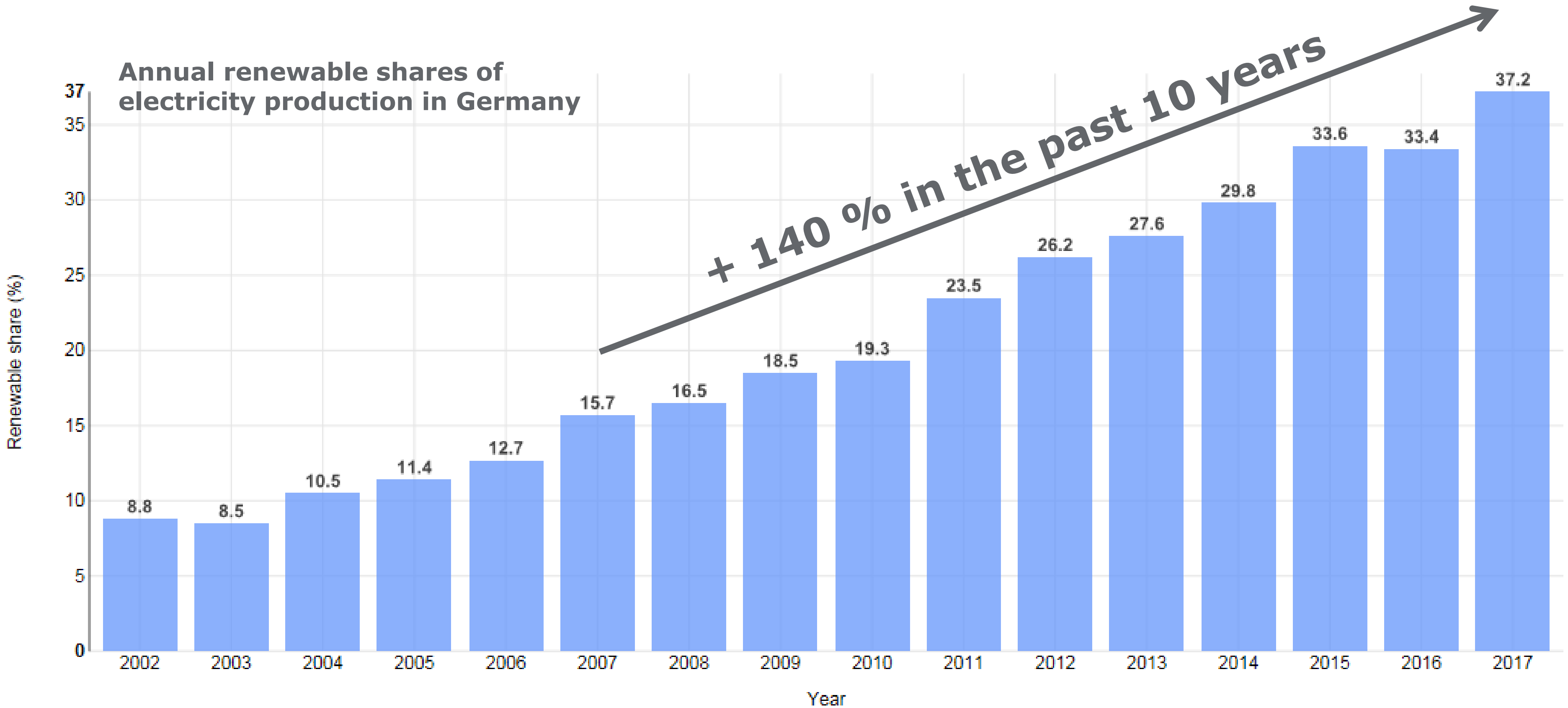
Boiler & Turbine Generation Plants

Geothermal Power Plants

Steam Turbines

Power Generating Plant Peripheral Equipment

Annual renewable shares of electricity production (TWh) in Germany increases dramatically.

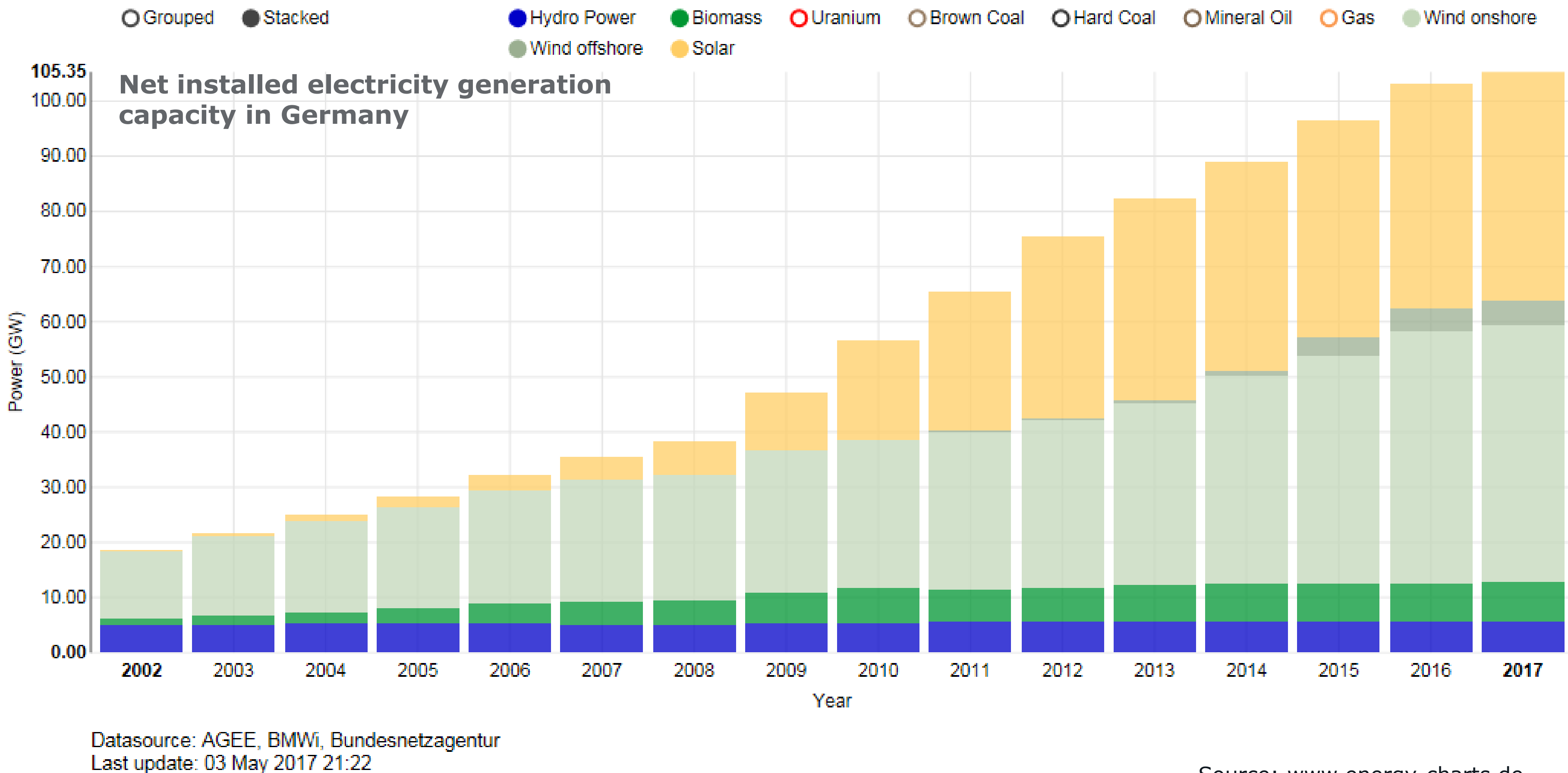


Net generation of power plants for public power supply.
Datasource: 50 Hertz, Amprion, Tennet, TransnetBW, Destatis, EEX
Last update: 05 May 2017 17:14

Source: www.energy-charts.de

How is the situation on EU energy markets? Germany as an example. (II)

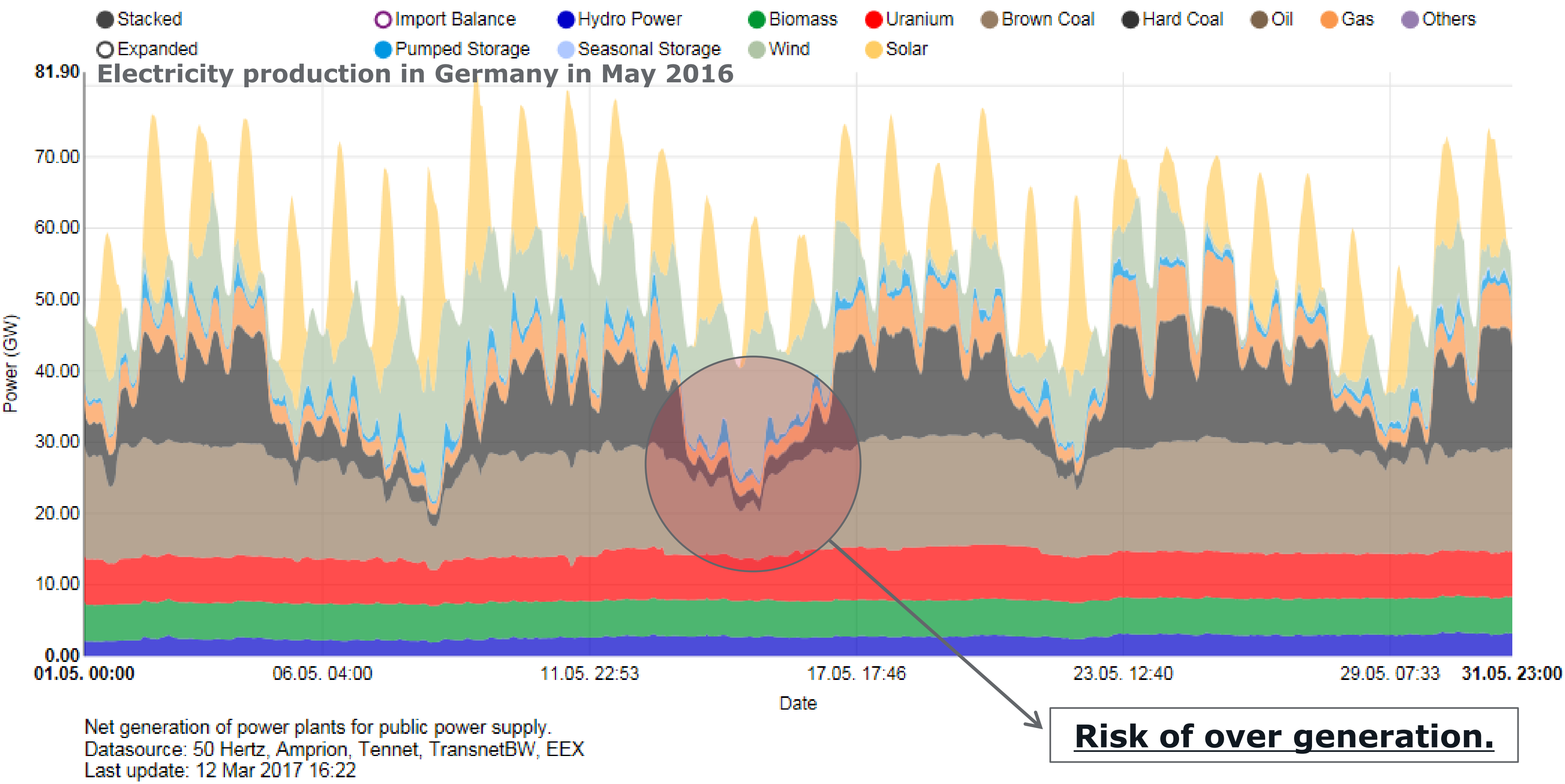
Increase of net installed electricity generation from renewable energy sources (RES) capacity in Germany is mainly non-controllable, variable RES (solar and wind).



Source: www.energy-charts.de

How is the situation on EU energy markets? Germany as an example. (III)

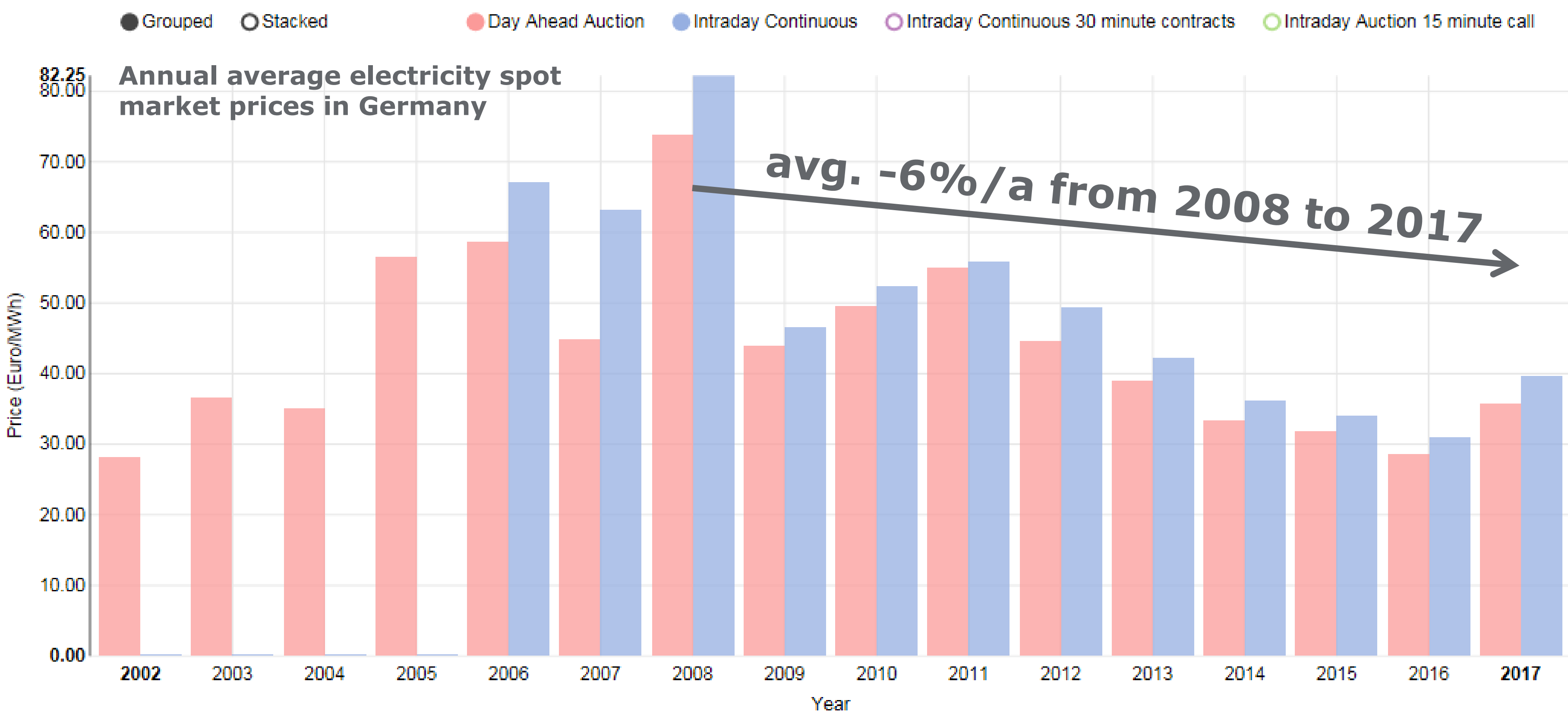
Fossil power plants must be operated more and more flexible (especially hard coal, but also lignite). RES have feed-in priority.



Source: www.energy-charts.de

How is the situation on EU energy markets? Germany as an example. (IV)

As a consequence of subsidies for the electricity generation from RES the electricity market price decreases and fossil power generation is squeezed out of the market.

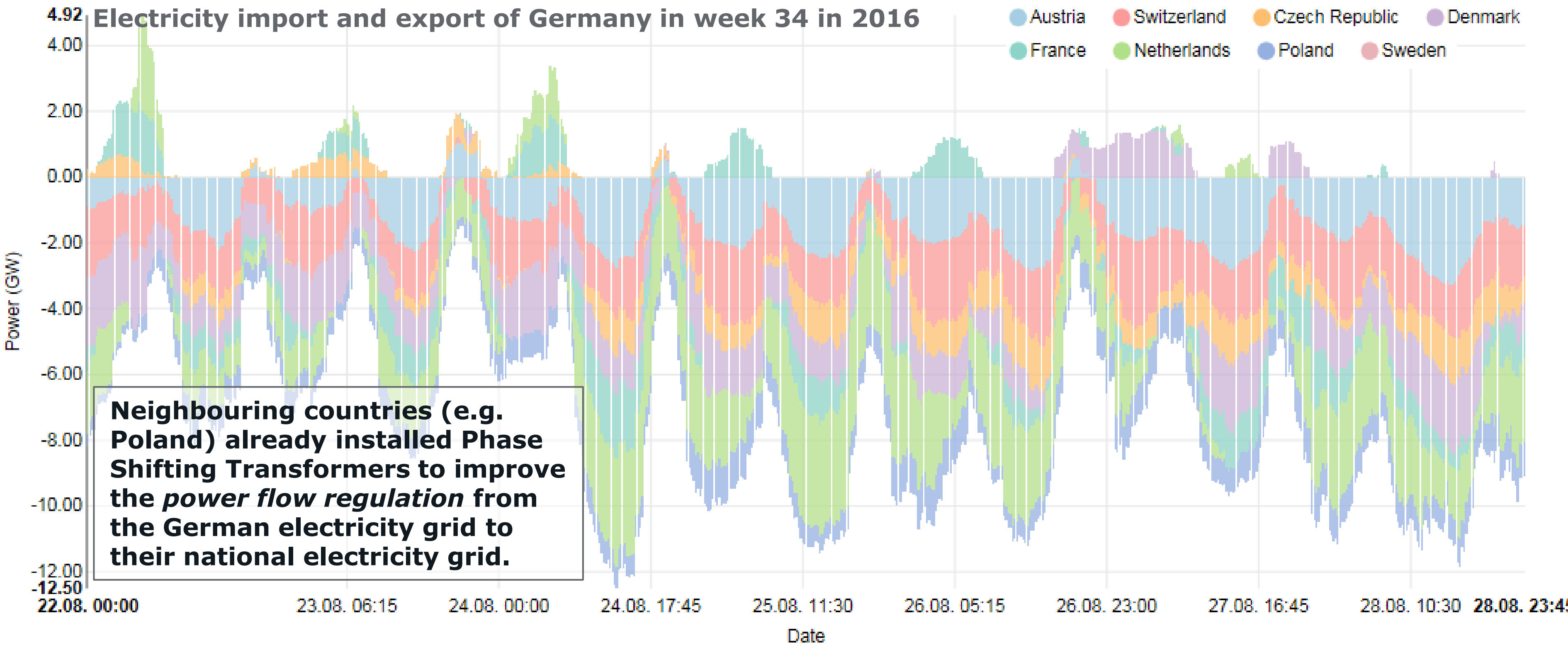


Real volume weighted average prices, adjusted for inflation rates.
Datasource: EPEX
Last update: 05 May 2017 16:13

Source: www.energy-charts.de

How is the situation on EU energy markets? Germany as an example. (V)

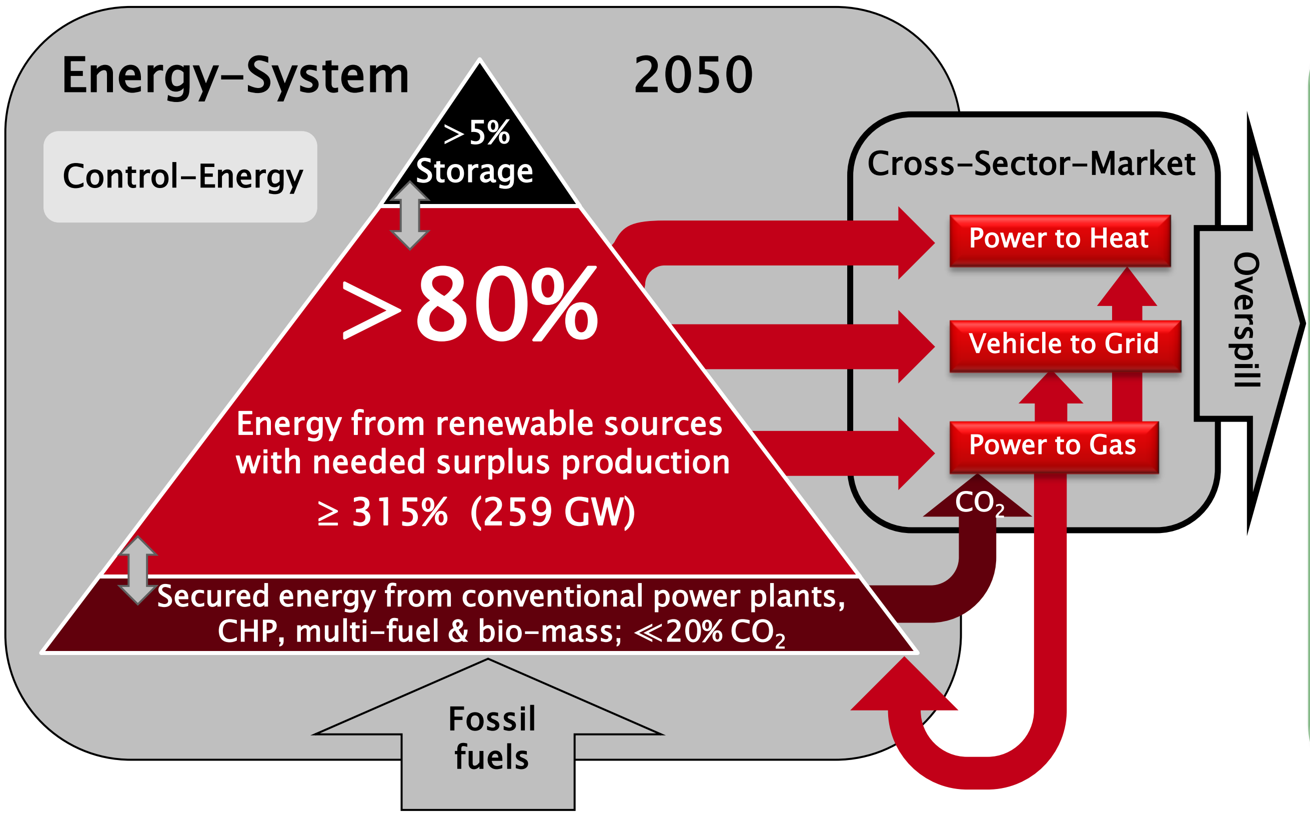
Over generation leads to significant electricity export. More flexible power plants and bulk enery storage plants will become crucial for energy systems with high penetration of RES.
But: Prices on electricity-only market are currently too low for implementation of flexibility measures and for bulk energy storage and the market for control energy is not able to compensate this lack of profit.



Physical flows. Positive values indicate import. Negative values indicate export.
Datasource: 50 Hertz, Amprion, Tennet, TransnetBW, ENTSO-E
Last update: 04 Sep 2016 00:13

Source: www.energy-charts.de

Projected German Energy System 2050



State 2050 (target)

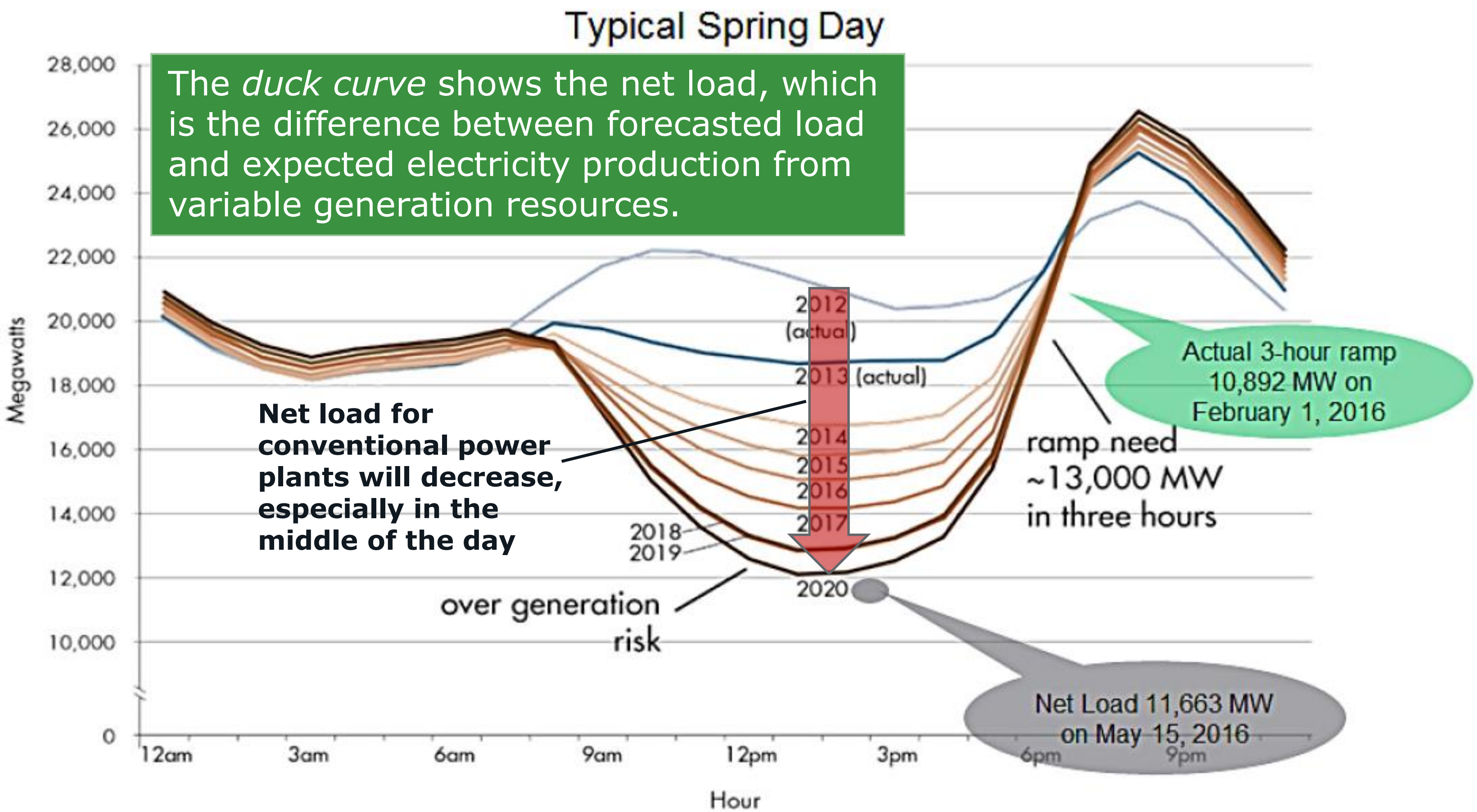
- 100 GW max. load demand
- 397 GW available capacity
- 59 GW conventional
- 259 GW renewables
- 14 GW storage
- 53 GW cross sector
- 12 GW biomass

- Load demand is expected to slightly rise until 2050 (13 GW)
- Demand Side Management to be planned and operated by big consumers
- Conventional power plant fleet to decrease to 50%
- electricity = a “cheap” commodity

Maximum load 87 GW + 13 GW in Demand Side Management (DSM)

How is the situation on other energy markets? California as an example.

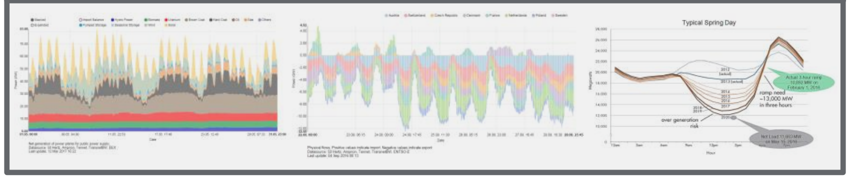
Also in the Californian electricity market RES will probably lead to a more flexible operation of fossil power plants, to decreasing electricity market prices and to over generation risk.



Source: California ISO, 2016

How to deal with over generation from renewable energy sources?

Over generation from RES



RES curtailment

- Contra climate goals

Flexible power plants | **Energy storage**

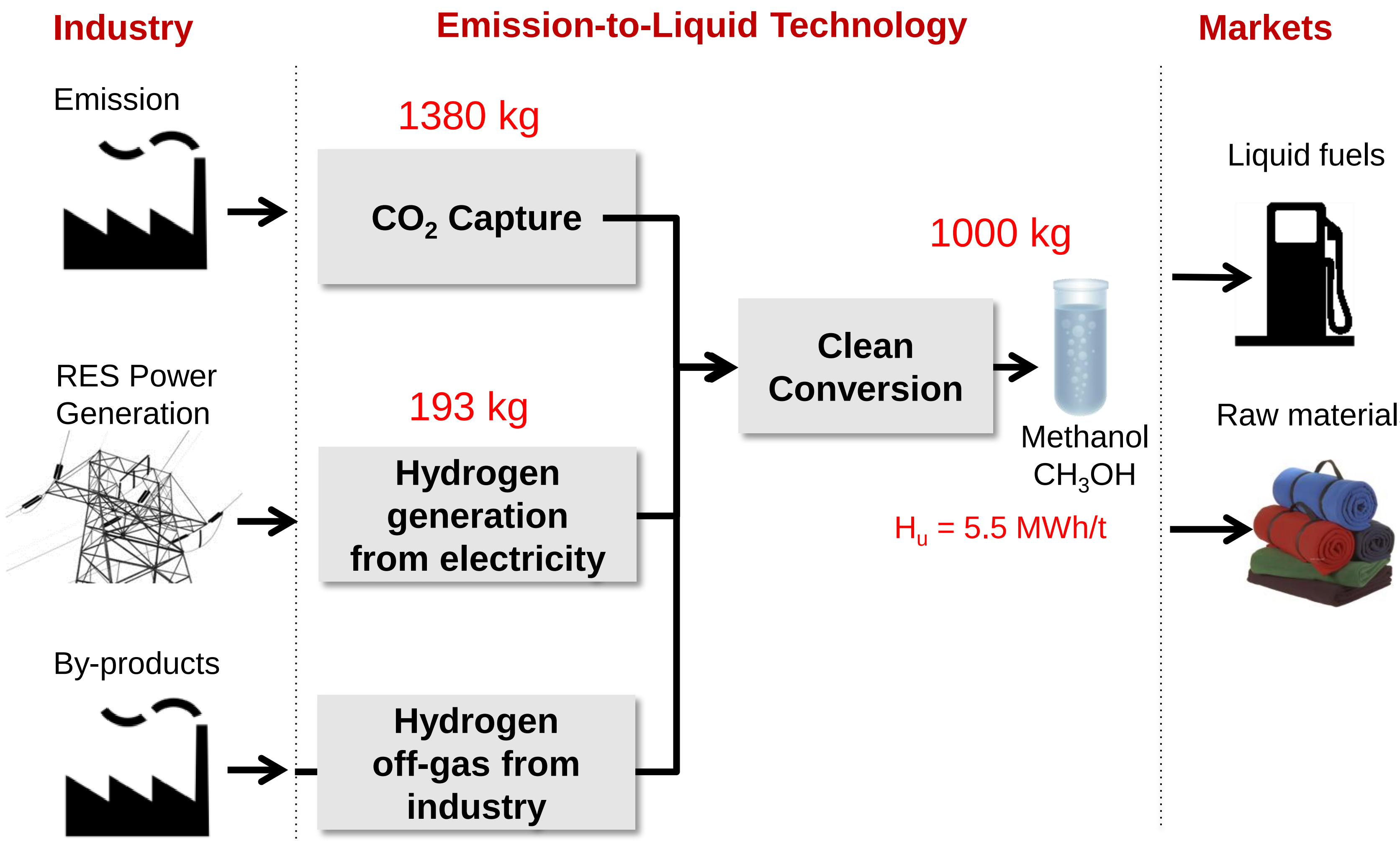
- Power-to-Fuel
- LAES/CAES
- TES in conventional PP

Store 'green energy' from RES in power plants!

Others

- DSM
- Consumers time-of-use rates
- Increase electricity market area (import/export)
- Vehicle-to-grid (storage)

Power-to-Fuel: Carbon recycling as a flexible solution for excess energy utilization



Courtesy of Carbon Recycling International

Status of the technology

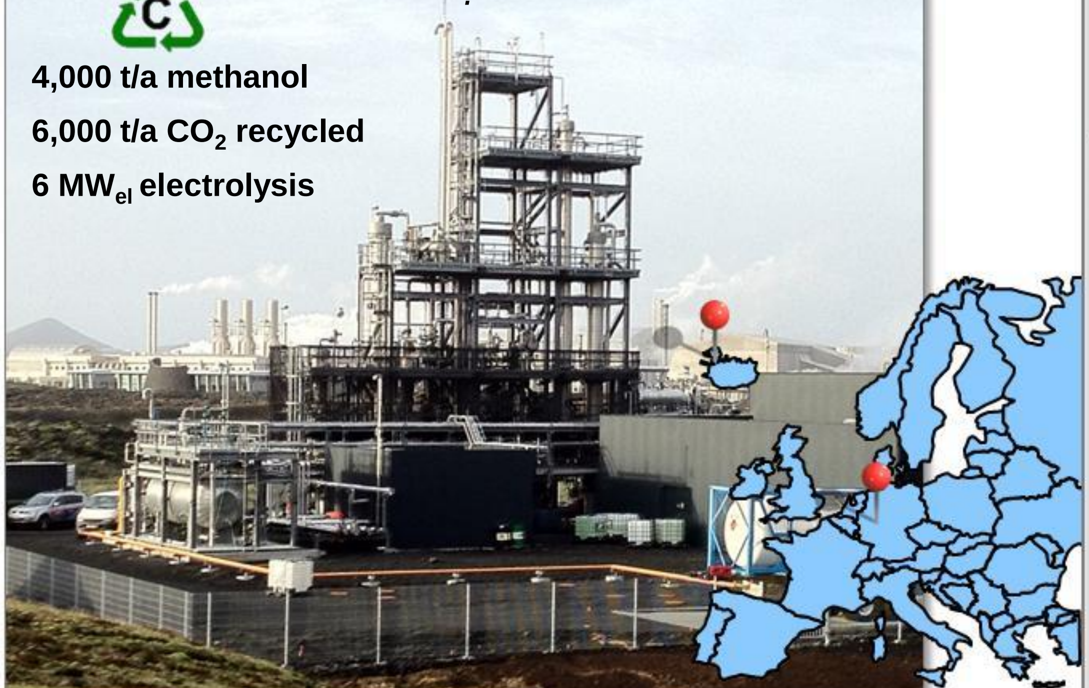
George Olah Plant at Carbon Recycling International

World's First Power to CO_2 Methanol Plant in Svartsengi, Iceland

4,000 t/a methanol

6,000 t/a CO_2 recycled

6 MW_{el} electrolysis



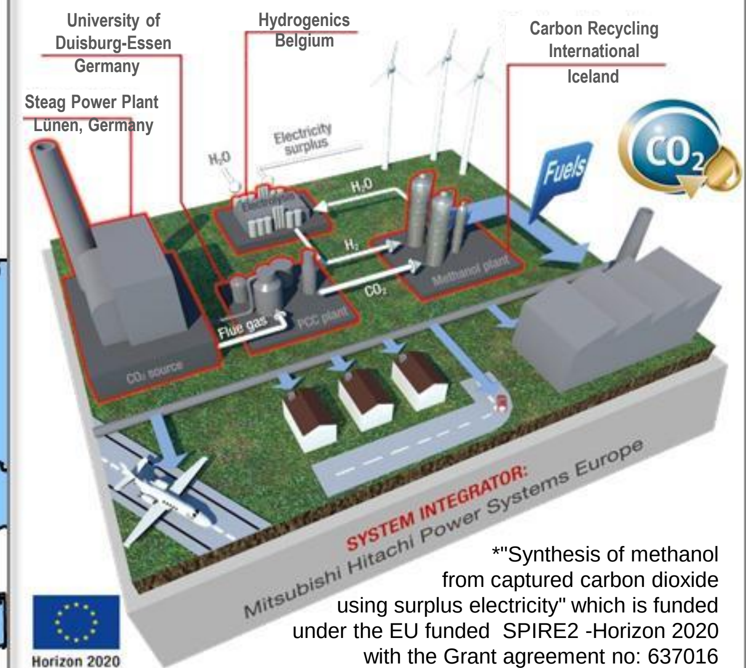
Courtesy of Carbon Recycling International

EU R&D Project to demonstrate Power Plant connected, flexible operation

1 MW_{el} (peak)
1 t/day Methanol

EUR 11million
80% EU funding *
Project start: 12.2014
Duration: 4 years

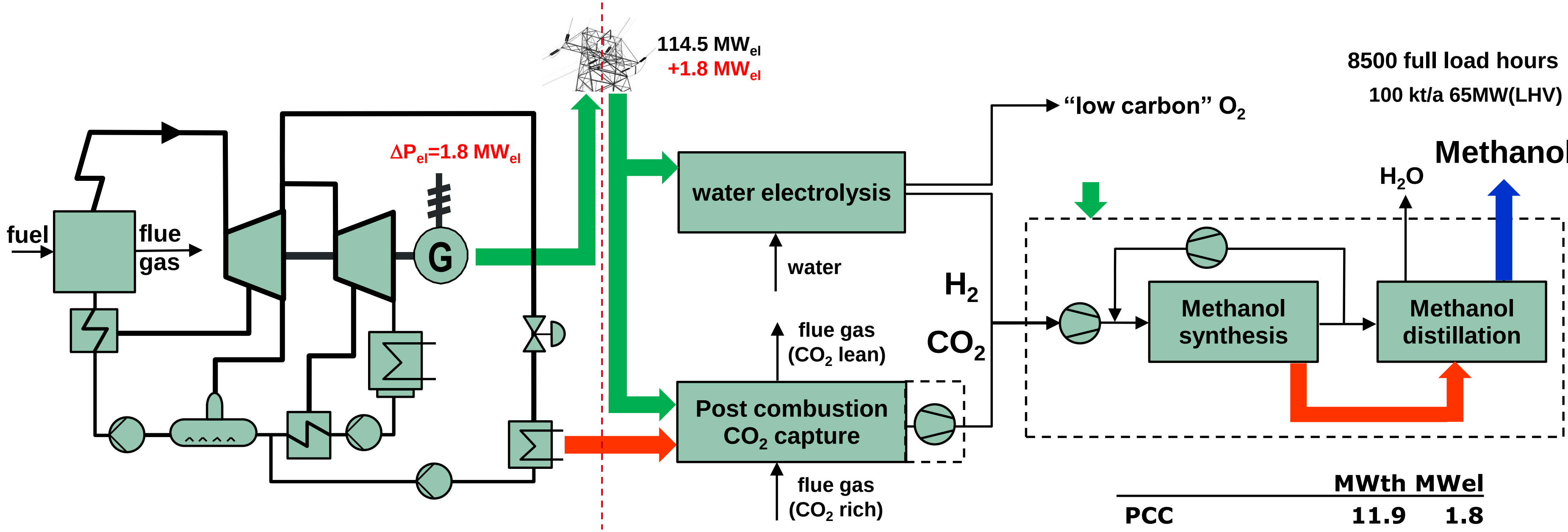
Other partners:
- Genoa University (Italy)
- Cardiff University (UK)
- Catalysis Institute (Slovenia)
- I-deals (Spain).



*"Synthesis of methanol from captured carbon dioxide using surplus electricity" which is funded under the EU funded SPIRE2 -Horizon 2020 with the Grant agreement no: 637016

- Power to Methanol (PtMeOH) is commercially available today in industrial scale
- Methanol and Methanol derived products can be supplied for the fuel sector immediately

Overall system energy balance of PtMeOH, grid connected plant with bleed steam used from PP



Electric Power P_{el} Thermal Power Q_{th}

	MWth	MWel
PCC	11.9	1.8
MeOH	0.0	2.4
Electrolyser	0.0	110.3
Bleed	-11.9	1.8

Total Δp_{el} = 116.3 MWel

- Industrial Scale Plant: 100kt/a, component efficiency as state-of-the-art 2016
  - Steam 1.01 MWh_{th}/t MeOH (electricity loss factor 15% ⇨ 0.15MWh_{el}/t)
  - Electricity 9.74 MWh_{el}/t MeOH
  - ⇨ Total 9.89 MWh/t ($\eta_{el \rightarrow th}$=55.9%)

Electrolyser: 4.4 kWhel(AC)/Nm³
Post combustion CO_2 capture: energy demand 2600 kJ/kg_{CO_2}

- Electricity 25.0 €/MWh
- Heat as electricity loss
- Auxiliaries 16.8 €/t
- Fixed OPEX 5.5 Mio€/a
- Investment 186 Mio€

- Equity 30%
- Interest rate 8%
- Debt 70%
- Interest rate 4%
- Depreciation time (calculated for full payback of the plant)

Case 1: Production with grid electricity in Germany from spot market, 570 g CO_2eq / kWh *

⇨ Fuel carbon footprint: **283 g CO_2eq / kWh** (200% increase[#])

⇨ "Fossil methanol" (265€/t)

⇨ Operation with negative EBITDA

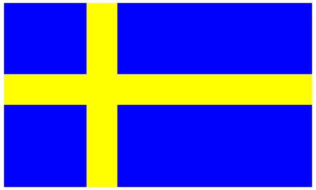
	Mio € /year
Electricity	-25.0
Methanol	26.5
Auxiliaries & Operating	-7.2
EBITDA	**-5.7**

⇨ The product needs the same premium that biofuels get & low carbon electricity has to be used

* UBA 2016, calculation for 2014

[#] fossil fuel baseline standard from COUNCIL DIRECTIVE (EU) 2015/652: 94.1 g CO_2eq / kWh

Low carbon methanol fuel from low carbon electricity



Case 2: Production of “low carbon” methanol in Sweden

- Use of grid electricity with **25 g CO_2eq / kWh**
- Carbon footprint methanol: **12.4 g CO_2eq/MJ = 87% reduction** ✓
- Sales in Germany 
- Premium assumed: 40% of 470€/t CO_2 emission saved*
- Premium: **306 €/t** (added to 265€/t)

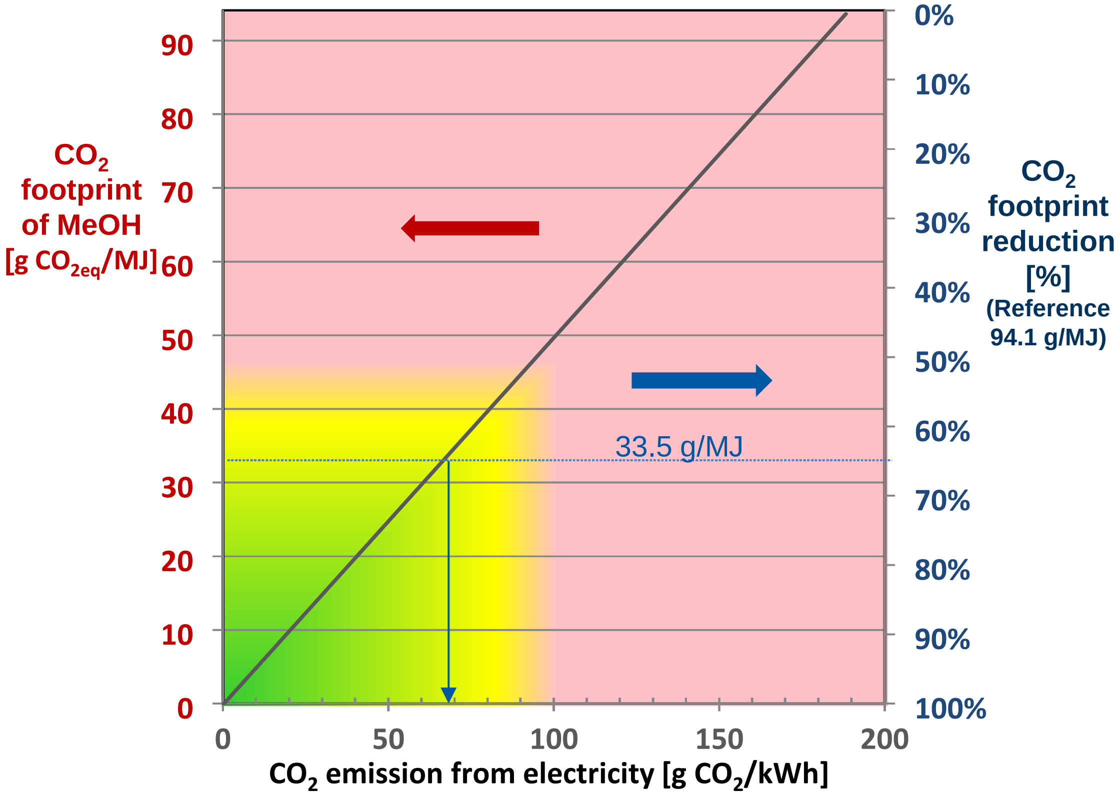
- Pay-off time: 9.82 years ✓

	Mio € /year
Electricity	-25.0
Methanol	26.5
Premium	30.6
Auxiliaries & Operating	-7.2
EBITDA	**17.2**

- Plants can be operated without other incentives or subsidies
  - when (proven) low carbon electricity is used
  - providing a premium price and competitive sales

*penalty from BImSchG, but new (future) reference value 94.1 g CO_2eq/MJ

CO_2 Intensity of the produced methanol fuel – calculated from grid carbon footprint



- 9.89 MWh_{el}/t
- Reference value for reduction:
  - 94.1g CO_2eq/MJ

	gCO_{2eq}/kWh
Iceland	0.207
Mozambique	0.493
Norway	2.458
Nepal	3.376
Switzerland	3.421
Zambia	3.549
Democratic Republic of Congo	4.609
Albania	10.133
Sweden	24.733
Tajikistan	25.737
Angola	42.117
Costa Rica	70.762
France	75.927
Georgia	99.045
Kyrgyzstan	101.392
Brazil	110.151
Ethiopia	132.020
Lithuania	135.098
New Zealand	214.553
Japan	467.380
United States	589.156
Germany	717.712
People's Republic of China and Hong Kong China	1081.061

M. Brander, A. Sood, C. Wylie, A. Haughton, J. Lovell: Technical Paper| Electricity-specific emission factors for grid electricity, Ecometrica, Emissionfactors. com, 2011

- Few countries offer suitable low carbon electricity directly from the grid
- Others ways for certification to be established!

33.5 g/MJ = value to be fulfilled by biofuels in future (60% reduction compared to biofuel baseline of 83.8 g CO_{2eq}/MJ)

Operational needs for Power to Fuel installations

- Power to Fuel is technically complex and requires high investments
- Thus, requirements
  - industrial scale plants (min. 50-100kt/year)

    for economy of scale & economic operation without subsidies
  - certain base load of low cost, low carbon electricity

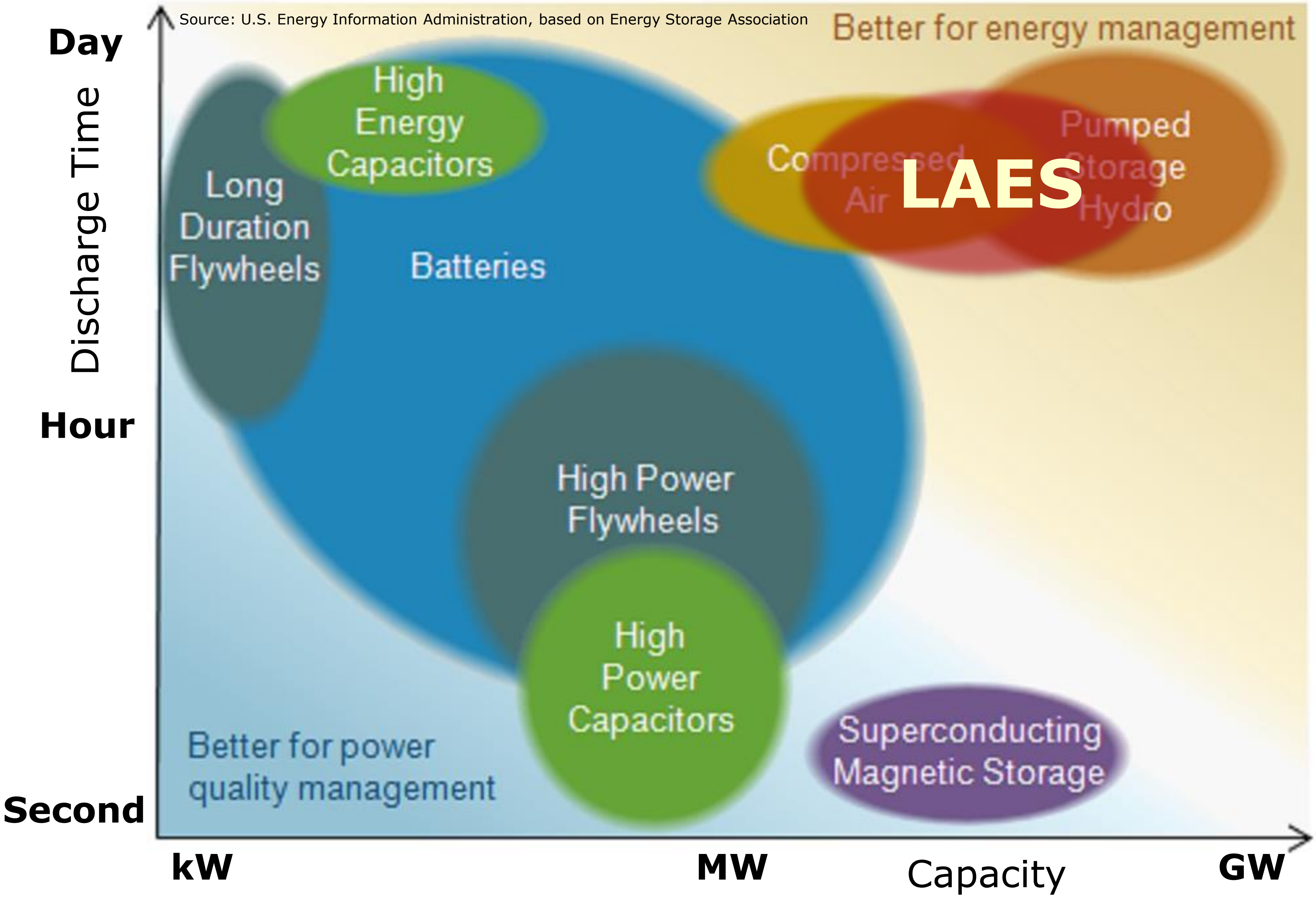
    to reach sufficient full load operation hours for the payback of the investment

but:

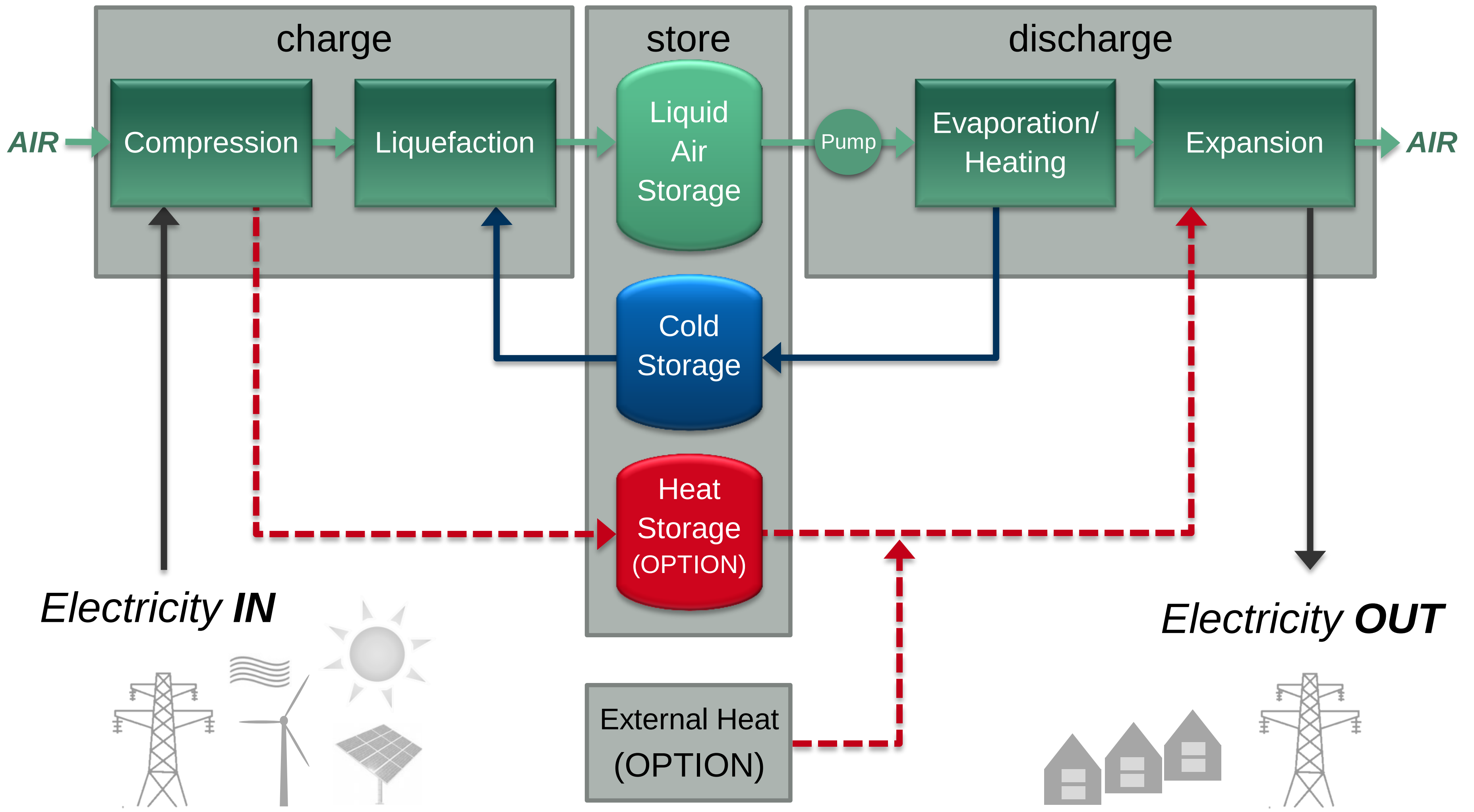
  - few base load RES electricity producers are available
    - hydro power (restricted availability)
    - waste incinerators (partially RES only ⇨ other electricity needed too)
    - electricity from biogas or biomass CHP (expensive)
  - grid services may serve only as an additional income

⇨Economic operation requires external low carbon electricity via grid in most cases

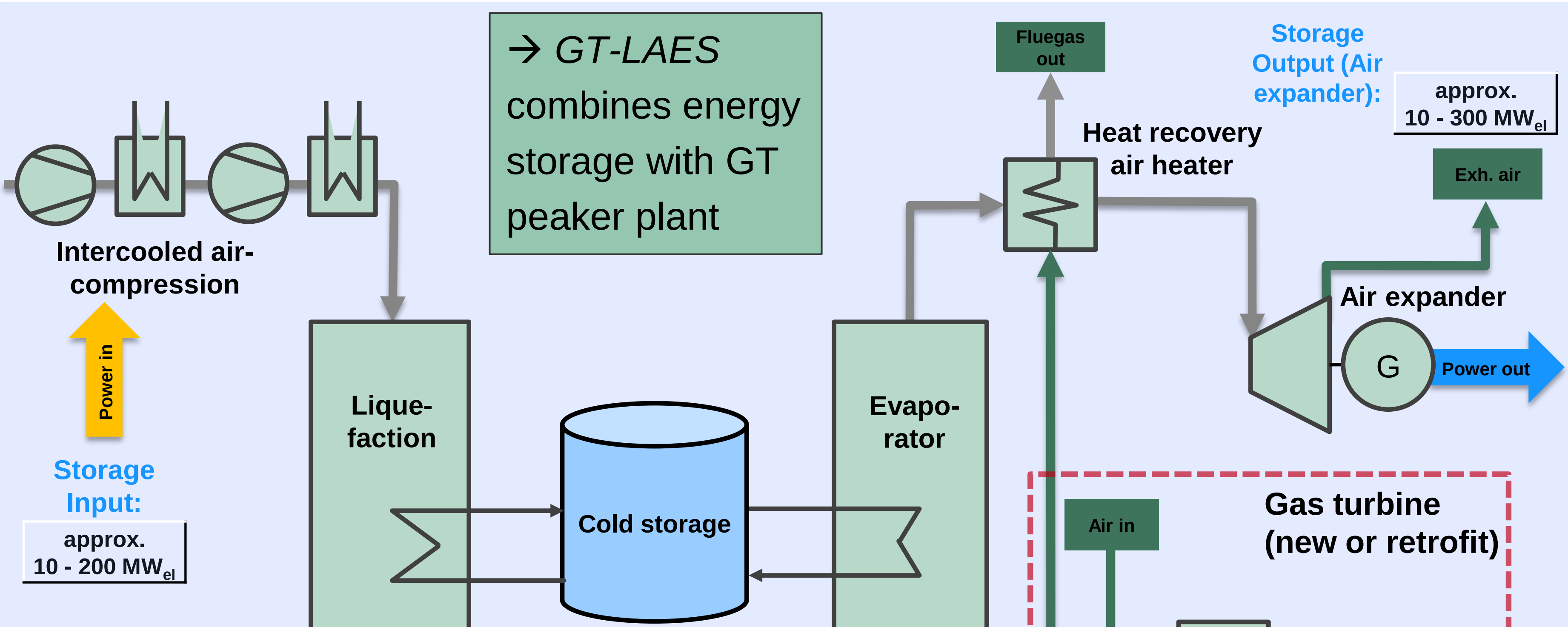
- Power to Methanol is a cross sectoral energy storage
  - avoids curtailment of RES & allows an increased RES installation
  - avoids cost of curtailment, extensive grid refurbishment & electricity storage
  - reduces agricultural land use for biofuels, and
  - reduces emissions in industry, energy and transport sectors
- Power to Methanol can be economically built today at industrial scale (100+kt/year)
- CO_2 capture and PtMeOH are commercially available today
- Reliable boundary conditions for the certification of low carbon fuels are needed
  - GHG savings to be proved case by case, focused on the origin of energy
  - Direct access to certified low carbon electricity is needed to allow a level playing field for investments in different (EU) countries


Source: U.S. Energy Information Administration, based on Energy Storage Association
Day
Discharge Time
Hour
Second
Better for energy management
High Energy Capacitors
Long Duration Flywheels
Batteries
Compressed Air
LAES
Pumped Storage Hydro
High Power Flywheels
High Power Capacitors
Superconducting Magnetic Storage
Better for power quality management
kW
MW
Capacity
GW

LAES – Liquid Air Energy Storage



GT-LAES – Stand-alone or Retrofit based on mature Components



Efficiency:

η_{system} = 81 – 83 %

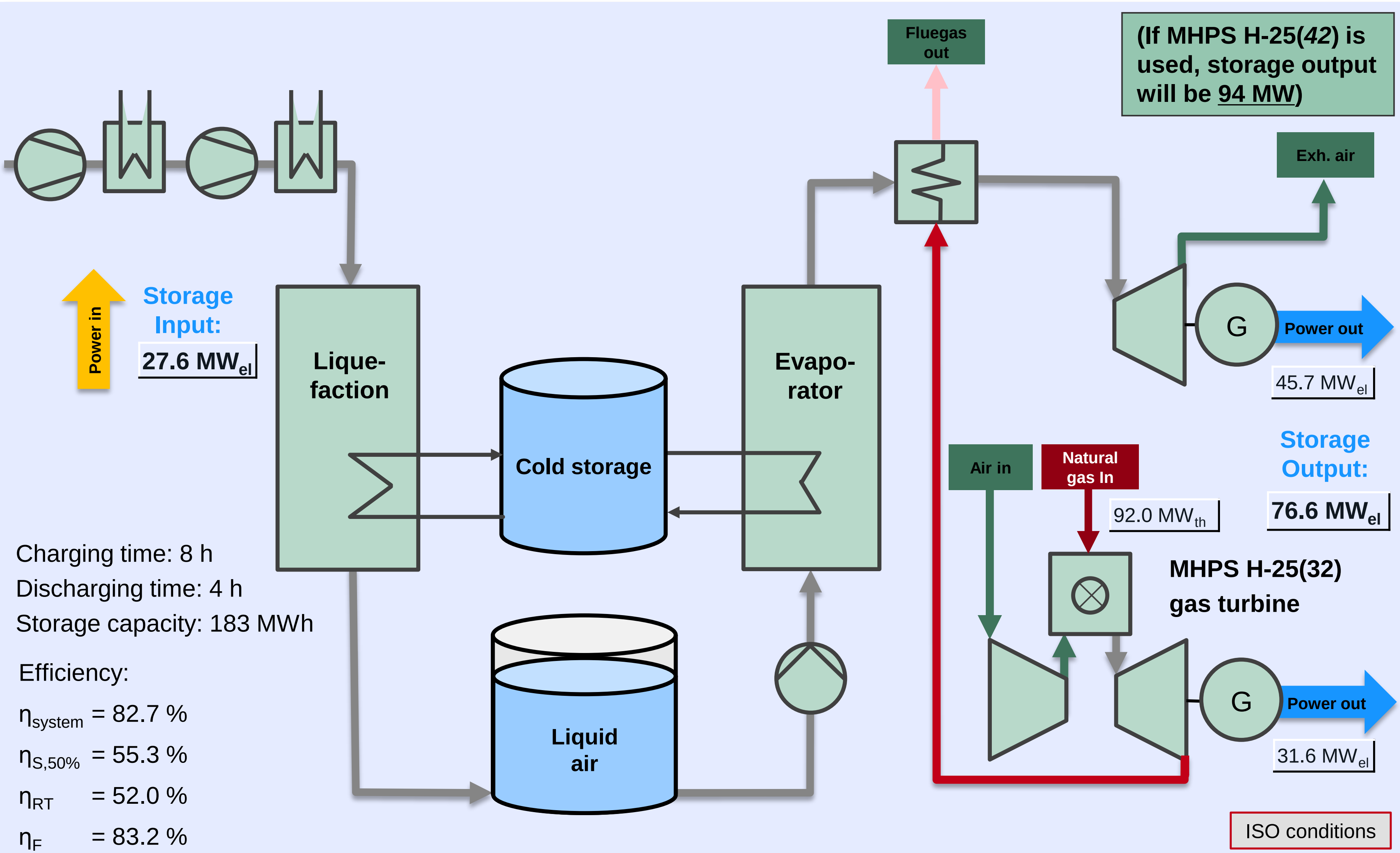
$\eta_{s,50\%}$ = 55 – 67 %

η_{RT} = 52 – 56 %

η_{F} = 83 – 86 %

m_{CO2} < 240 kg/MWh_{el}

LAES Process in Detail – 76 MW GT-LAES with H-25(32) Gas Turbine



Charging time: 8 h

Discharging time: 4 h

Storage capacity: 183 MWh

Efficiency:

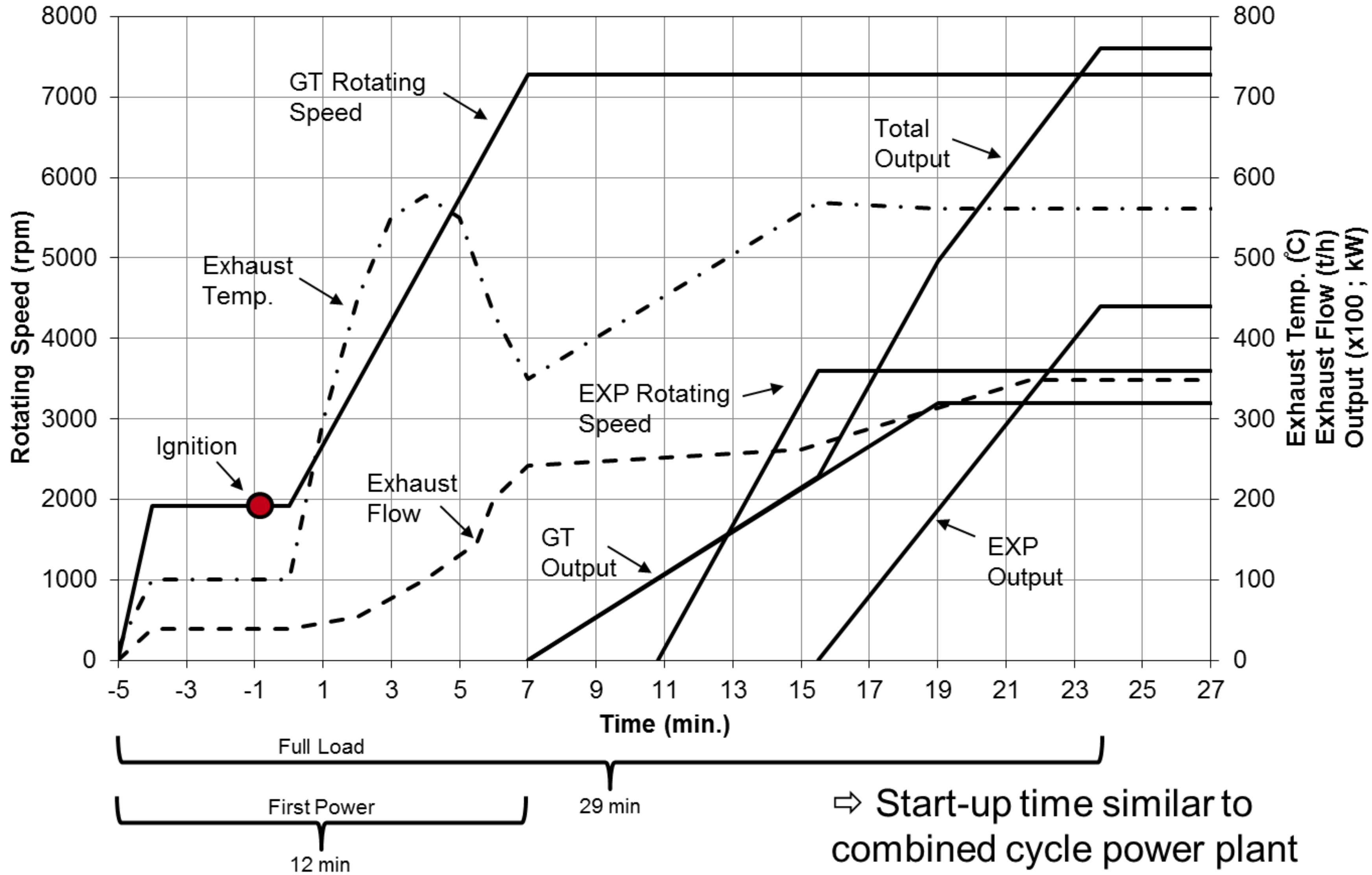
η_{system} = 82.7 %

$\eta_{S,50\%}$ = 55.3 %

η_{RT} = 52.0 %

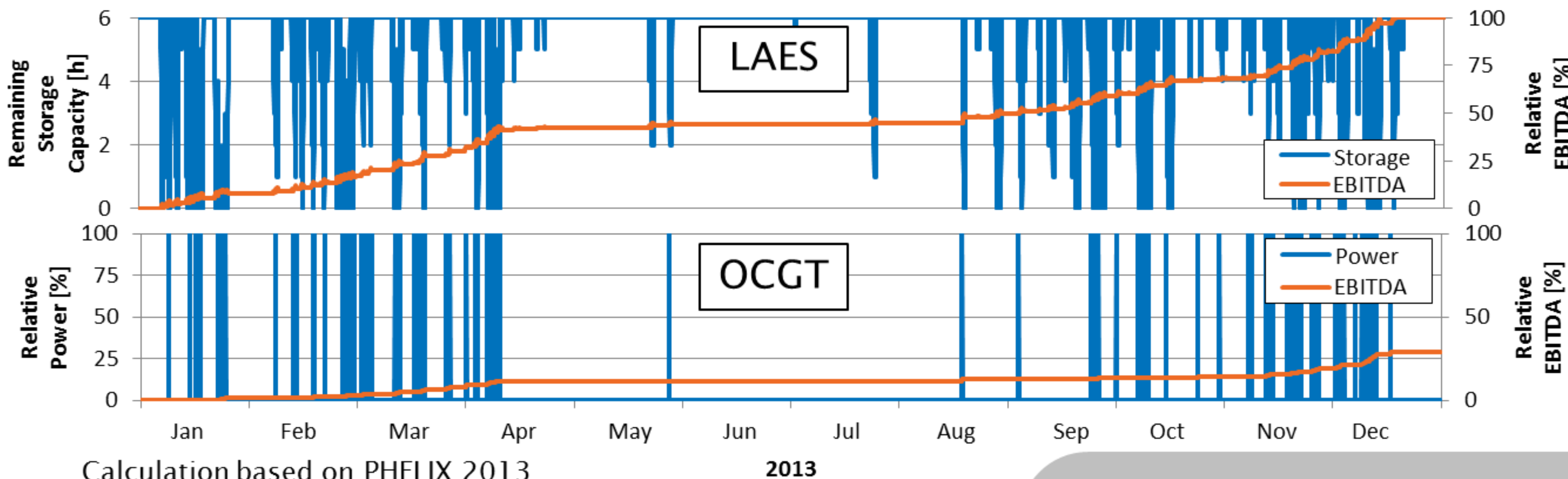
η_{F} = 83.2 %

Start-up of a GT-LAES system



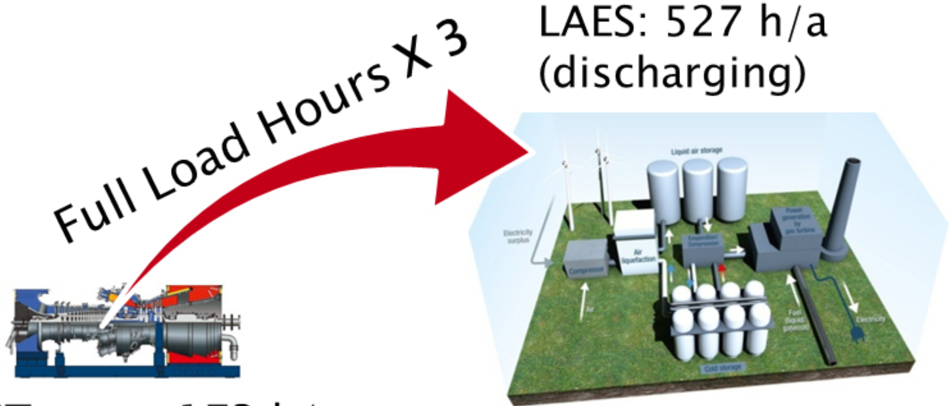
⇨ Start-up time similar to combined cycle power plant

Comparison with an OCGT



Calculation based on PHELIX 2013
and NG price 27 €/MWh

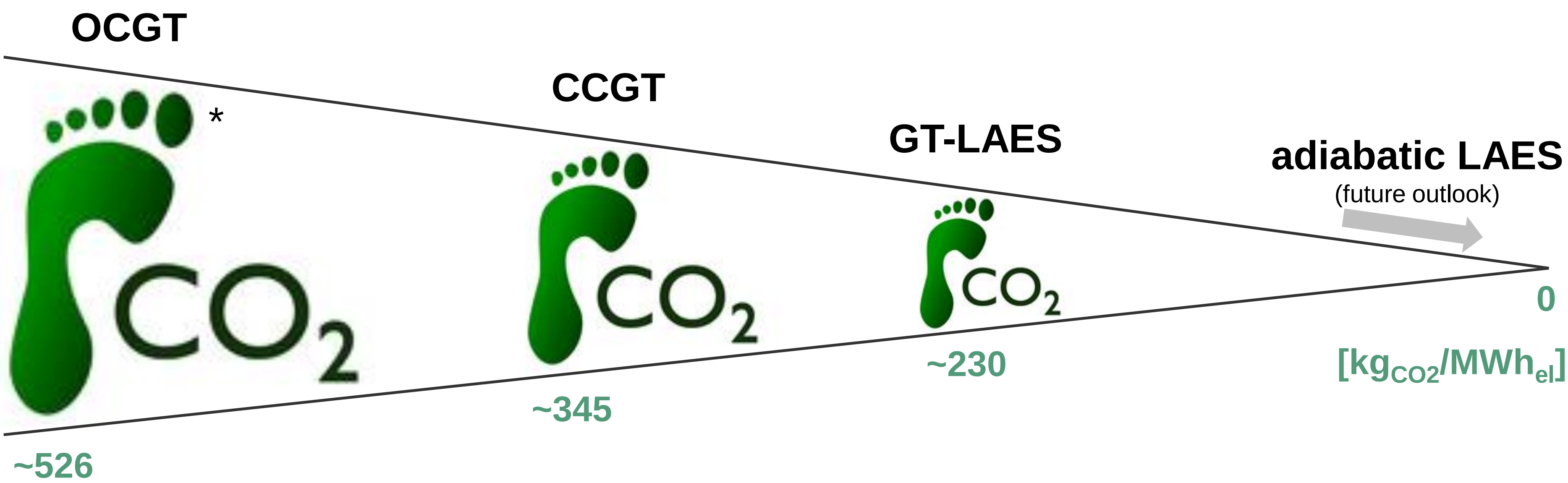
LAES: 527 h/a
(discharging)



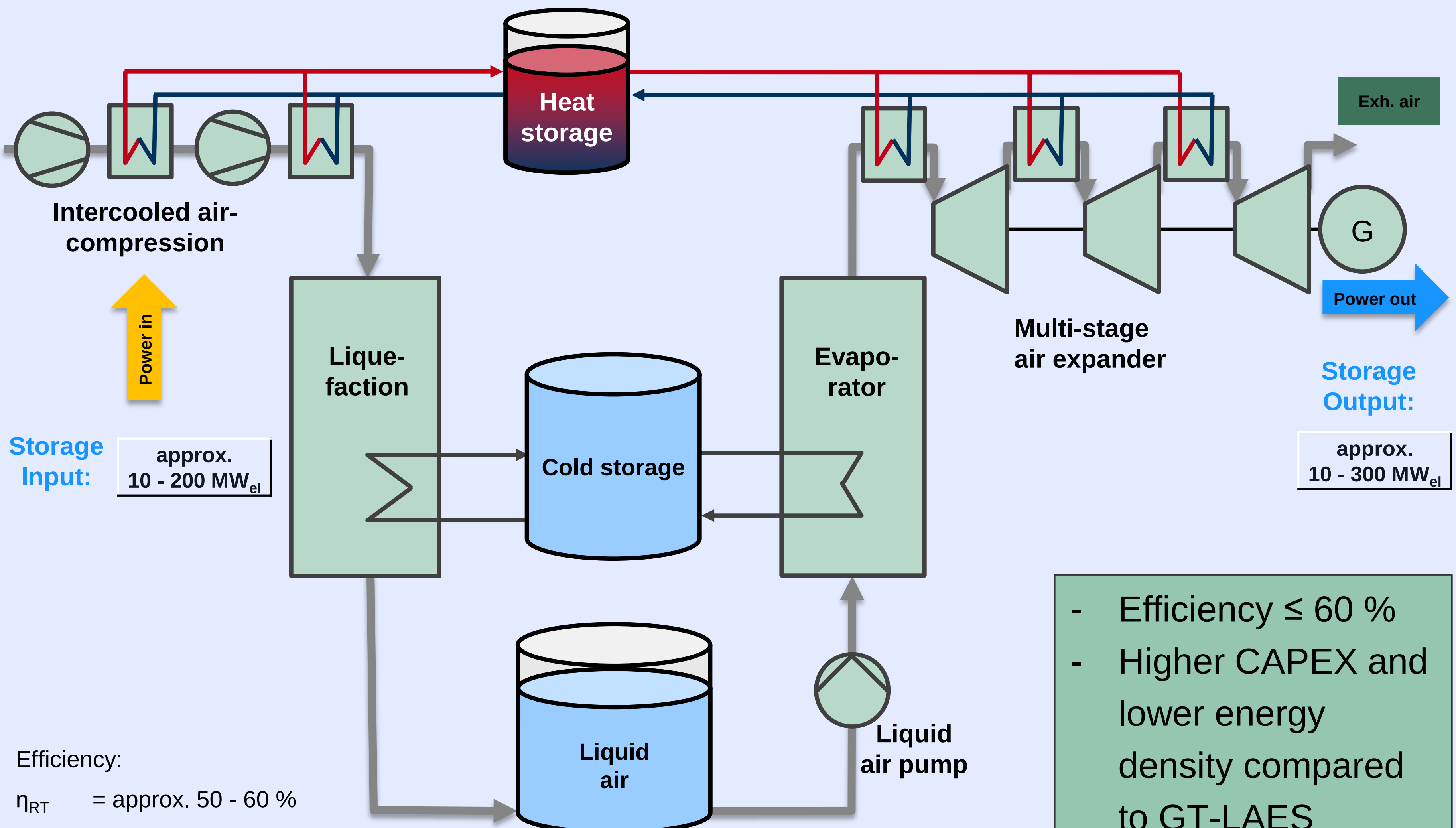
OCGT: max. 173 h/a

All Natural Gas consuming power plants are suffering from **high European gas prices**, compared to relatively low electricity prices. So is LAES with yearly EBITDA in arbitrage business < **1Mio.€**. In addition, **high PV capacity** inhibits economical operation of LAES and OCGT in **peak time hours**, especially in **summer months**.

CO_2-Footprint OCGT / CCGT / LAES



LAES Process in Detail – Adiabatic-LAES

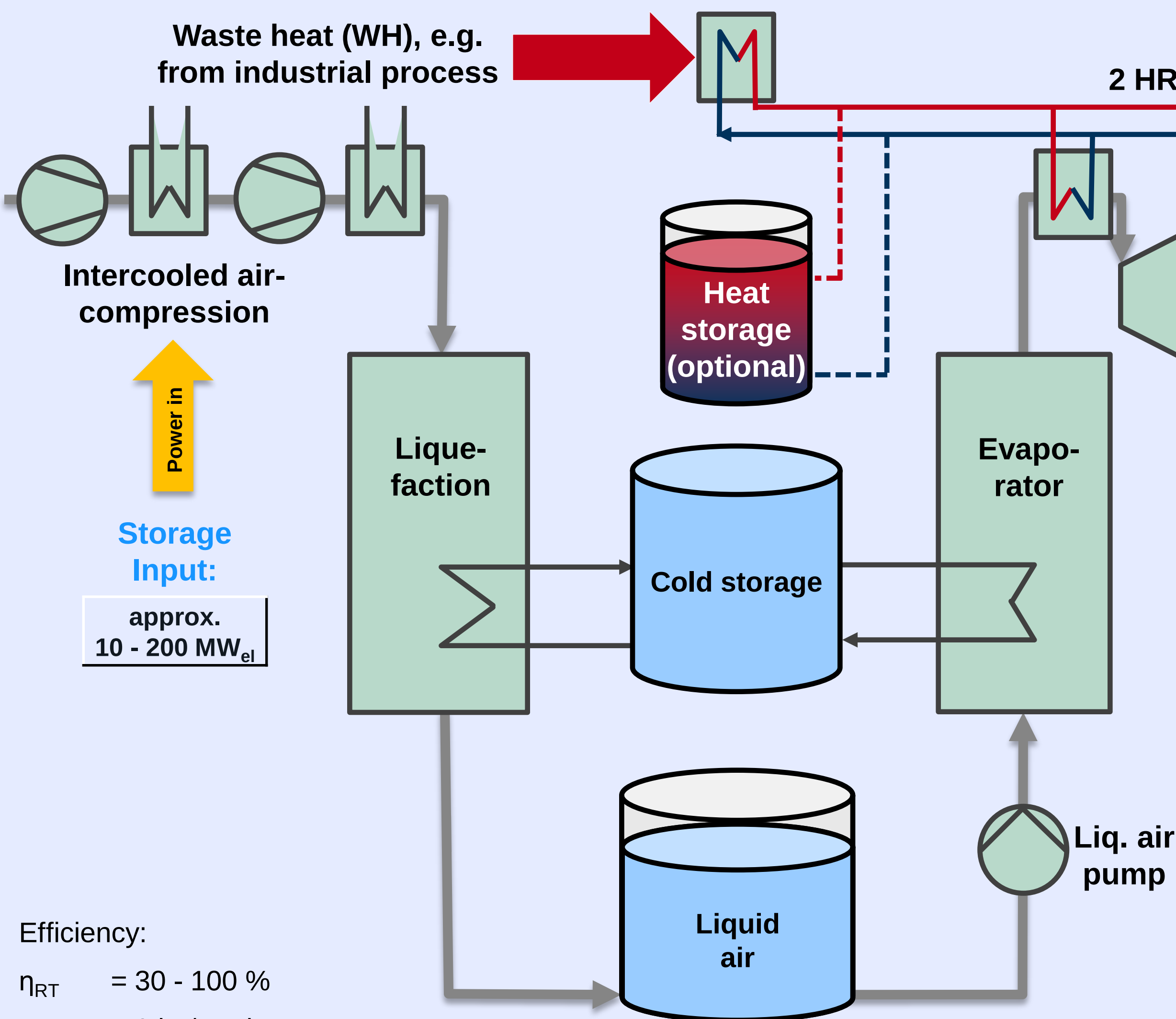


Efficiency:

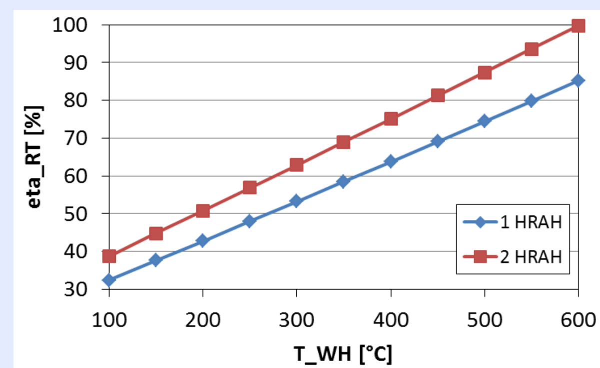
η_{RT} = approx. 50 - 60 %

m_{CO2} = 0 kg/MWh_{el}

- Efficiency ≤ 60 %
- Higher CAPEX and lower energy density compared to GT-LAES



Efficiency dependent on waste heat temperature:

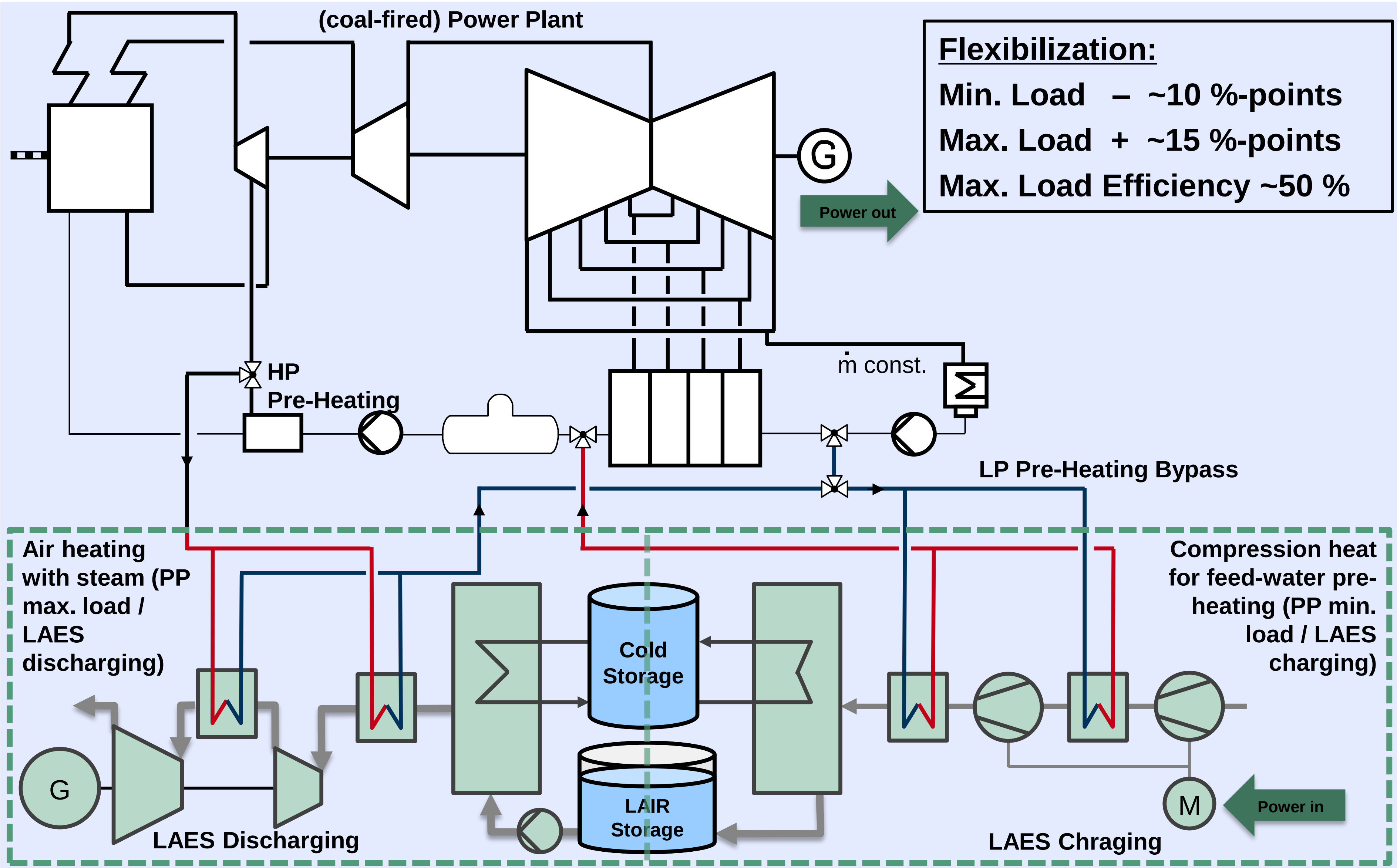


Efficiency:

η_{RT} = 30 - 100 %

m_{CO2} = 0 kg/MWh_{el}

Flex-LAES – Flexibilization of conventional Power Plants

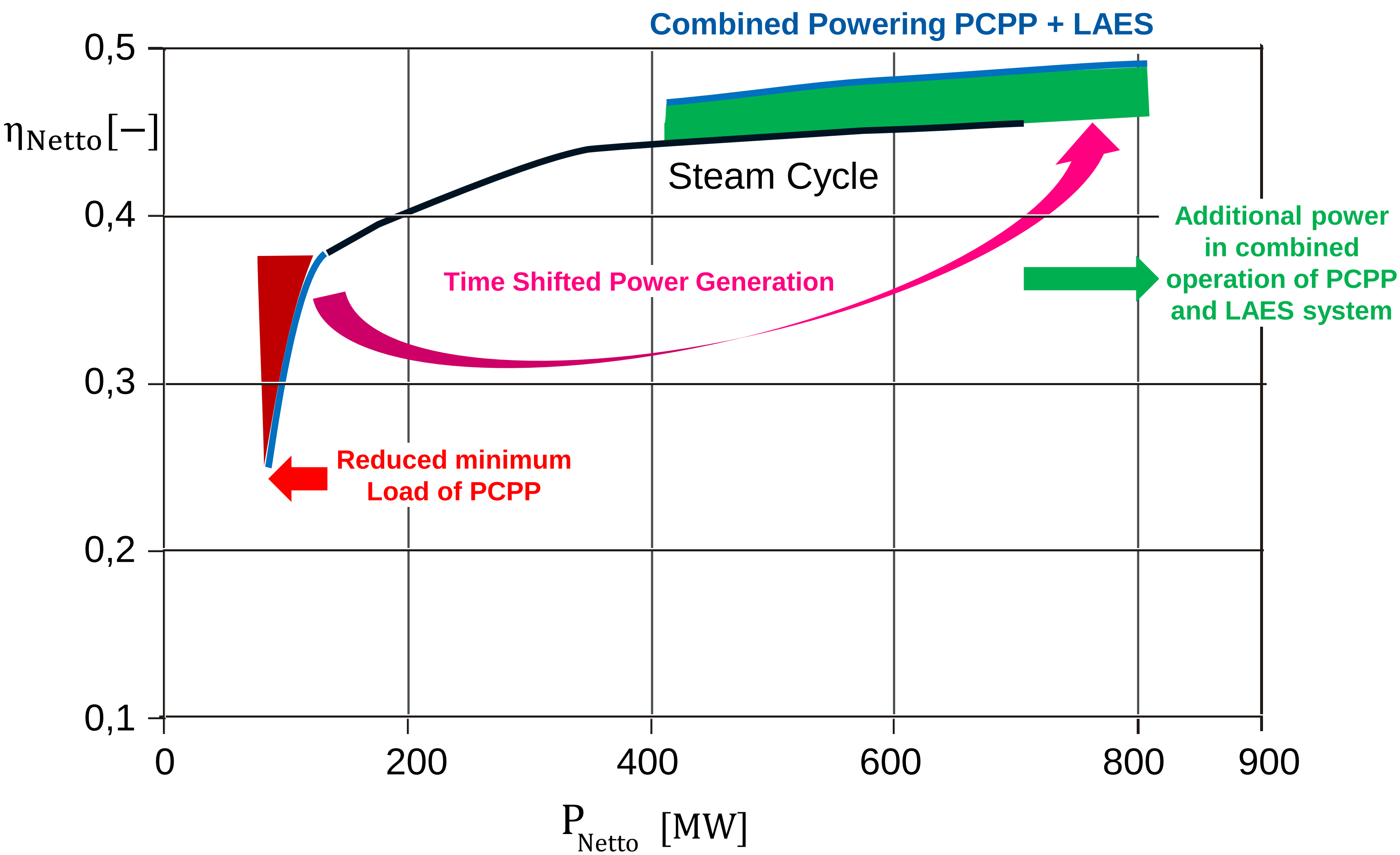


Flexibilization:

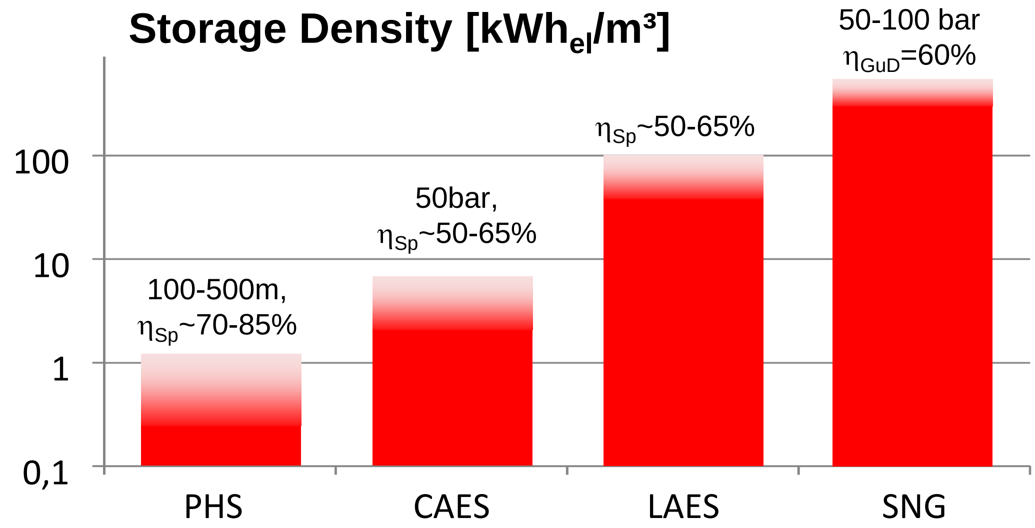
Min. Load – ~10 %-points

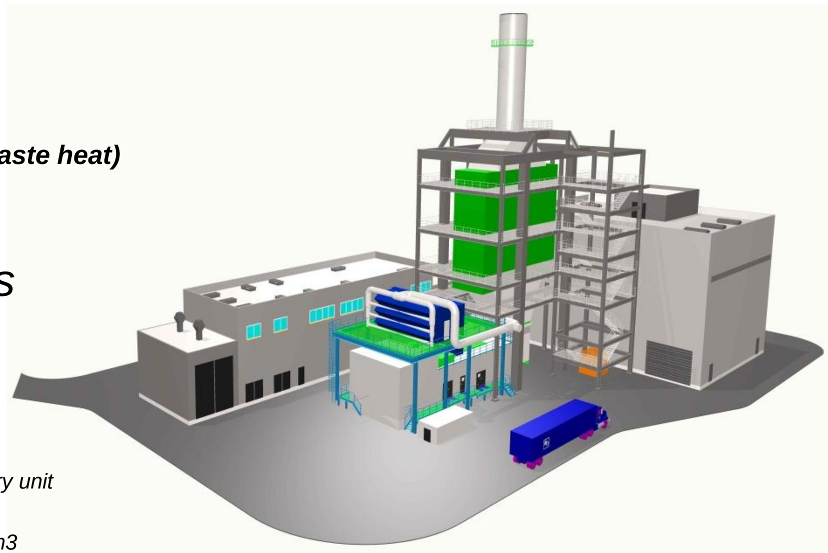
Max. Load + ~15 %-points

Max. Load Efficiency ~50 %


Combined Powering PCPP + LAES
0,5
0,4
0,3
0,2
0,1
η Netto [−]
Steam Cycle
Additional power in combined operation of PCPP and LAES system
Time Shifted Power Generation
Reduced minimum Load of PCPP
0
200
400
600
800
900
P Netto [MW]

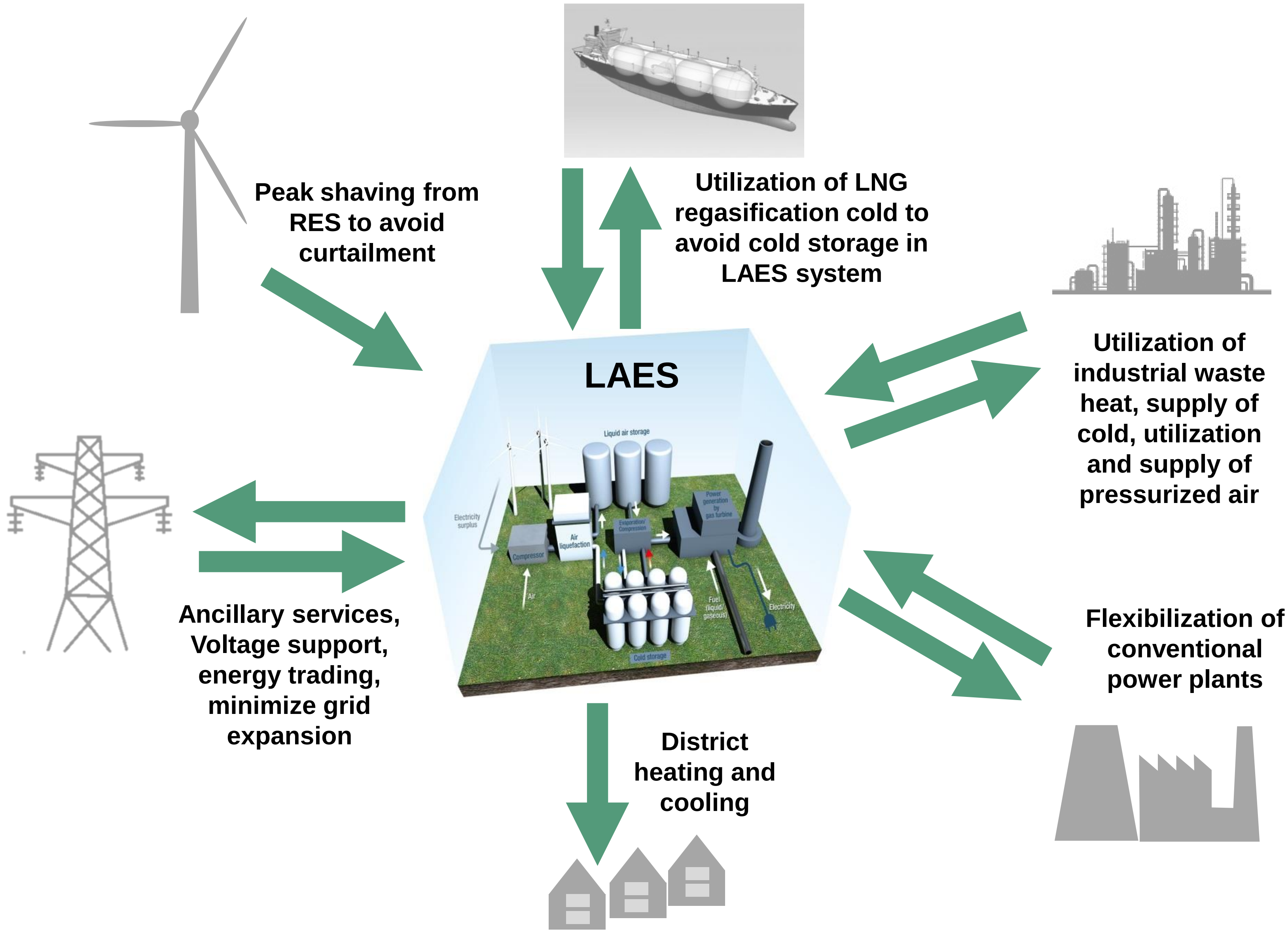
- Energy Density:
  70 – 100 kWh/m3
- Power output:
  10 – 600 MW
- Storage Capacity:
  > 1000 MWh
- Discharging duration:
  2 – 12 h
- Efficiency:
  50 – 65 %
  (>65 % by utilizing waste heat)
- Lifetime:
  20 – 30 years



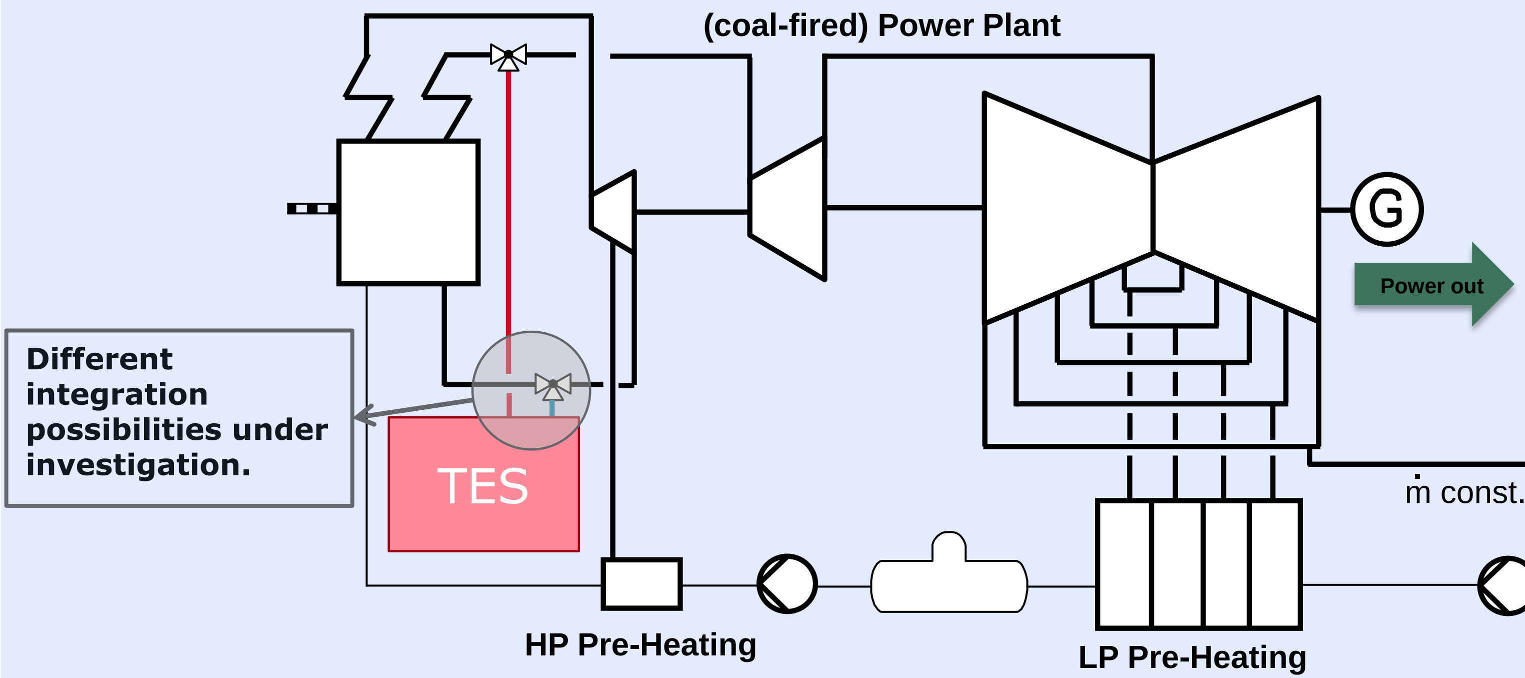


Pictures:
1) 3D plot of LAES power recovery unit (MHPSE)
2) Cryogenic storage tank 1600 m3 (Source: The Linde Group)

LAES – Integration Capabilities



Thermal Energy Storage (TES) for flexible Operation of fossile Power Plants



- TES can be integrated in the steam cycle to shift heat (power generation) from times of low electricity prices to times high el. prices
- Storage medium can be PCM (Phase Change Material), molten salt, thermal oil, solid material, or pressurized water

- The necessity of extreme over installation of RES to reach the target of 80% of renewable supply of electric energy must lead to a new market regulation
- Power to Methanol is a cross-sectorial technology for energy storage integrating mobility in the power plant technology
- Methanol production improves utilization of energy rich off-gases from industry and provides high value creation
- LAES is an hybrid storage technology for bulk electricity storage with a round-trip-efficiency of up to 65 % and a high storage density (Storage & Back-up Power)
- Integrating a TES into the steam cycle of a power plant increases the flexibility of operating conditions
- Power plants become more flexible and profitable by integrating the three concepts
- The three technologies are available, proven and ready for deployment

Power for a Brighter Future

Back-up

System Efficiency:

$$\eta_{system} = \frac{\text{Air Expander Output}}{\text{Compressor Input}}$$

Storage Efficiency:

$$\eta_{s,50\%} = \frac{\text{LAES Output} - \eta_{NG} \cdot \text{Gas Input}}{\text{Compressor Input}}$$

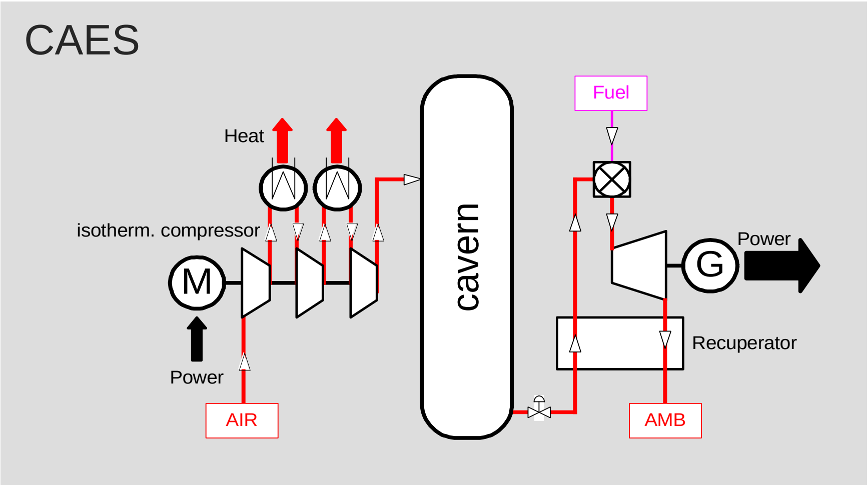
Round-trip Efficiency:

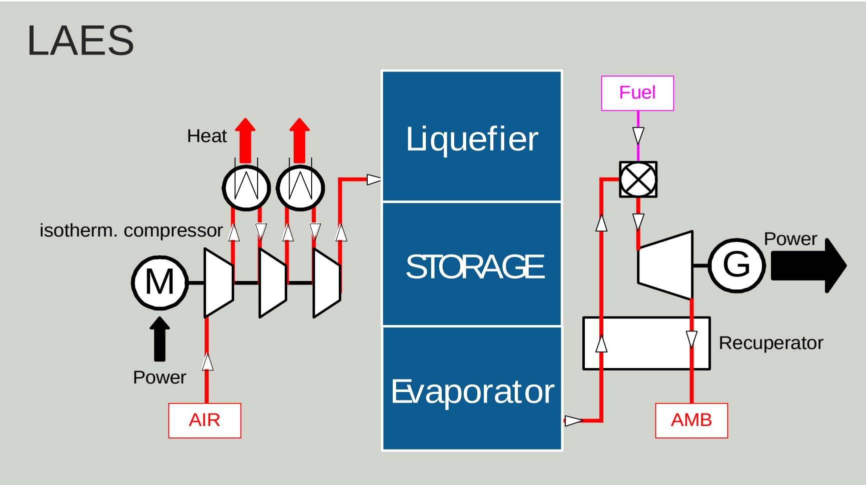
$$\eta_{RT} = \frac{\text{LAES Output}}{\text{Compressor Input} + \text{Gas Input}}$$

Fuel Efficiency:

$$\eta_{F} = \frac{\text{LAES Output}}{\text{Gas Input}}$$

LAES - Comparison to CAES





	Huntorf CAES	McIntosh CAES	GT-LAES Technology (4h dis.) (H25(32) / H80 / M501JAC)
Capacity, MWh	480	1060	304 / 1004 / 2564 *
Power-Output, MW	321	110	76 / 251 / 641 *
Round trip efficiency, %	42	54	52 / 54 / 56
Storage volume, m^3	310 000	538 000	1 900 / 6 000 / 11 300 **
Storage density, kWh/m^3	**1.55**	**1.97**	**160 / 167 / 227**

Source: The Linde Group

Time-factor (Charging-/Discharging-time): Huntorf 4 / McIntosh 1.6 / LAES 2 (variable)

* GT power incl.
** LAIR