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Research Councils UK
Energy
For a Low Carbon Future

INTEGRATED, MARKET-FIT AND AFFORDABLE GRID-SCALE ENERGY STORAGE

WARWICK
THE UNIVERSITY OF WARWICK

The University of Nottingham

Loughborough University

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

http://integratedenergystorage.org/

What we aim to achieve

Economic analysis:

- to reveal the multi-dimensional true values of energy storage
- to identify the way for maximising the value of energy storage

Network analysis:

- to clarify the role of energy storage from demand and supply balance
- to exam network operation rule for energy storage integration

Techno-economic-network analysis:

- to derive a matrix of performance/cost of energy storage
- to examine technical characteristics for network integration

To provide essential information to government policy makers and regulation bodies

To support UK industry for technology development

What we aim to achieve

Technology breakthrough – CAES:

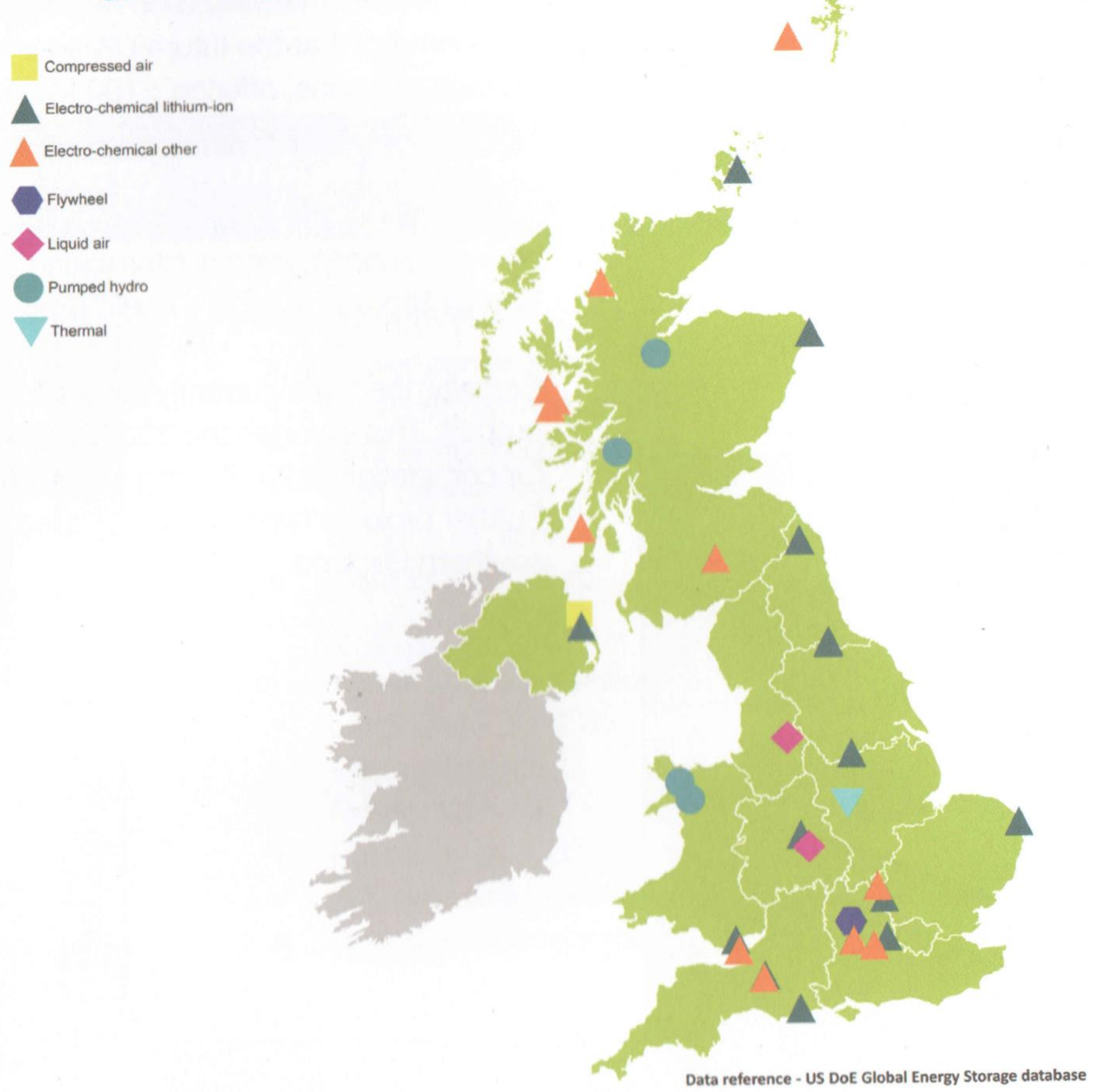
- to avoid involvement of fossil fuel
- to improve the round trip efficiency
- to gain a clear picture of national storage resources
- to study the methodology of engineering storage
- to map the storage with the renewable power generation locations

Technology innovation:

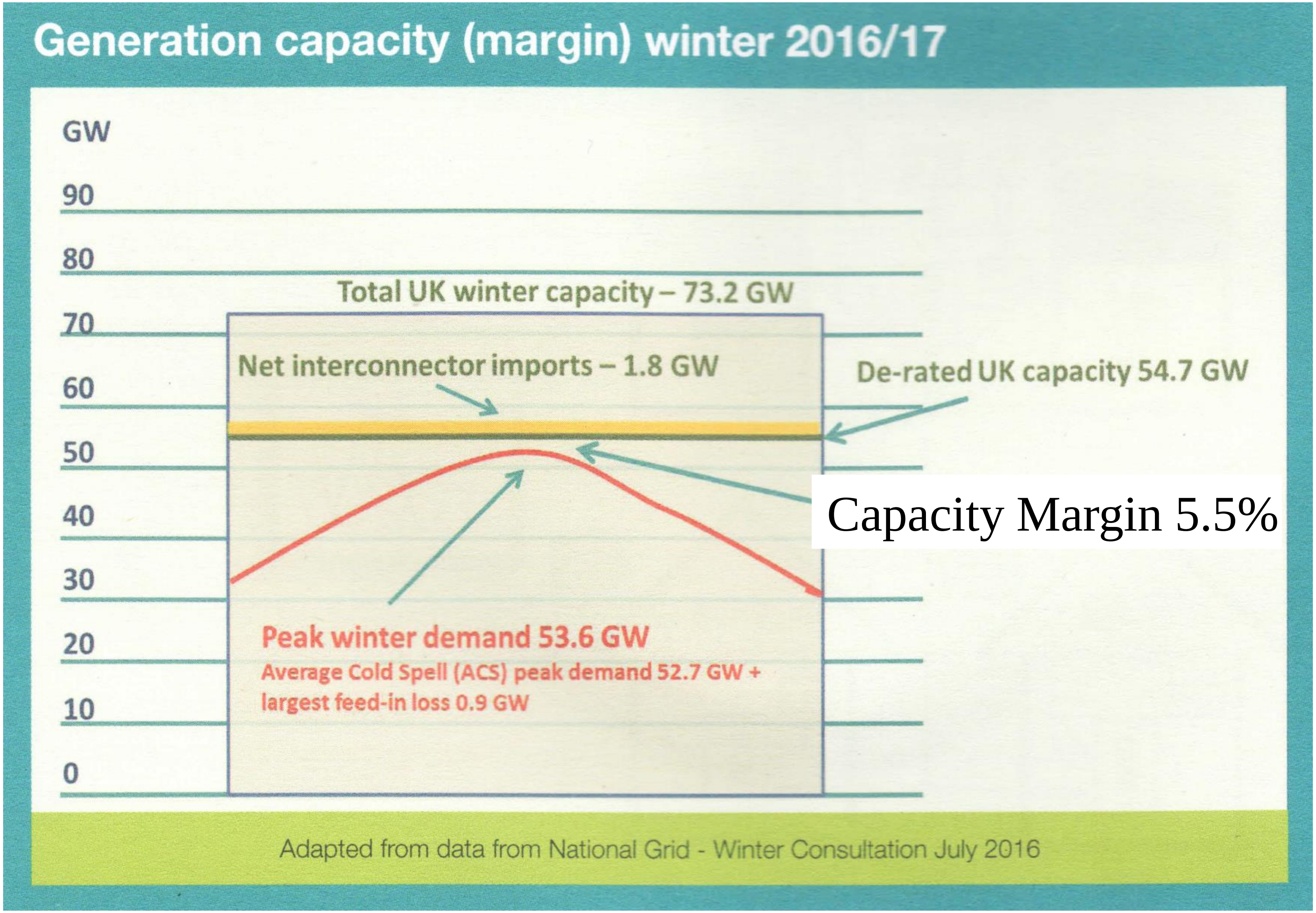
- to research innovative HTTS technology
- to find the cheap materials for HTTS
- to improve energy efficiency by direct conversion
- to develop innovative technology for combination of CAES and HTTS

Technology for potential deployment

Energy storage projects in the UK



Data reference - US DoE Global Energy Storage database



Generation capacity (margin) winter 2016/17

Adapted from data from National Grid - Winter Consultation July 2016

Capacity Margin 5.5%

Driving for Flexibility

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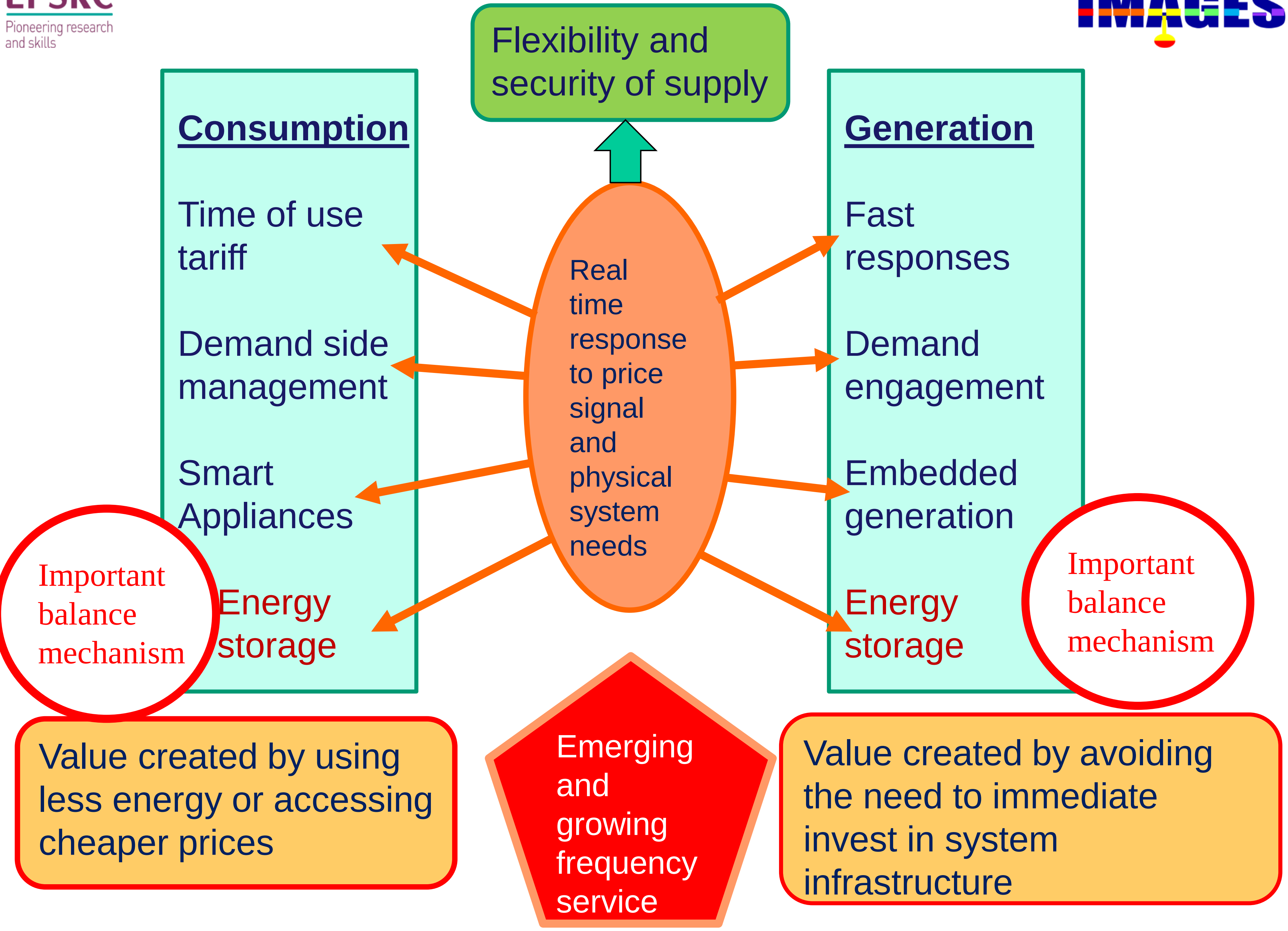


Flexibility and security of supply

Consumption

Time of use tariff

Demand side management

Smart Appliances

Energy storage

Real time response to price signal and physical system needs

Generation

Fast responses

Demand engagement

Embedded generation

Energy storage

Important balance mechanism

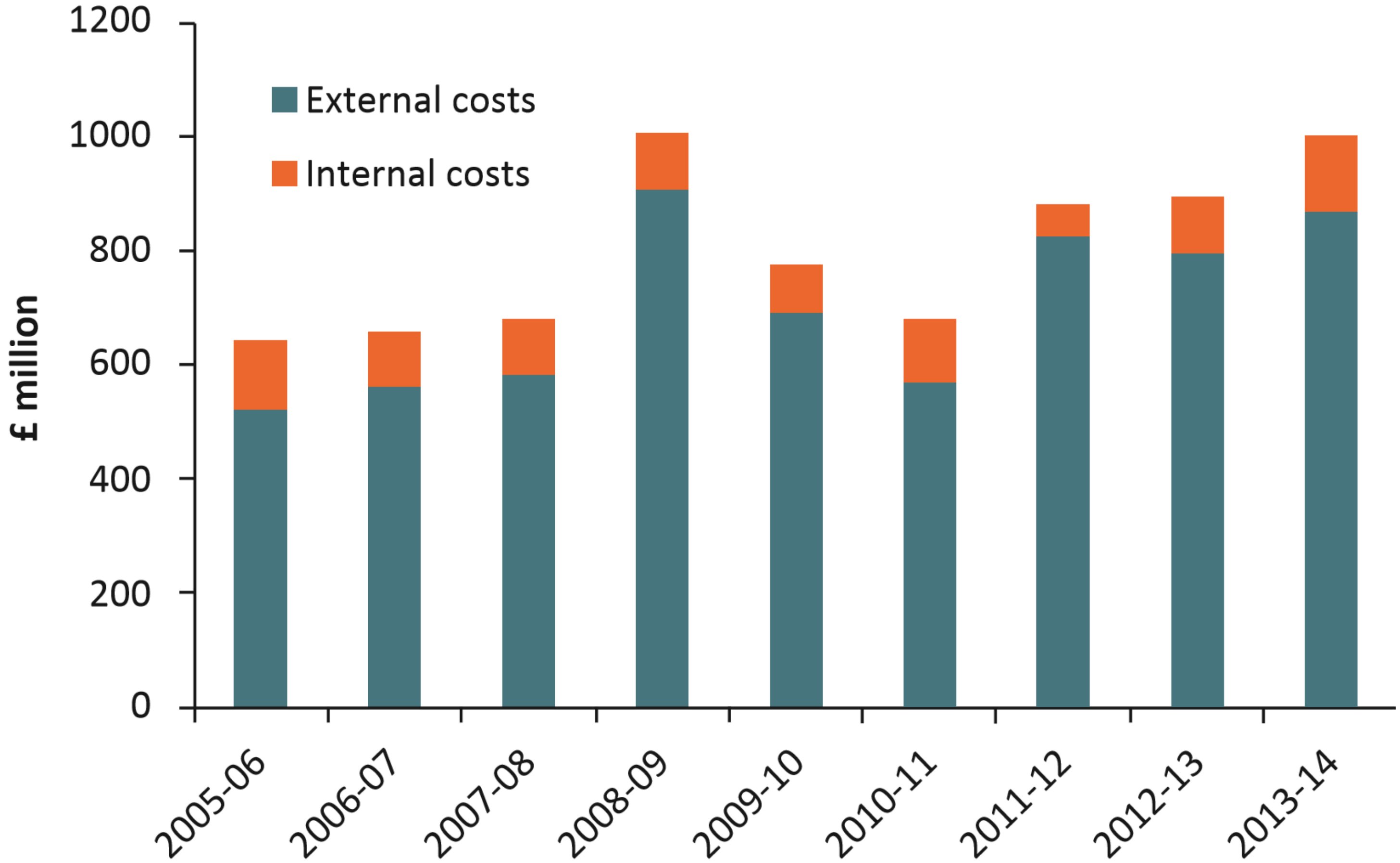
Important balance mechanism

Value created by using less energy or accessing cheaper prices

Emerging and growing frequency service

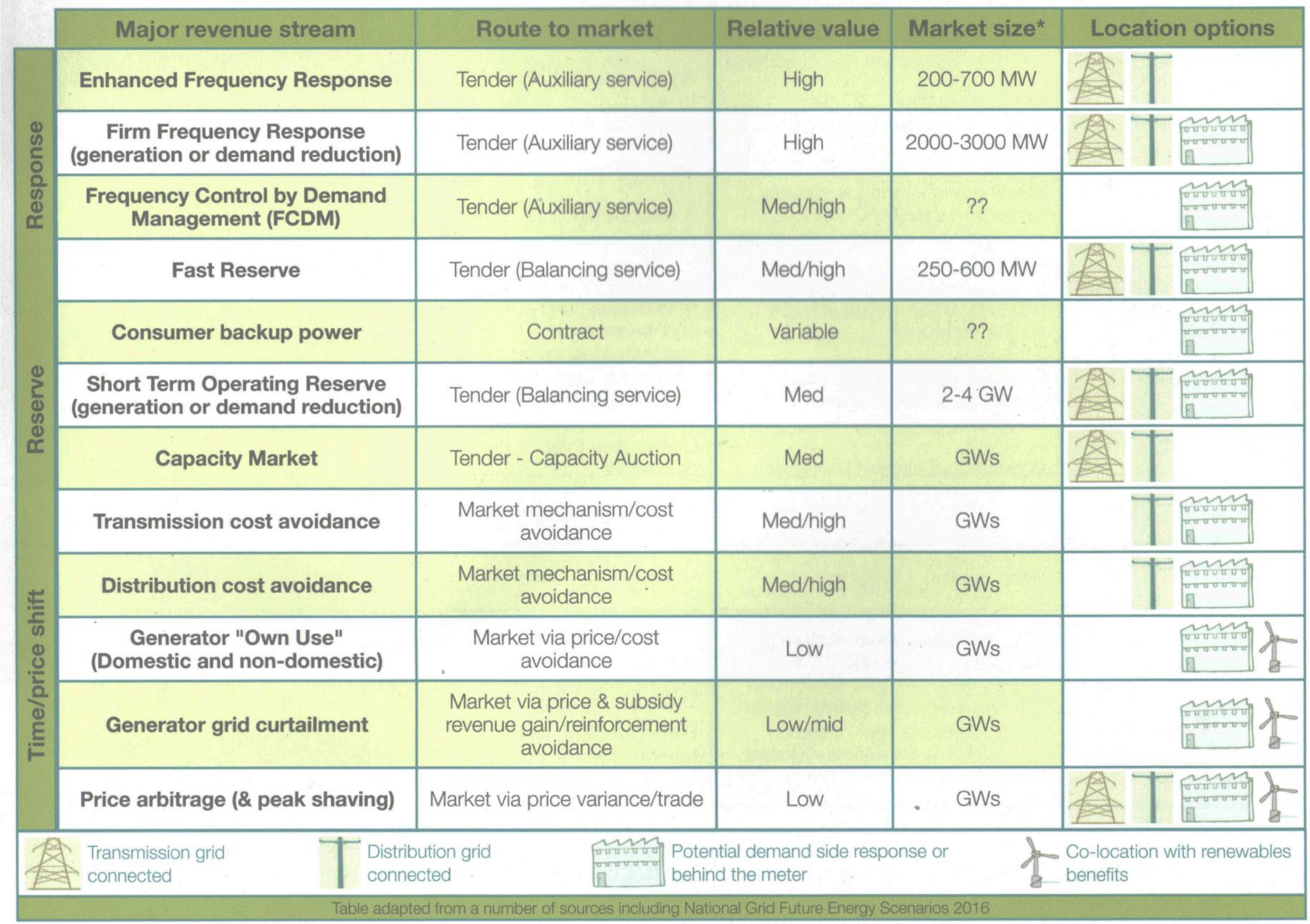
Value created by avoiding the need to immediate invest in system infrastructure

Figure 2.10: Total cost of balancing services[54]



From Power 2.0, by Richard Howard and Zoe Bengherbi

Potential revenues streame (report by REGENSW)



	Major revenue stream	Route to market	Relative value	Market size*	Location options
Response	Enhanced Frequency Response	Tender (Auxiliary service)	High	200-700 MW	🗼 ⊤
	Firm Frequency Response (generation or demand reduction)	Tender (Auxiliary service)	High	2000-3000 MW	🗼 ⊤ 🏭
	Frequency Control by Demand Management (FCDM)	Tender (Auxiliary service)	Med/high	??	🏭
Reserve	Fast Reserve	Tender (Balancing service)	Med/high	250-600 MW	🗼 ⊤ 🏭
	Consumer backup power	Contract	Variable	??	🏭
	Short Term Operating Reserve (generation or demand reduction)	Tender (Balancing service)	Med	2-4 GW	🗼 ⊤ 🏭
	Capacity Market	Tender - Capacity Auction	Med	GWs	🗼 ⊤
Time/price shift	Transmission cost avoidance	Market mechanism/cost avoidance	Med/high	GWs	⊤ 🏭
	Distribution cost avoidance	Market mechanism/cost avoidance	Med/high	GWs	⊤ 🏭
	Generator "Own Use" (Domestic and non-domestic)	Market via price/cost avoidance	Low	GWs	🏭 🌬
	Generator grid curtailment	Market via price & subsidy revenue gain/reinforcement avoidance	Low/mid	GWs	🏭 🌬
	Price arbitrage (& peak shaving)	Market via price variance/trade	Low	GWs	🗼 ⊤ 🏭 🌬

🗼 Transmission grid connected

⊤ Distribution grid connected

🏭 Potential demand side response or behind the meter

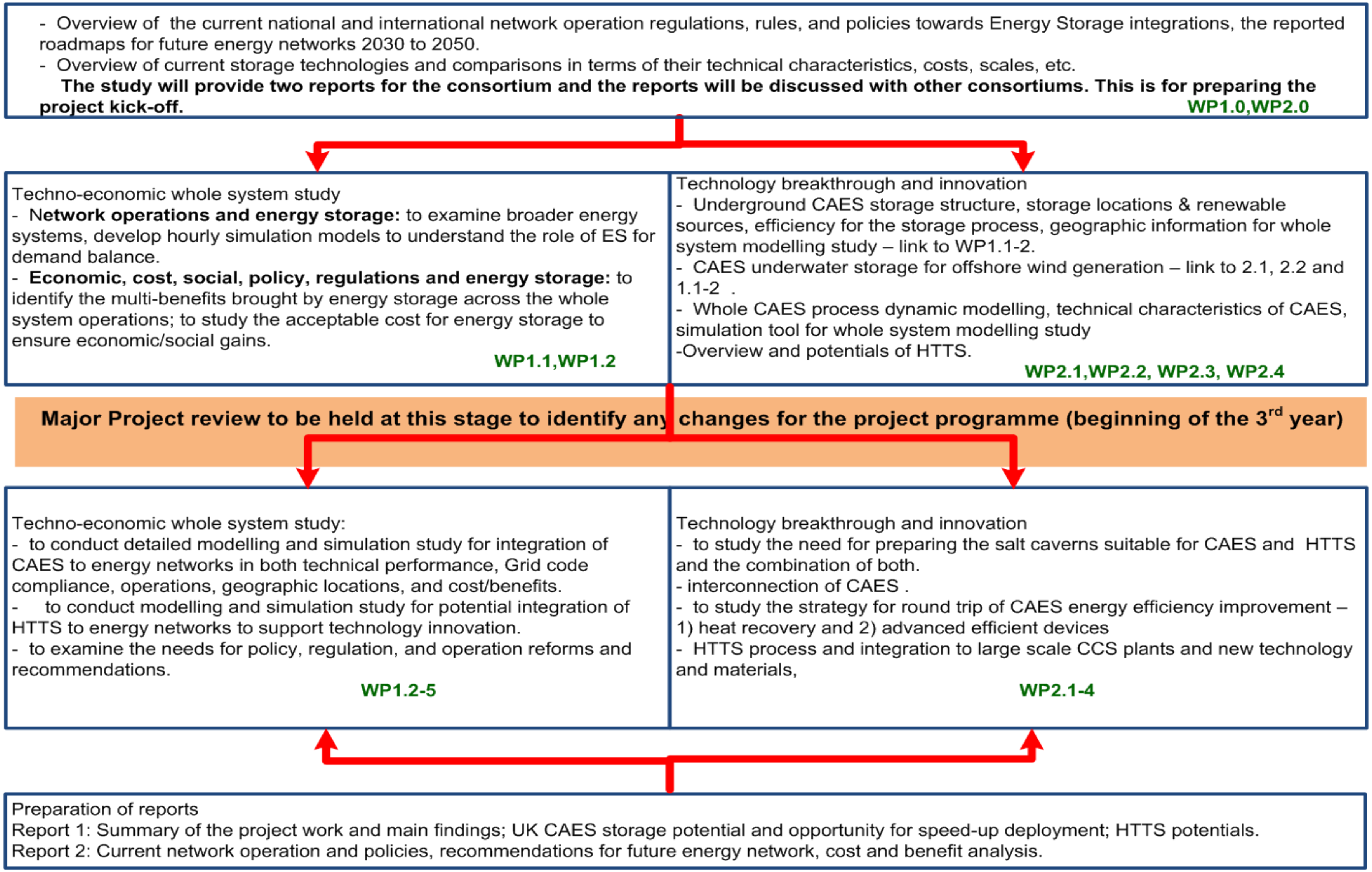
🌬 Co-location with renewables benefits

Table adapted from a number of sources including National Grid Future Energy Scenarios 2016

From the study conducted by REGENSW, it is predicted:

- A market growth projection towards an UK energy storage sector in excess of 10 GW power capacity in the 2030’s is achievable.
- In the short term battery storage projects will lend to focus on higher value rapid response and targeted network cost avoidance revenue stream. In the next decade, reserve and time/price shift solutions will become viable.
- Large scale energy storage such as compressed air energy storage will play an important role in offering reserve and balance service.
- High energy user – cost avoidance “behand the meter” is the most immediately attractive.

Our Methodology and Programme



- Overview of the current national and international network operation regulations, rules, and policies towards Energy Storage integrations, the reported roadmaps for future energy networks 2030 to 2050.
- Overview of current storage technologies and comparisons in terms of their technical characteristics, costs, scales, etc.

The study will provide two reports for the consortium and the reports will be discussed with other consortiums. This is for preparing the project kick-off.

WP1.0,WP2.0

Techno-economic whole system study

- **Network operations and energy storage:** to examine broader energy systems, develop hourly simulation models to understand the role of ES for demand balance.
- **Economic, cost, social, policy, regulations and energy storage:** to identify the multi-benefits brought by energy storage across the whole system operations; to study the acceptable cost for energy storage to ensure economic/social gains.

WP1.1,WP1.2

Technology breakthrough and innovation

- Underground CAES storage structure, storage locations & renewable sources, efficiency for the storage process, geographic information for whole system modelling study – link to WP1.1-2.
- CAES underwater storage for offshore wind generation – link to 2.1, 2.2 and 1.1-2 .
- Whole CAES process dynamic modelling, technical characteristics of CAES, simulation tool for whole system modelling study
- Overview and potentials of HTTS.

WP2.1,WP2.2, WP2.3, WP2.4

Major Project review to be held at this stage to identify any changes for the project programme (beginning of the 3rd year)

Techno-economic whole system study:

- to conduct detailed modelling and simulation study for integration of CAES to energy networks in both technical performance, Grid code compliance, operations, geographic locations, and cost/benefits.
- to conduct modelling and simulation study for potential integration of HTTS to energy networks to support technology innovation.
- to examine the needs for policy, regulation, and operation reforms and recommendations.

WP1.2-5

Technology breakthrough and innovation

- to study the need for preparing the salt caverns suitable for CAES and HTTS and the combination of both.
- interconnection of CAES .
- to study the strategy for round trip of CAES energy efficiency improvement – 1) heat recovery and 2) advanced efficient devices
- HTTS process and integration to large scale CCS plants and new technology and materials,

WP2.1-4

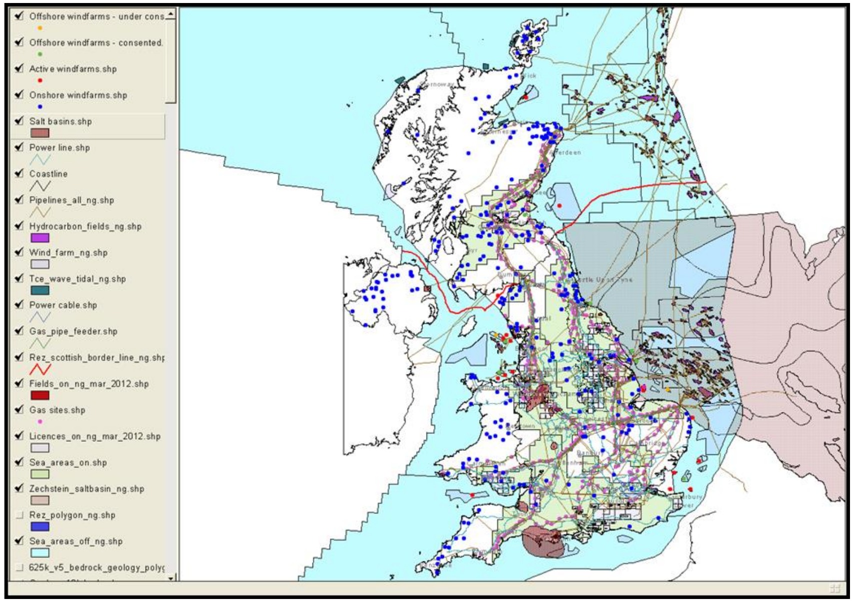
Preparation of reports

Report 1: Summary of the project work and main findings; UK CAES storage potential and opportunity for speed-up deployment; HTTS potentials.

Report 2: Current network operation and policies, recommendations for future energy network, cost and benefit analysis.

Our Work 1: UK Underground CAES Capacity

- A review of underground gas storage operational parameters is progressing well, with the **salt cavern storage facilities l**argely reviewed and relevant facility designs and operational parameters tabulated.
- A project **GIS (Geologic Information System)** has been constructed and populated with relevant databases relating to boreholes, main geological formations, main saltfields with thickness and depth to top and base main halite formations, oil and gas fields, cultural data including pipelines, renewable sites etc.
- Reviews of **salt cavern hosted gas storage, hydrogen and CAES facilities** (both in the UK and overseas) has been undertaken, with key factors and variables collated for each operational facility or proposed site.



Our Work 1: UK Underground CAES Capacity

Survey the salt field in the UK

↓

Estimate the volume of craven formation

↓

Estimate the exergy of compressed air stored under assumptions

$$\Delta m = (\rho_2 - \rho_1)V_C$$

$$\begin{cases} \rho_2 = P_2/(RT_2), & z = 1 \\ \rho_2 = P_2/(zRT_2), & z = z(P,T) \end{cases}$$

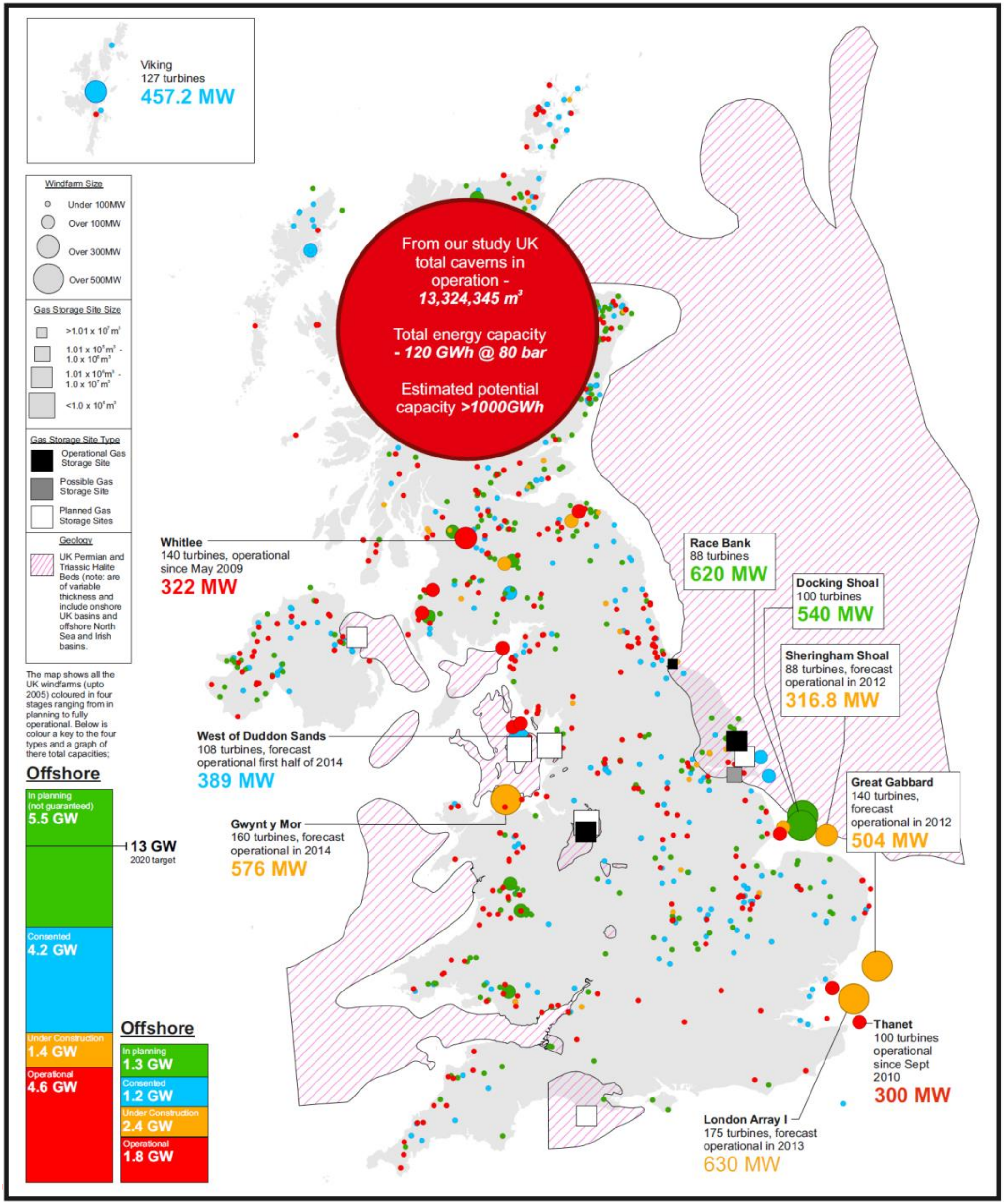
$$\dot{E} = \dot{m}[h - h_0 - T_0(s - s_0)]$$

$$h - h_0 = c_p(T - T_0)$$

$$s - s_0 = c_p \ln(T/T_0) - R\ln(P/P_0)$$

$$E_{store} = \int_{Charging} \dot{E}dt = E_2 - E_1$$

$$= P_0 V_C [(\frac{P_H}{P_0}\ln(\frac{P_H}{P_0}) - \frac{P_H}{P_0}) - (\frac{P_L}{P_0}\ln(\frac{P_L}{P_0}) - \frac{P_L}{P_0})]/z$$



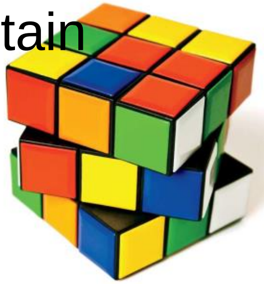
From our study UK total caverns in operation - ***13,324,345 m³***

Total energy capacity ***- 120 GWh @ 80 bar***

Estimated potential capacity ***>1000GWh***

Development of a suite of detailed, customisable algorithms through which to evaluate storage outcomes

- Outcomes can be evaluated in terms of profit maximisation through arbitrage, smoothing optimisation and other possibilities
- The model can be customised with respect to input and output efficiencies, storage capacity, input and output flow ratings, and the extent to which greater operation of the store impacts on the market itself (through for example, the prices obtainable).
- This enables a store to be tailored for a particular use, once factors such as a time series of prices/ quantities is inputted.
- The output includes (in the profit max case) not only potential earnings but also required “look ahead” times, which can act as a check on expected outcomes.
- Hence it moves away from the common assumption of certain future prices



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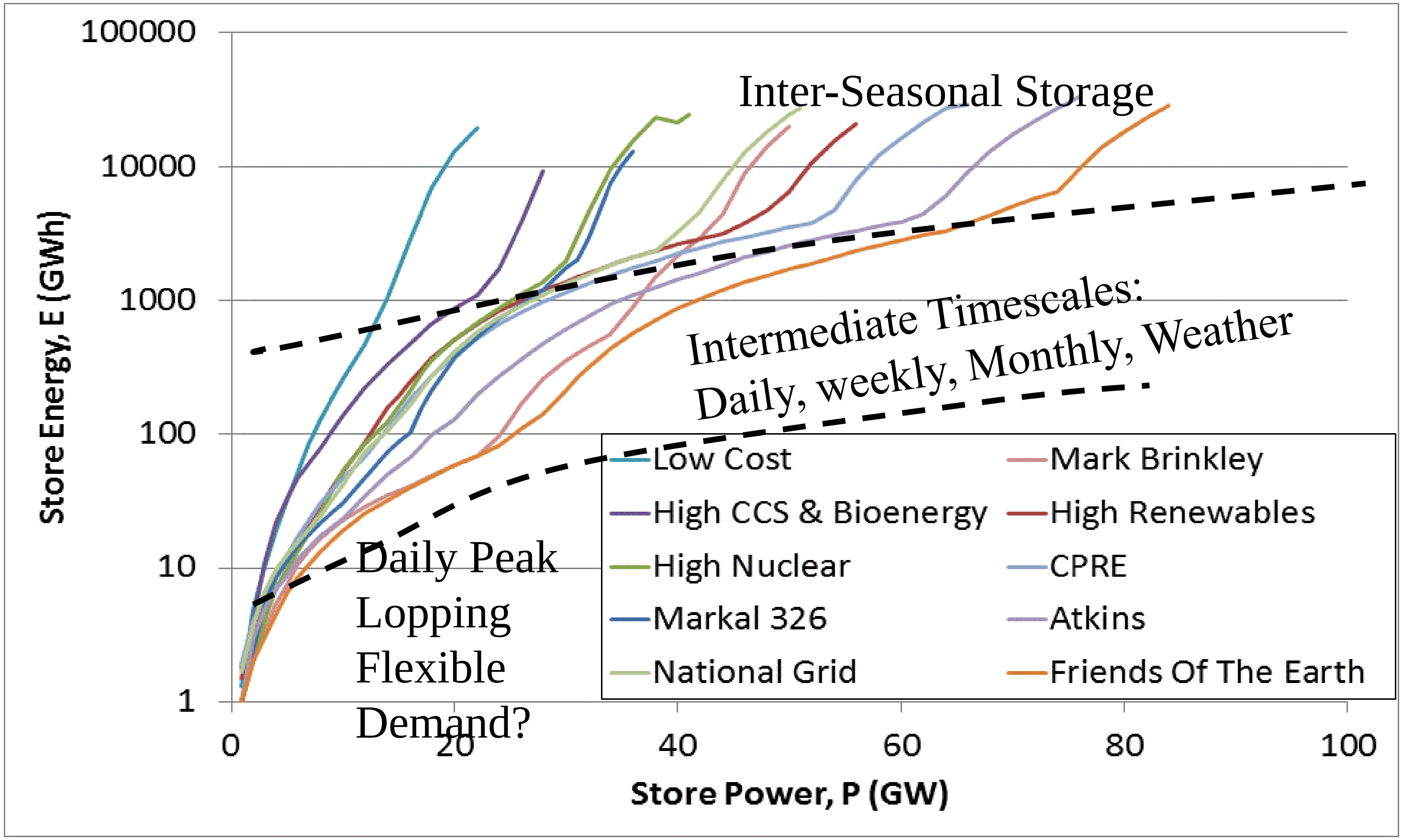
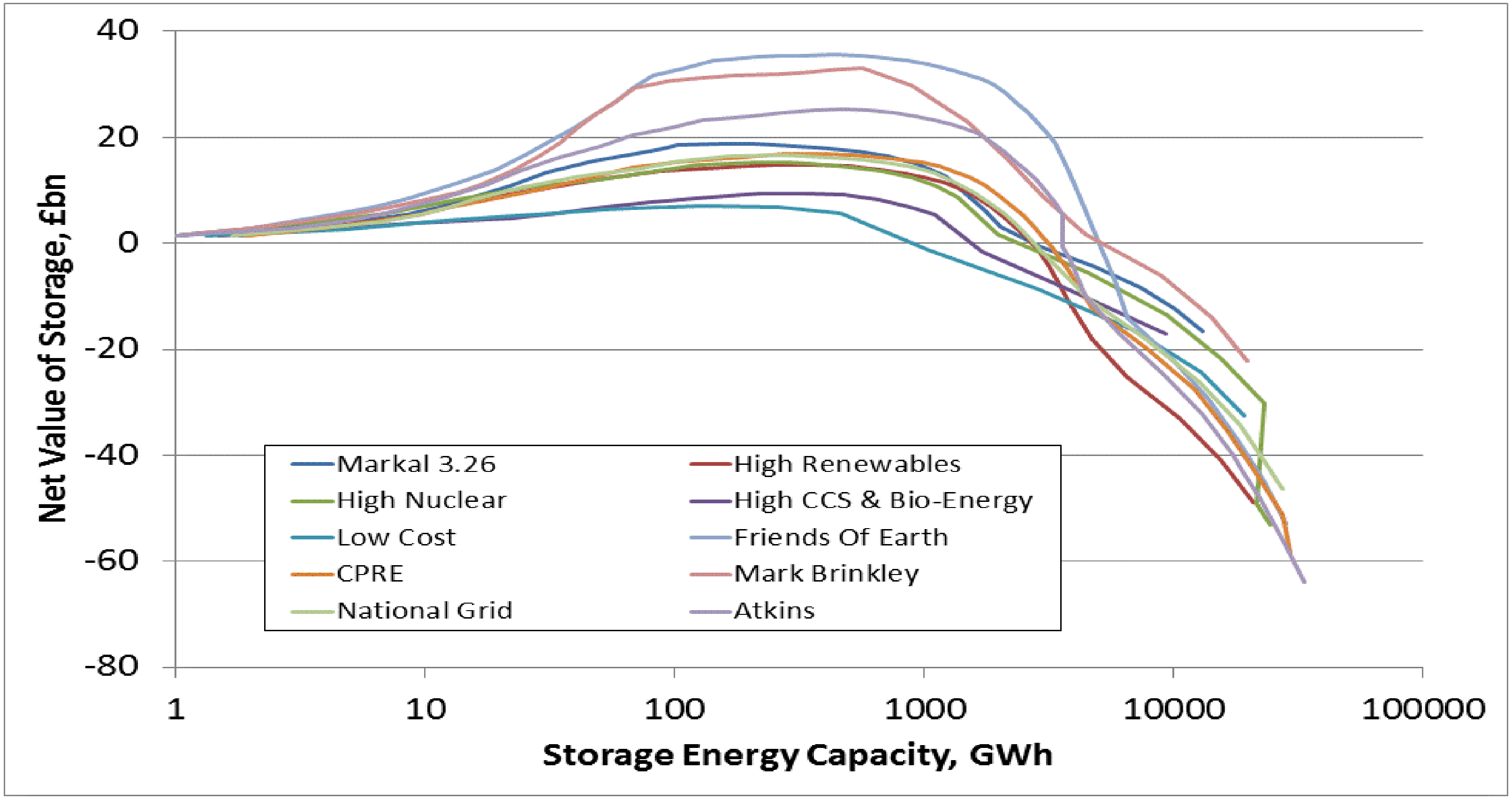
Our Work 2:
Size of store needed to meet annual peak demand



Time-Step Analyses of the UK Power System to Determine the Optimal Amount and Mix of Energy Storage Technologies, and Alternatives to Grid-Scale Energy Storage

Our Work 2: Net Total Lifetime Value of Storage



Time-Step Analyses of the UK Power System to Determine the Optimal Amount and Mix of Energy Storage Technologies, and Alternatives to Grid-Scale Energy Storage

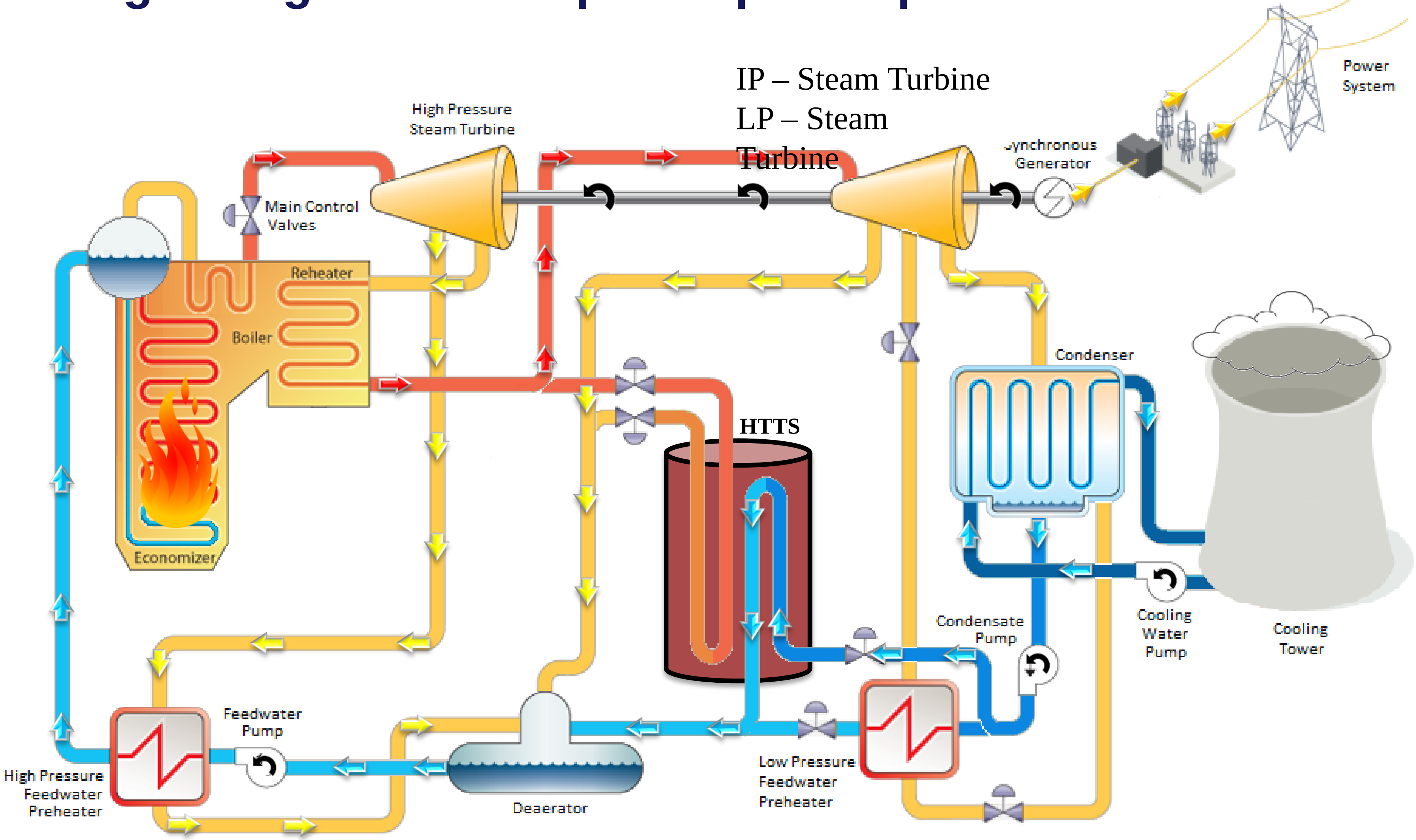
Our Work 3:
Integration of Thermal Energy Storage with power plant

Inflexible power plant operation

Thermal storage

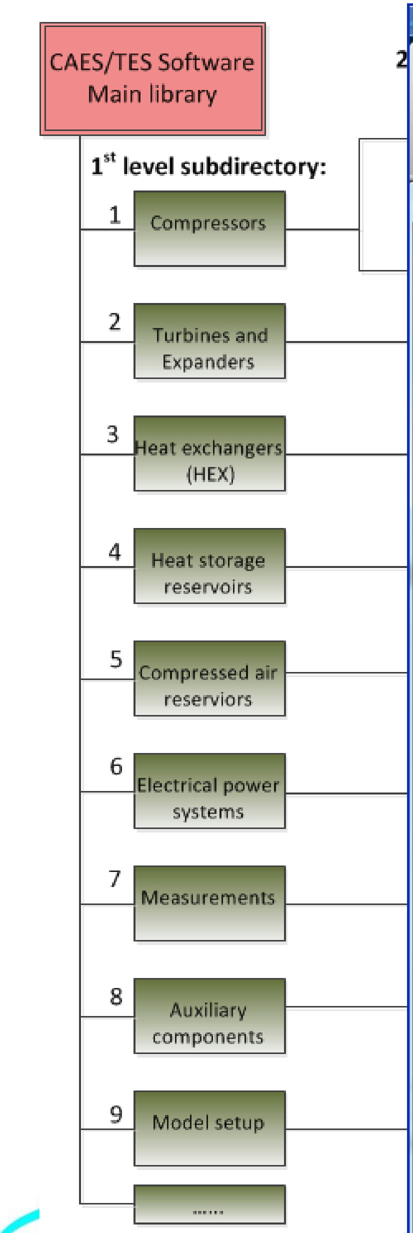
Flexible operation

Our Work 3: Feasibility study of Thermal Energy Storage integration with power plant operation



HTTS discharging process during high load demand.

Our Work 4: Software tool development for CAES systems



CAES/TES Software Main library

1^{st} level subdirectory:

1 Compressors

2 Turbines and Expanders

3 Heat exchangers (HEX)

4 Heat storage reservoirs

5 Compressed air reservoirs

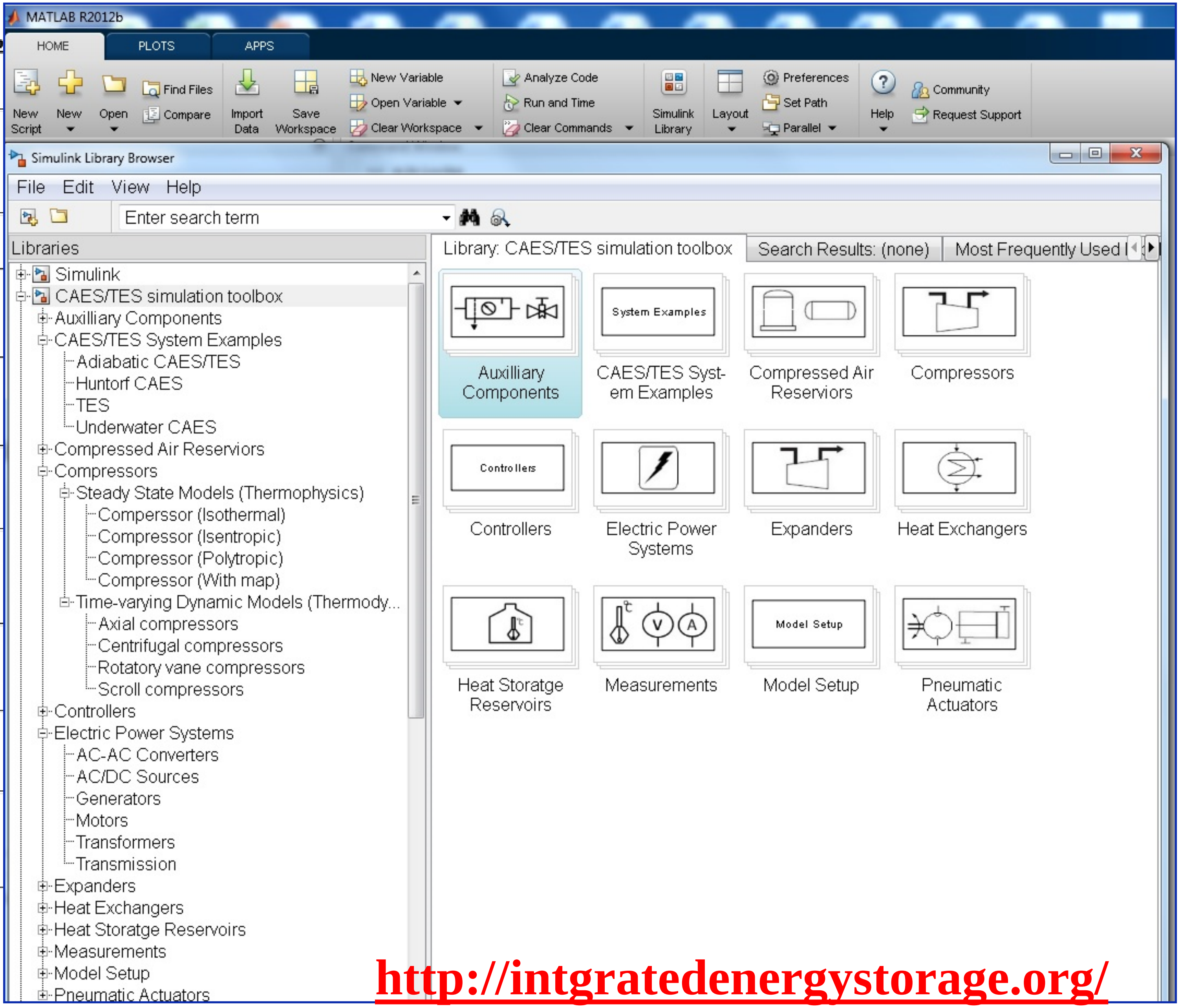
6 Electrical power systems

7 Measurements

8 Auxiliary components

9 Model setup

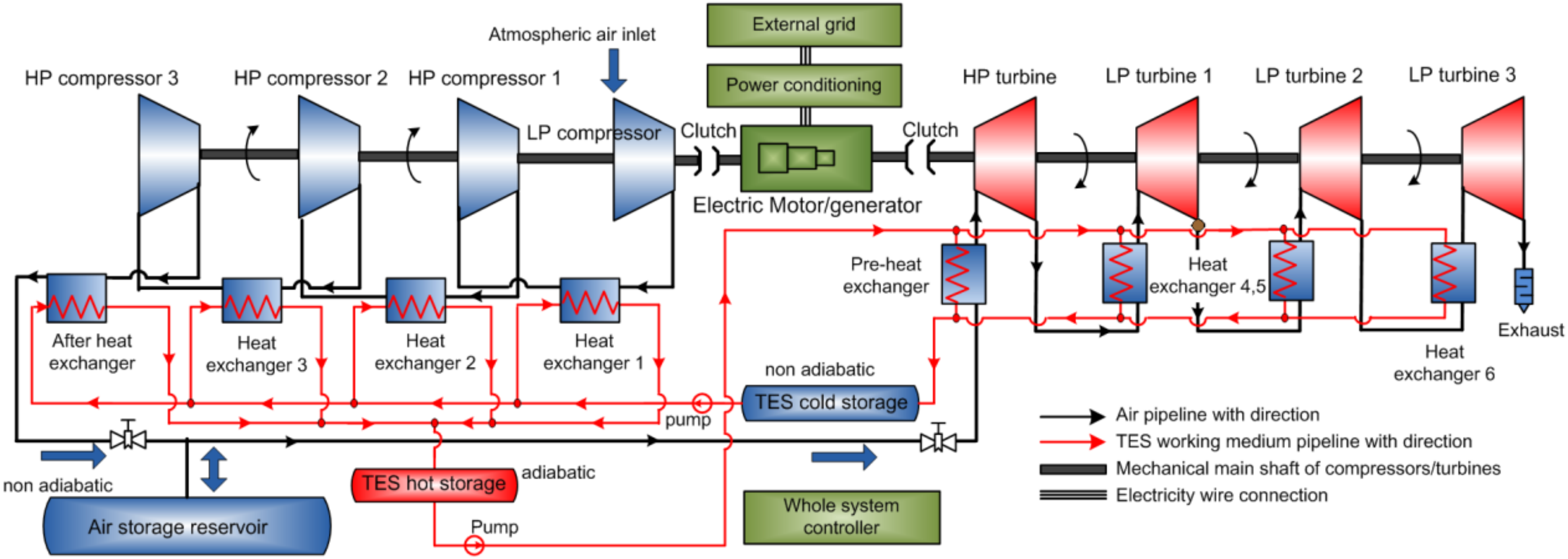
....



- Simulink
- CAES/TES simulation toolbox
  - Auxilliary Components
  - CAES/TES System Examples
    - Adiabatic CAES/TES
    - Huntorf CAES
    - TES
    - Underwater CAES
  - Compressed Air Reservoirs
  - Compressors
    - Steady State Models (Thermophysics)
      - Comperssor (Isothermal)
      - Compressor (Isentropic)
      - Compressor (Polytropic)
      - Compressor (With map)
    - Time-varying Dynamic Models (Thermody...
      - Axial compressors
      - Centrifugal compressors
      - Rotatory vane compressors
      - Scroll compressors
  - Controllers
  - Electric Power Systems
    - AC-AC Converters
    - AC/DC Sources
    - Generators
    - Motors
    - Transformers
    - Transmission
  - Expanders
  - Heat Exchangers
  - Heat Storatge Reservoirs
  - Measurements
  - Model Setup
  - Pneumatic Actuators

http://intgratedenergystorage.org/

Our Work 5: CAES Whole Process Efficiency Analysis

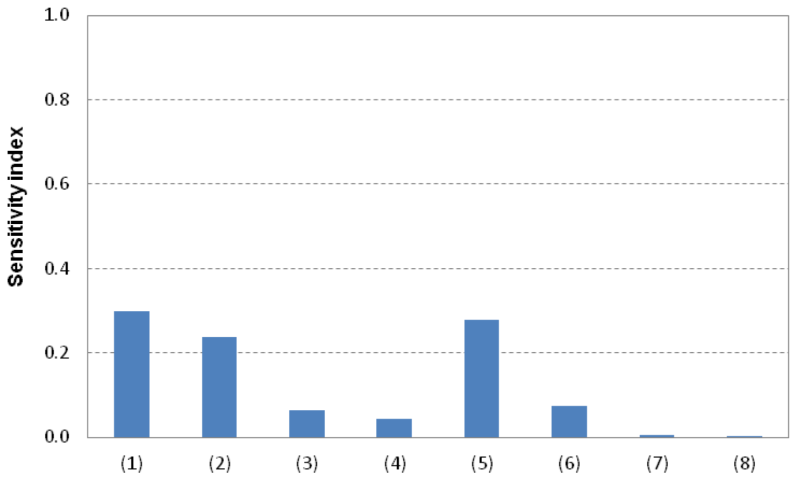


Sensitivity level to the cycle efficiency

Max

- **Isentropic eff. of compress**
- **Heat transfer rate of HEXs**
- **Isentropic eff. of expanders**
- **Charging-discharging time**
- **Air/water flow rates**
- **Wall temperature**
- **Pressure loss in the HEXs**

Min



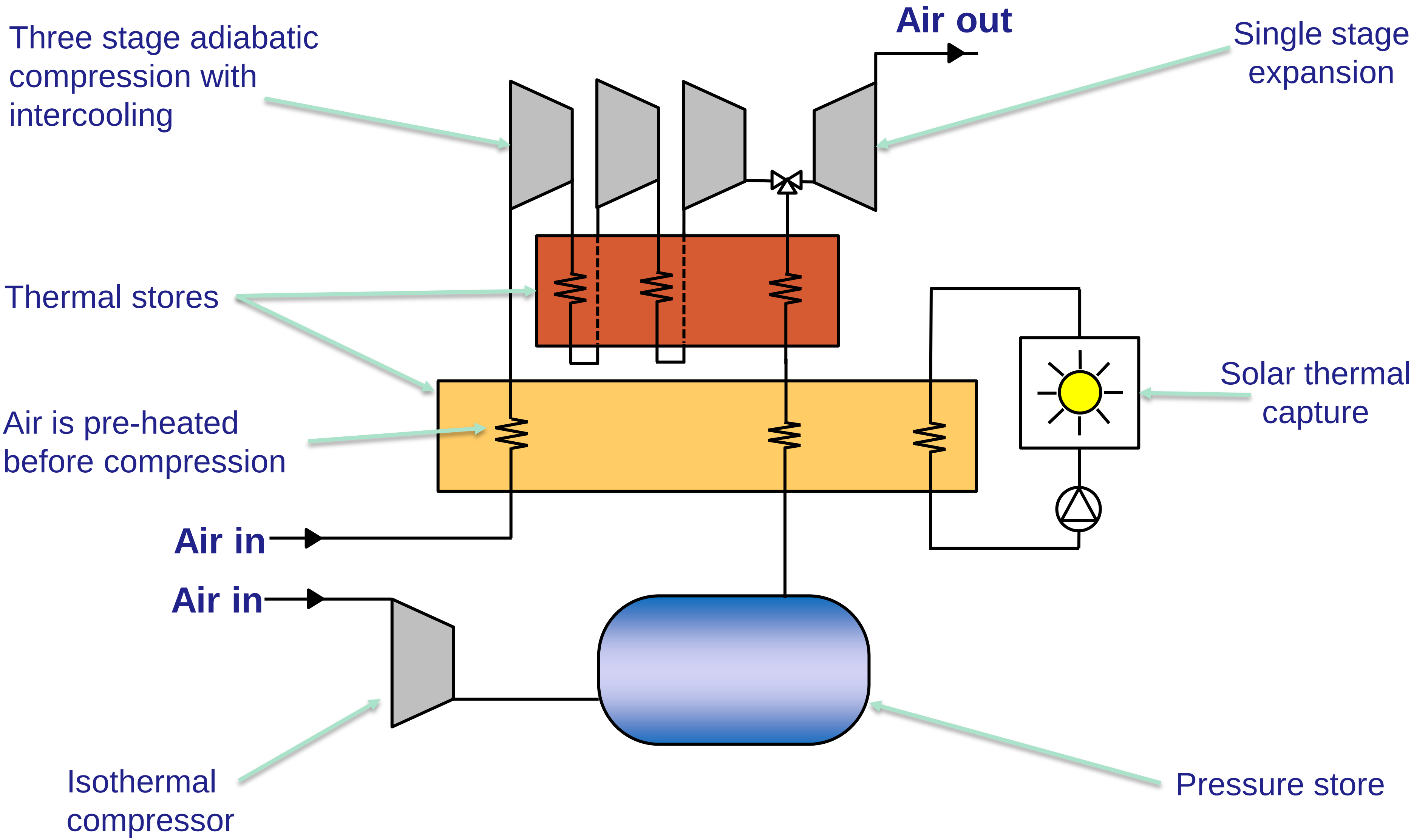
Our Work 6: CAES with pre-heating and solar integration

- Engineers at Nottingham University have identified a promising hybrid of CAES and Concentrating Solar Power (CSP).

- The system uses solar thermal input to output more electricity than it received.
- Pre-heating of air before compression is key to the successful CSP integration, by producing the heat of compression at high temperatures.
- Such a system would be a powerful source of flexibility in areas of high solar PV uptake.

For more information, contact seamus.garvey@nottingham.ac.uk.

Our Work 6: CAES with pre-heating and solar integration



Three stage adiabatic compression with intercooling

Thermal stores

Air is pre-heated before compression

Air in

Air in

Isothermal compressor

Air out

Single stage expansion

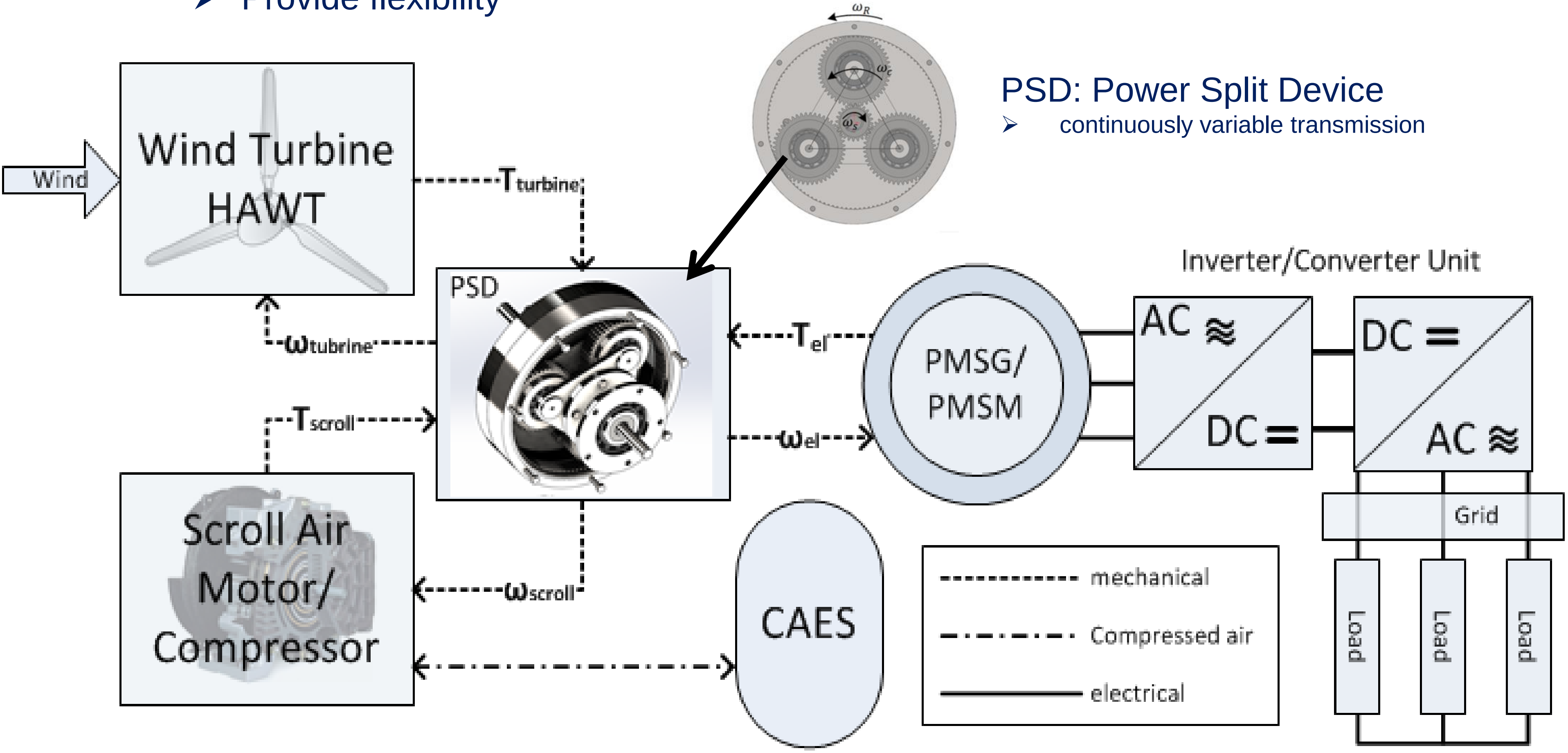
Solar thermal capture

Pressure store

For more information, contact seamus.garvey@nottingham.ac.uk.

Out work 7. Hybrid wind turbine integrating CAES

- To augment a wind turbine with CAES on the turbine level with a flexible mechanical transmission device
- Control generator power output under fluctuating wind speed and enable CAES provision
  - Provide flexibility



PSD: Power Split Device

- continuously variable transmission

Out work 7. Hybrid wind turbine integrating CAES

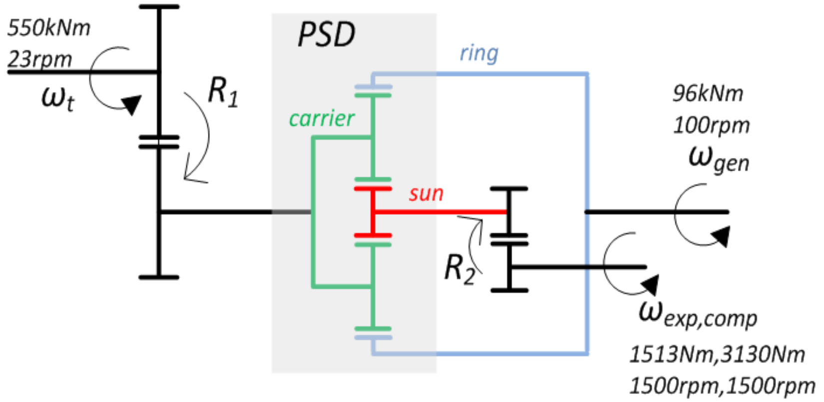
Extension to 1MW wind turbine:

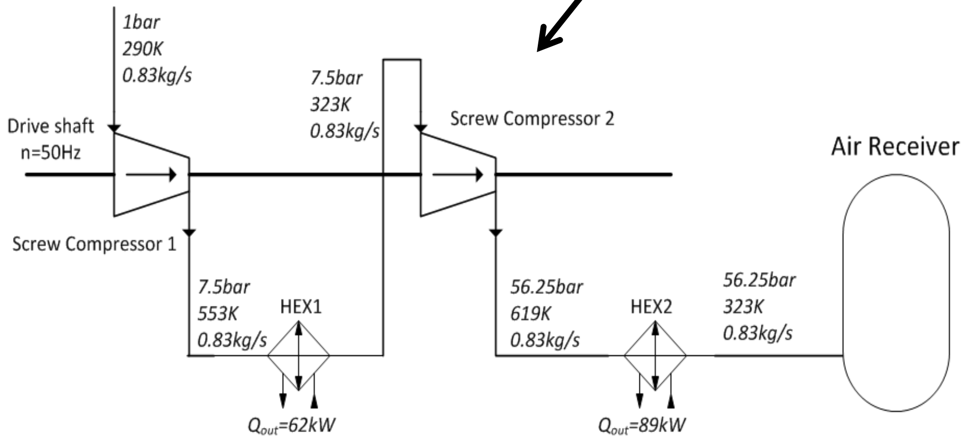
	HAWT (at 12.5m/s)	**PMSG**	**Expander**	**Compressor**
Rated Power	1.3MW	1MW	240kW	490kW
Rated Speed	23rpm	100rpm	1500rpm	1500rpm
Rated Torque	550kNm	96kNm	1513Nm	3130Nm
Vessel size	500m^3			
Storage Capacity	3MWh			
Time Charging	≈ 11hrs (at 1500rpm, 626 l/s FAD)			
Time Discharge	≈ 5hrs (at 1500rpm, 626 l/s FAD per expander)			

1MW hybrid wind turbine specifications

2 screw compressors in series (to increase air pressure in air receiver)

Mechanical Transmission:





Eight Patents are Filed; one is assigned to industry

1. Garvey SD: Direct-Drive Power Conversion System for Wind Turbines Compatible with Energy Storage. (Submitted June 16, 2013)
2. Garvey SD: High-efficiency adiabatic compressor/expander uses covered liquid pistons, GB1509508.6, July 2015
3. Garvey SD, Cárdenas B, Kantharaj BK, Pimm AJ: Compressed air energy storage system uses high grade thermal store to increase exergy storage capacity, September 2015
4. Wang, J and Luo X: Direct Electricity Generation from Magnetic Scrolls, GB2014051062, 2014 (in the process of signing assignment of license agreement).
5. Garvey SD, Cárdenas B, Kantharaj BK, Pimm AJ: System for Compressed Air Energy Storage Boosts Net Work Output Using Low-Grade Heat. October 2015
6. Garvey, Pimm, & Kantharaj., GB1516599.6. “Compressed Air Energy Storage System uses High Grade Thermal Store to Increase Exergy Storage Capacity” Filed Sept. 18, 2015.
7. Garvey, Pimm, Cardenas, Simpson and Kantharaj., GB1521372.1. Compressed Air Energy Storage System Exploits Low Grade Heat Capture to Increase Exergy Output – Filed Dec. 2, 2015
8. GB1612878.7. “Energy Storage System Blends Two Different Air Compression Resources and Exploits External Low Grade Heat Input” Increase Exergy Output”

Thank you!