Integrated Market-fit and Affordable Grid-scale Energy Storage (IMAGES)

Four Months Progress Meeting

Prof Jihong Wang (PI), Dr Jacek Wojcik (Project Manager)
Dr Jianguo Wang (RF funded by IMAGES)
Dr Xing Luo and Dr Mark Dooner (RFs funded by non-IMAGES funding)
James Lam (SPERC industry CASE), Songshan Guo (School of Engineering + industry)

WARWICK
THE UNIVERSITY OF WARWICK

Outline of the presentation

1. Overview
2. Publications and activities
3. Project progress report
    - CAES-TE simulation tool
    - Integration of CAES with Grid
    - Integration of HTTS with a CCGT power plant
    - ES integration with Warwick campus energy system
4. Future work

1. Overview

Staff: Dr Jianguo Wang (Research Fellow)
Dr Jacek Wojcik (Project Manager)

Students:
Mr Anand Ganesan, Deferred to Jan 2018
Mr James Lam, joined us in May 2017 (EPSRC CASE)
Mr Songshan Guo, to be involved in some work related to IMAGES

Dr Xing Luo and Dr Mark Dooner have been giving their support to the project.

Research work

- Further development on CAES-TE simulation toolbox
- Study of integration of CAES with grid
- The role of energy storage in VPP

2. Publications and Activities

Papers published or accepted

- J Wang, X Luo, M Dooner, C Krupke, "Compressed Air Energy Storage" in Energy Storage, One book chapter, World Scientific series in current energy issues, volume 4, to be published, 2017.
- W He, Y Wang, J Wang, Pumped seawater combined with Compressed Air Energy Storage system: an integrated solution for co storage/production of electricity and freshwater for offshore islands, OSES, 2017, USA

Papers under revision

- X Luo, J Wang, L Shpanin, M Dooner, "A New Scroll-type Air Motor with Magnetic Spirals", *IEEE/ASME Transactions on Mechatronics*, completed the first round review, under modification.
- W He, J Wang, Optimal Selection of air expansion machine in Compressed Air Energy Storage: a review, Renewable and Sustainable Energy Review

2. Publications and Activities

Papers submitted

- W He, X Luo, D Evans, J Busby, S Garvey, D Parkes, J Wang, Exergy storage of compressed air in cavern and cavern volume estimation of the large-scale Compressed Air Energy Storage System, submitted to *Applied Energy.*
- W He , J Wang, Y Wang, Y Ding, H Chen, Y Wu, S Garvey, Study of cycle-to-cycle Dynamic characteristics of adiabatic Compressed Air Energy Storage using packed bed Thermal Energy Storage, submitted to *Energy*
- W He, J Wang, New radial turbine dynamic modelling in a low-temperature adiabatic Compressed Air Energy Storage system discharging process, submitted to *Energy Conversion and Management for consideration*

Papers under preparation:

- J D Wojcik, J Wang: Technical feasibility study of Combined Cycle Gas Turbine (CCGT) integration with Adiabatic Compressed Air Energy Storage (ACAES) plant.
- X Luo, J Wang, W He, M Dooner, YW Li, DC Li, O Kiselychnyk, "A Software Tool for Dynamic Modelling and Transient Control of Advanced Compressed Air Energy Storage with Thermal Energy Storage Systems", draft finish, aiming for *Energy* or *Applied Energy*
- X Luo, J Wang, J D Wojcik, . M Draganescu. "Study of Power Network Grid Code Requirements for Electrical Energy Storage Applications", under writing, aiming for *Energies*

2. Publications and Activities

- J Wang, presentation at the EERA meeting for finalising European Energy Storage Roadmap document, Brussels, 15th March 2017.
- Jianguo Wang, performed experiments on grid-connected inverters in Liverpool, 30th March – 1st April.
- X Luo, visited HUST university at April 2017, international cooperation, dSPACE training & CAES laboratory at HUST.
- J Wang, M Dooner, attended Energy Storage Hub meeting, Oxford, 3rd May 2017. (given an overview about IMAGES project activities)
- J Wang, P Mawby, attended the sandpit workshop in Nanjing for potential joint grant application (smart grid and energy storage) with 14 partner universities, 26th May 2017.
- J Wang, UK-Guangdong joint workshop for potential Innovate UK Newton Fund project application (was selected to join the mission to China by KTN), 14th June 2017.

3. Project progress

WPs that Warwick leads

WP1.2 Task 2. Update the overview in CAES and other ES technology development. ✔ Completed

WP1.4 Task 2. CAES specific opportunities in the UK ✔ Continue

WP2.2 Task 1. Improving the round trip efficiency of large scale adiabatic CAES systems ✔ Completed

WP2.2 Task 2. Hybrid integration of wind power generation with CAES ✔ Completed

WP2.2 Task 3. Software tool development for complete CAES processes ✔ Continue

WP2.2 Task 4. Supporting the whole system techno-economic study ✔ Continue (to VPP)

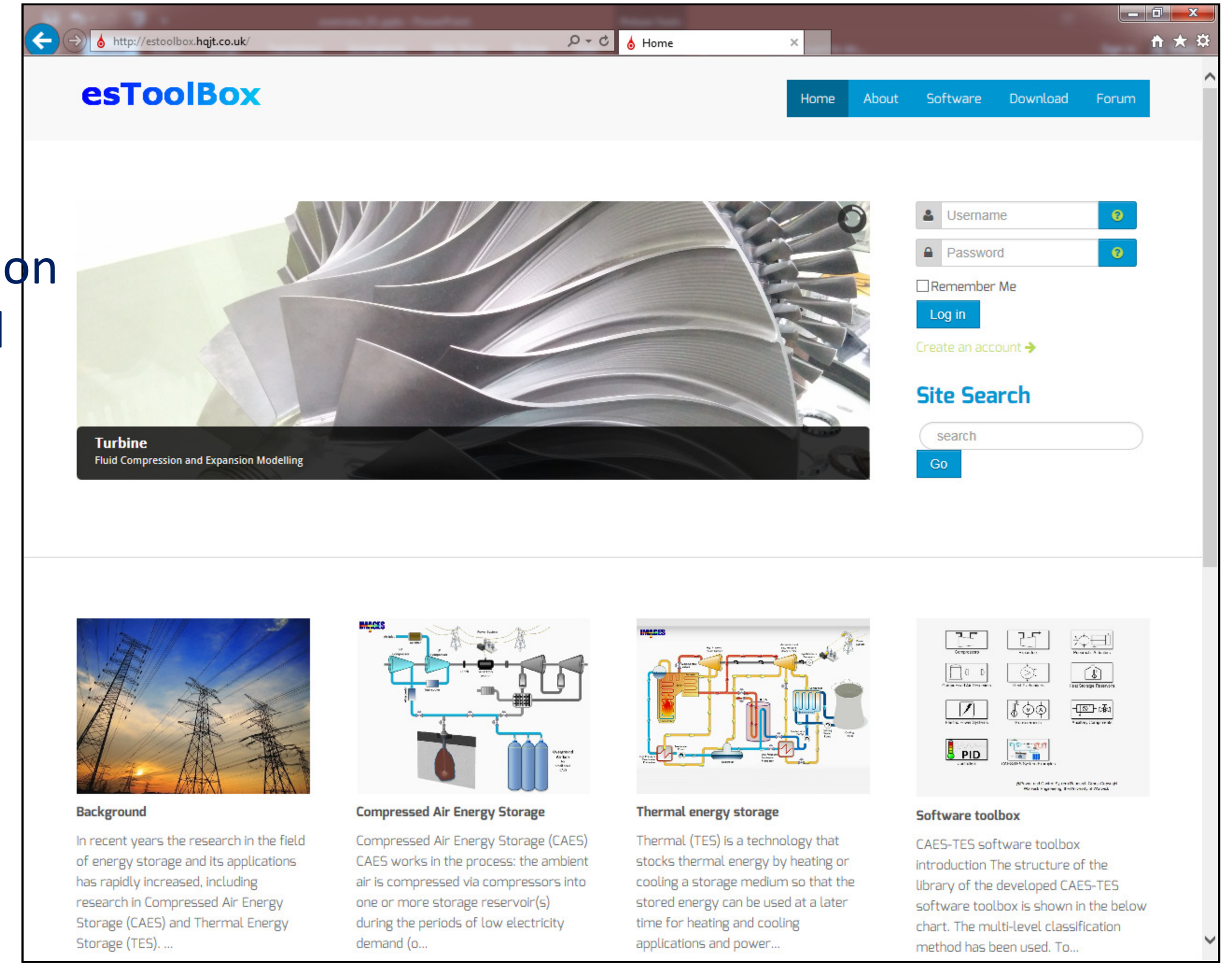
WPs that Warwick supports

WP2.3 Integrated ES: Warwick team has developed a number of thermal storage model and simulation library blocks which can be used by WP2.3. ✔ Continue linked to WP2.2 T3

WPs1.5/2.4 HTTS: Using the unique simulation facility at Warwick, Warwick team has conducted the feasibility study of HTTS integration into power plant cycle for both subcritical oil-fired power plant model and supercritical coal-fired power plant model. ✔ Extended

3. Project progress - CAES-TE simulation tool

- Improvement of the website
- On-line exergy/storage capacity calculations
- Development of new simulation blocks (power grid block)
- Study of new modelling methods for implementation of CAES-TE simulation tool

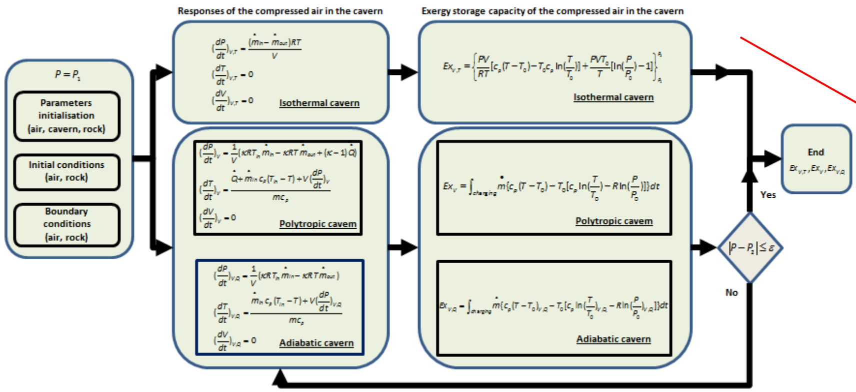


http://estoolbox.hqjt.co.uk/

3. Project progress - CAES-TE simulation tool

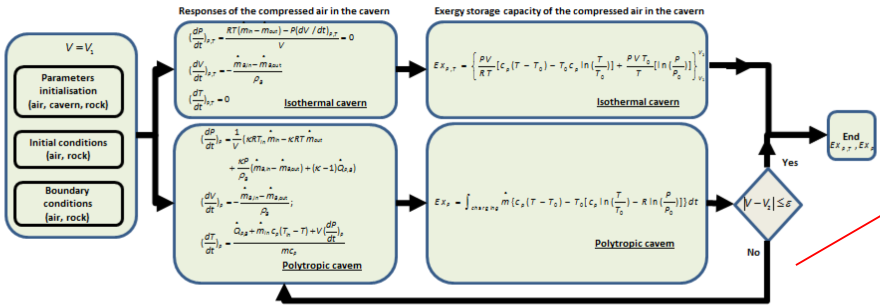
Flowchart of exergy storage calculation:

Exergy storage capacity of uncompensated isochoric air storage



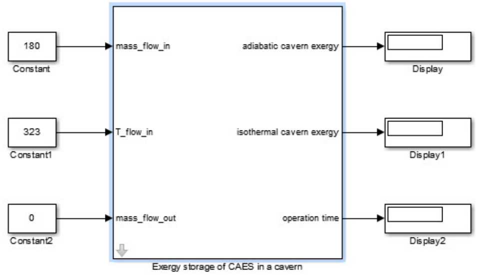
uncompensated isochoric air storage

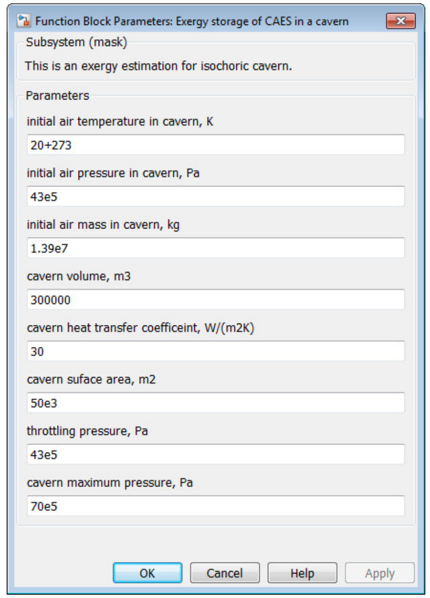
Exergy storage capacity of compensated isobaric air storage



compensated isobaric air storage

Simulation block

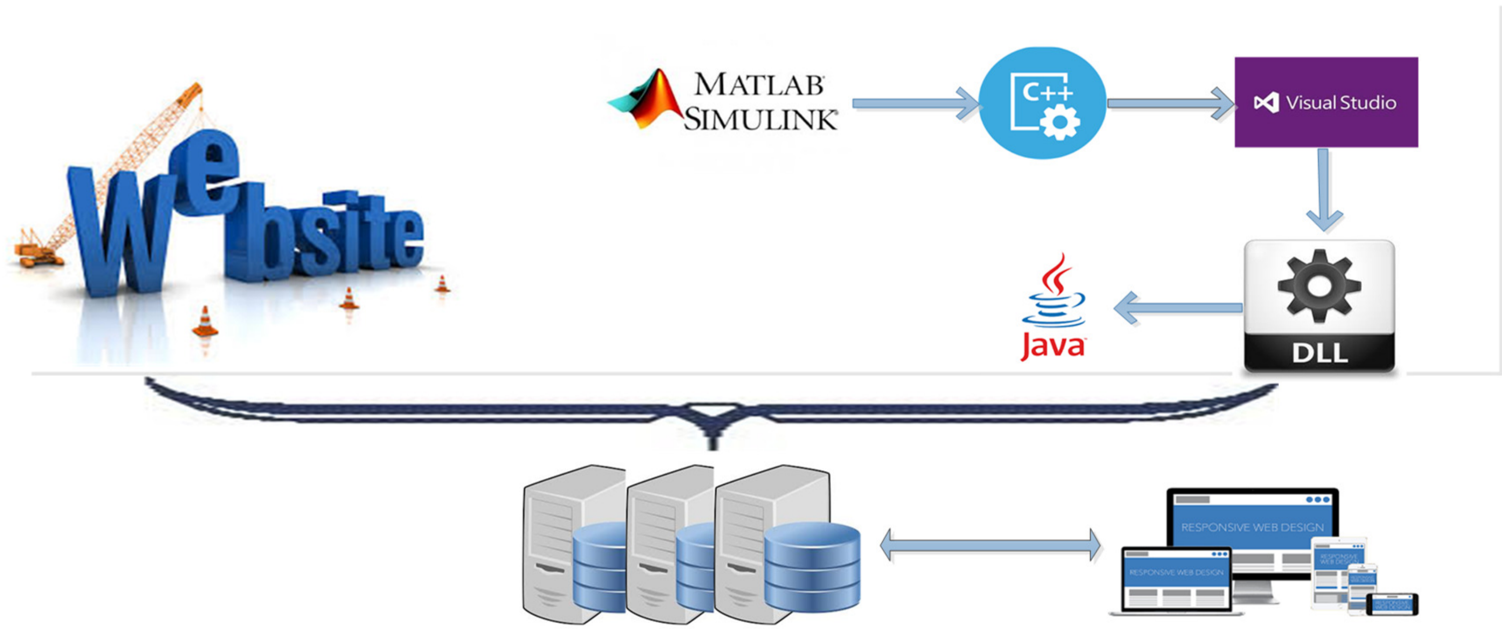




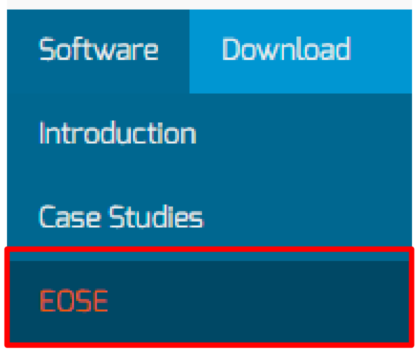
IMAGES

WARWICK

3. Project progress - CAES-TE simulation tool



Website https://estoolbox.hqjt.co.uk/



3. Project progress - CAES-TE simulation tool

Accurate estimation of energy storage capacity of a cavern

Home | Introduction | Calculation

mass_flow_in (Kg/s)	108	Input of mass flow
T_inlet (K)	323	Temprature of input mass
mass_flow_out (Kg/s)	0	Output of mass flow
cavern_air_T0 (K)	293	Initial air temprature in cavern
throttle_P (Pa)	4300000	Throttling pressure
cavern_sur_area (m^2)	50000	Area of cavern surface area
cavern_P_max (Pa)	7000000	Cavern maximum pressure
cavern_HT_coeff (W/m^2K)	30	Cavern heat transfer coefficient
cavern_air_P0 (Pa)	4300000	Initial cavern air pressure
cavern_volume (m^3)	30000	Cavern volume

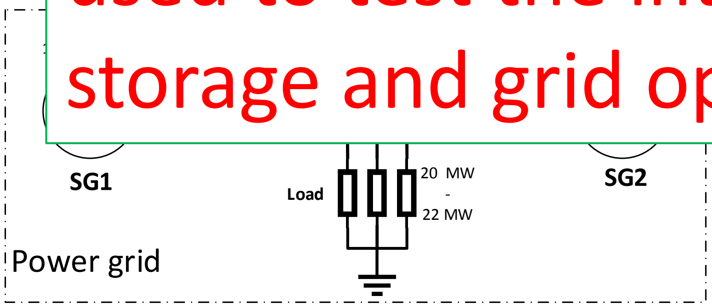
adiabatic_cavern_exergy (MW) — Energy in adiabatic cavern

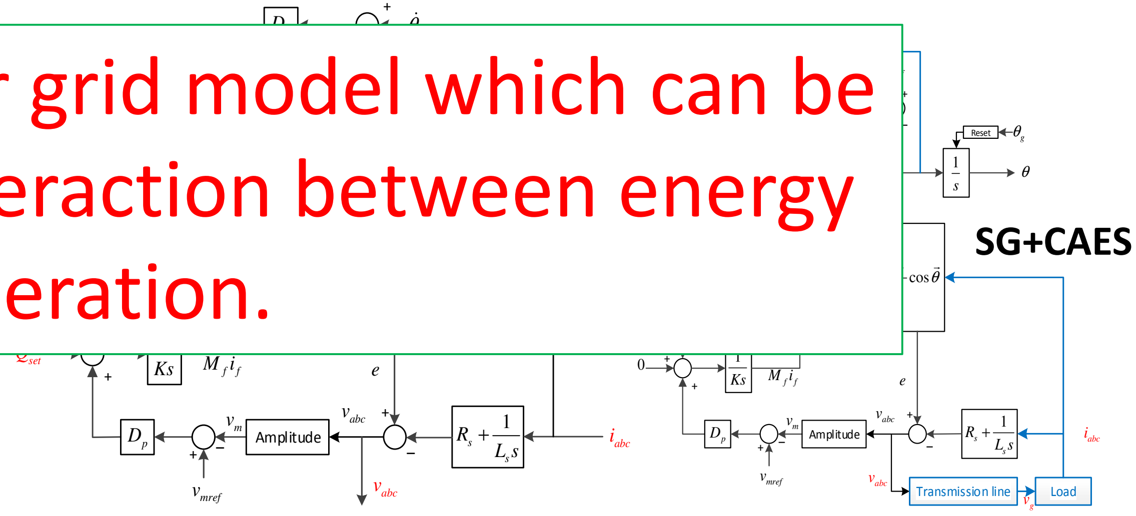
isothermal_cavern_exergy (MW) — Energy in isothermal cavern

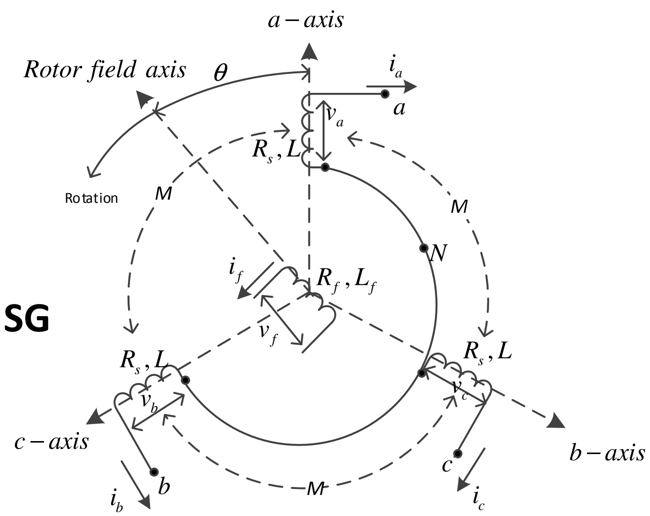
CALCULATE

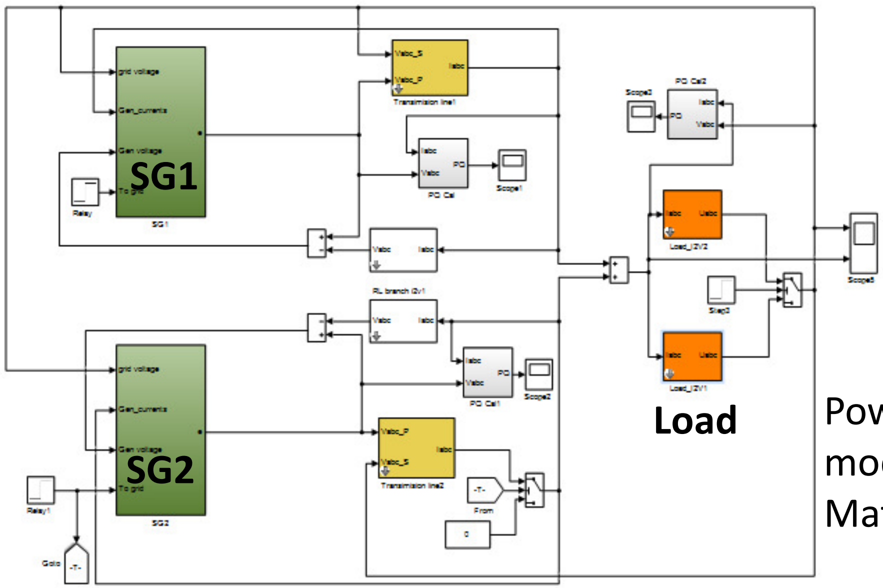
3. Project progress - Grid model simulation block

To develop a power grid model which can be used to test the interaction between energy storage and grid operation.





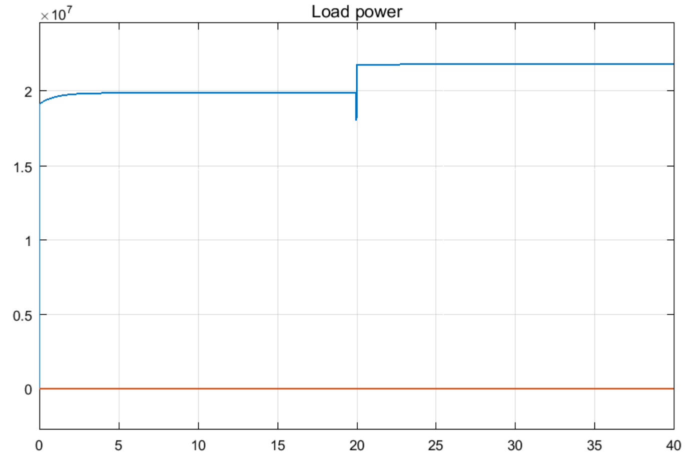




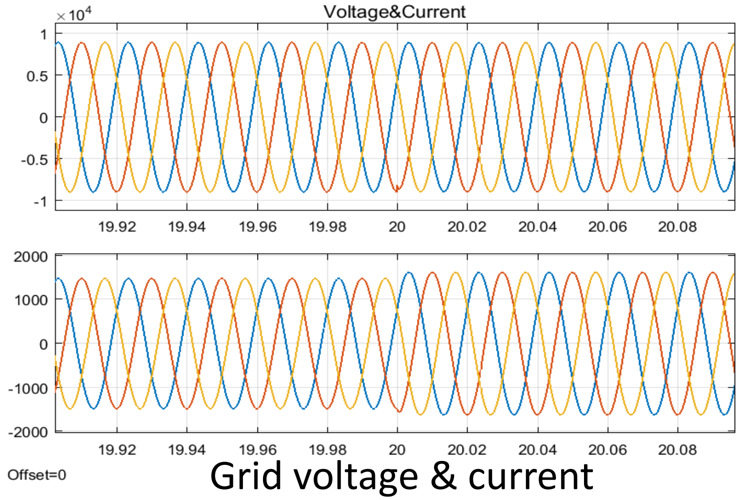
Power grid model in Matlab

3. Project progress - Grid model simulation block

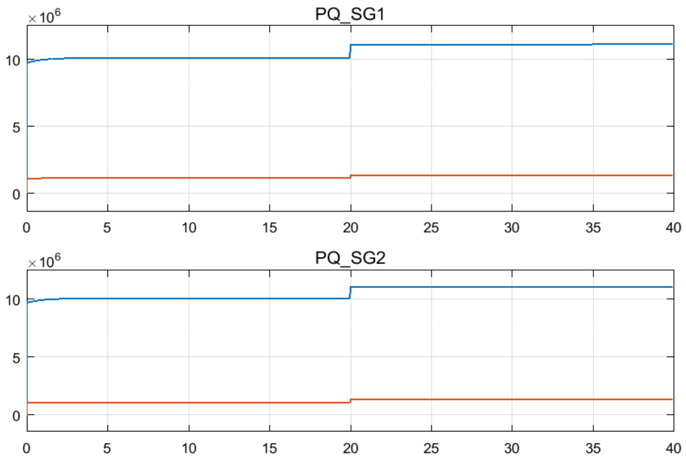
Grid responses to load change



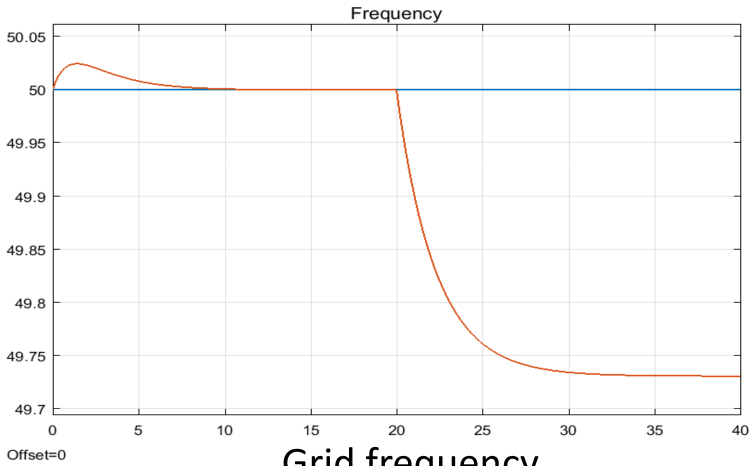
Load power



Grid voltage & current



P&Q of SG1,SG2



Grid frequency

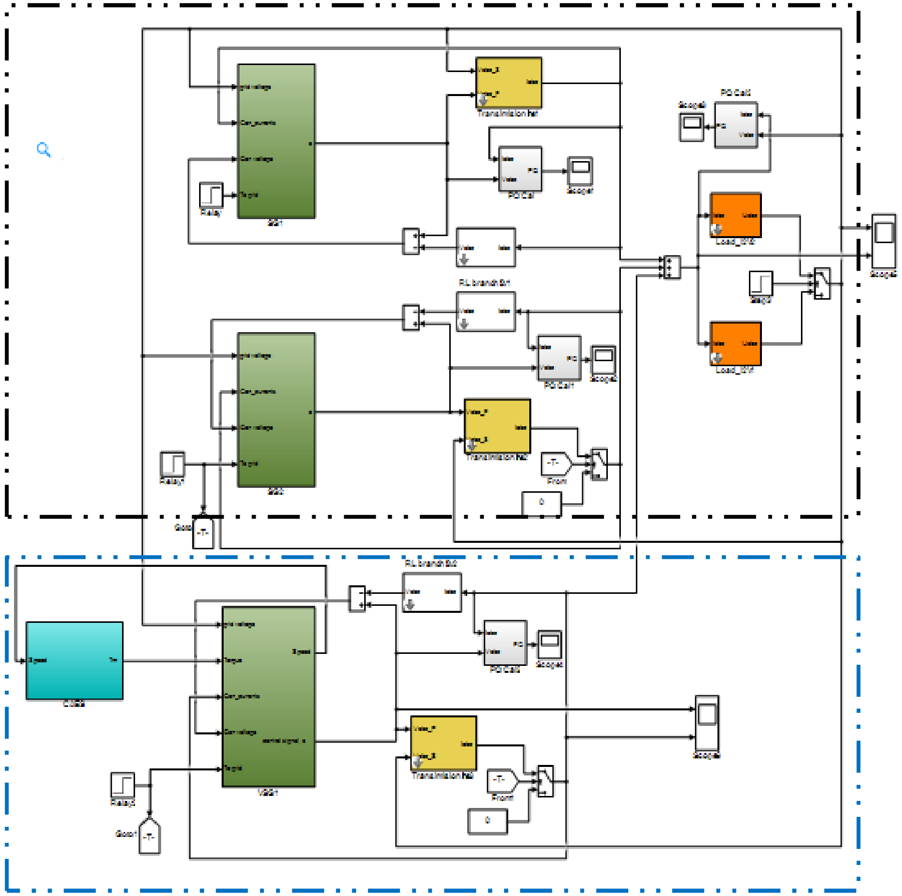
IMAGES

WARWICK

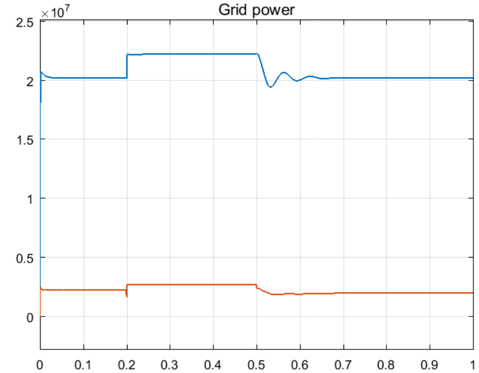
3. Project progress - Integration of CAES to Grid

Software simulations

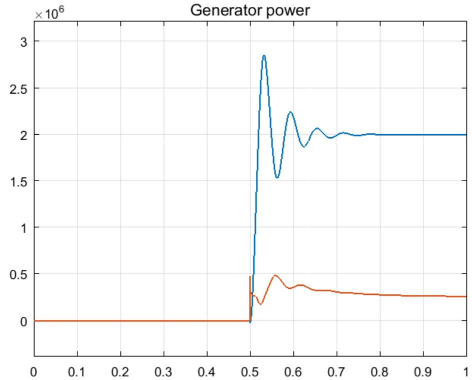
Power grid



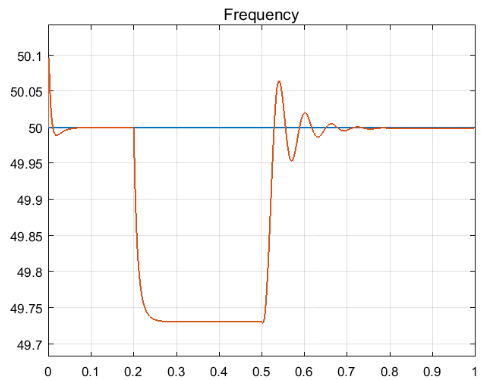
CAES



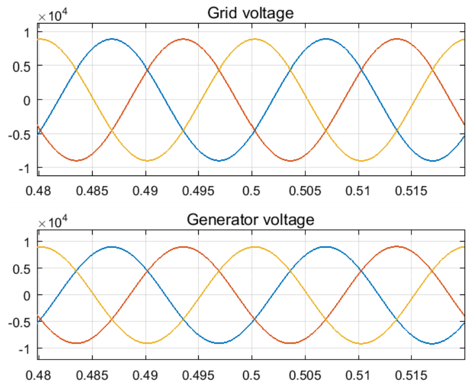
Grid power



Generated power



Grid frequency

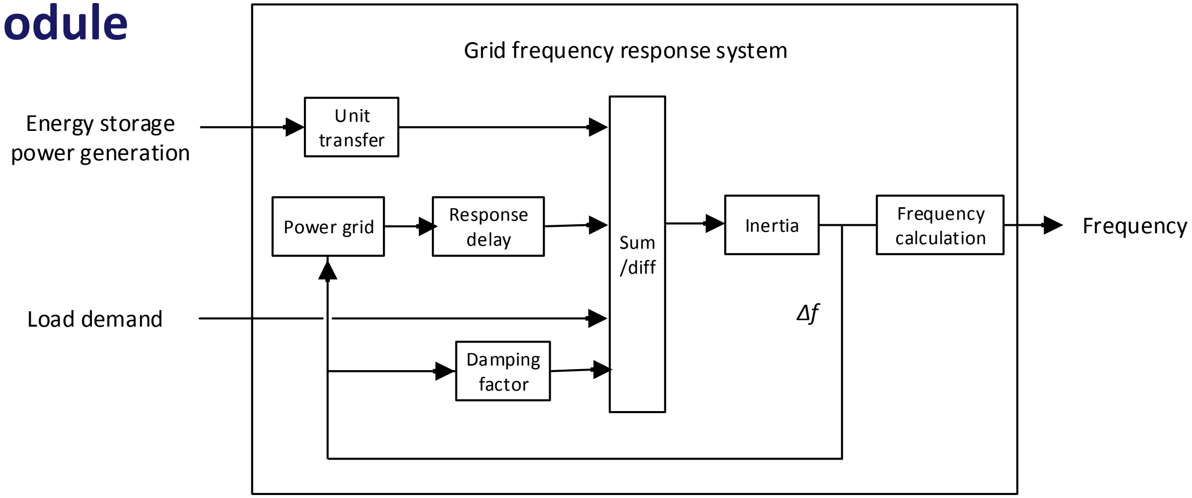


Grid & generated voltage

3. Project progress - Integration of CAES to Grid

Simplified grid frequency module

The developed model in the software tool can be used for simulating the grid frequency response with the electrical system power balance variation.



If there are a group of base generators in a power system, the system inertia constant is,

$$H_{sys} = \sum_{i=1}^{n} H_i S_i \Big/ S_{sys}$$

H_{sys} is nominal power; S is nominal power.

The power system droop constant describes the power versus frequency characteristics of the generator speed governor setting, which can be:

$$R_{sys} = -\frac{\Delta f}{f_0} \Big/ \frac{\Delta P}{S_{sys}}$$

Δf is frequency deviation; ΔP is change of the system active power; f_0 is normal frequency

The relationship between power and frequency deviation can be:

$$P_{Gen} + P_{ESdischar} - P_{Load} = 2H_{sys}\frac{d\Delta f}{dt} + D\Delta f$$

D is grid damping factor.

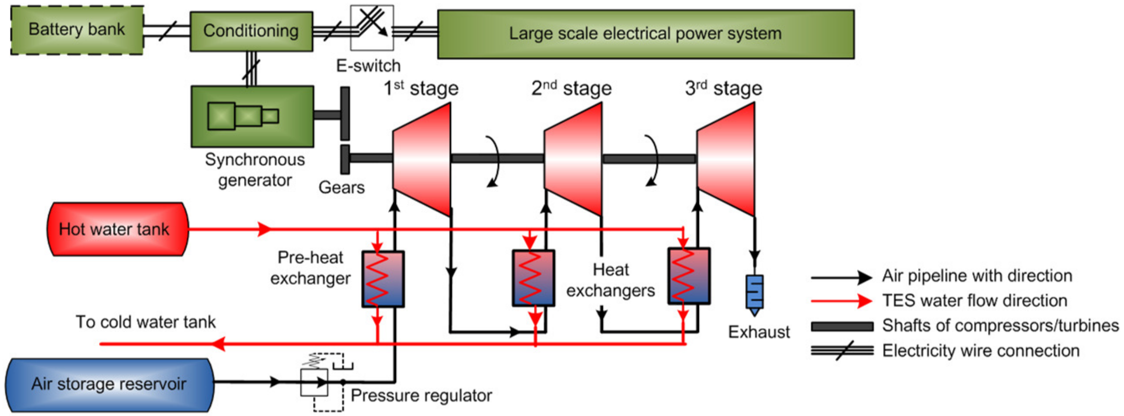
IMAGES

WARWICK

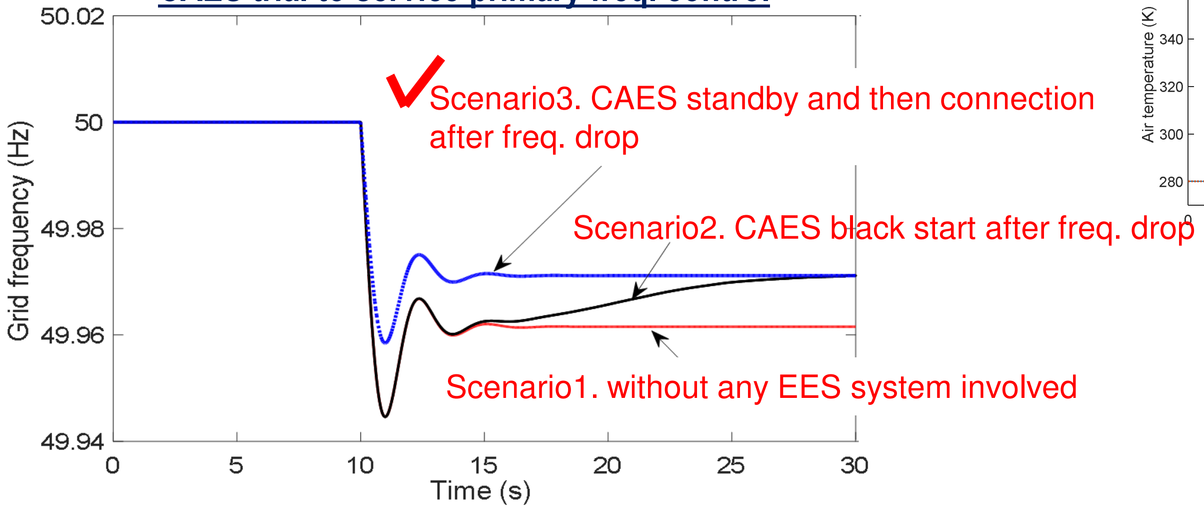
3. Project progress - Integration of CAES to Grid

Pre-study of CAES servicing grid primary frequency control:

The simulation study of a MW-scale CAES discharging with grid connection

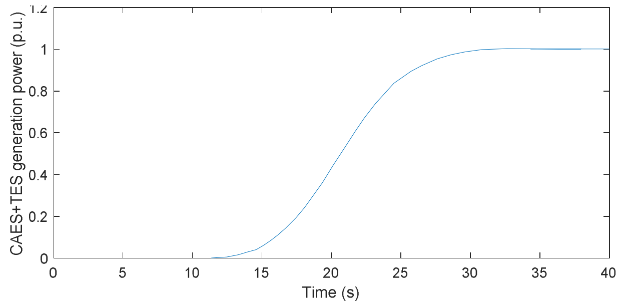


CAES trial to service primary freq. control

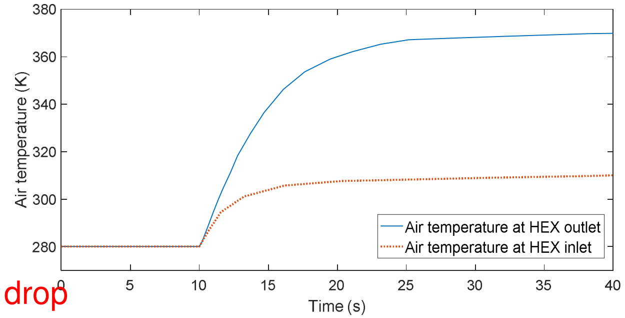


Dynamic process of CAES discharging black start

Dynamic process of power generation from CAES



Dynamic process of 3rd HEX inlet, outlet temperatures

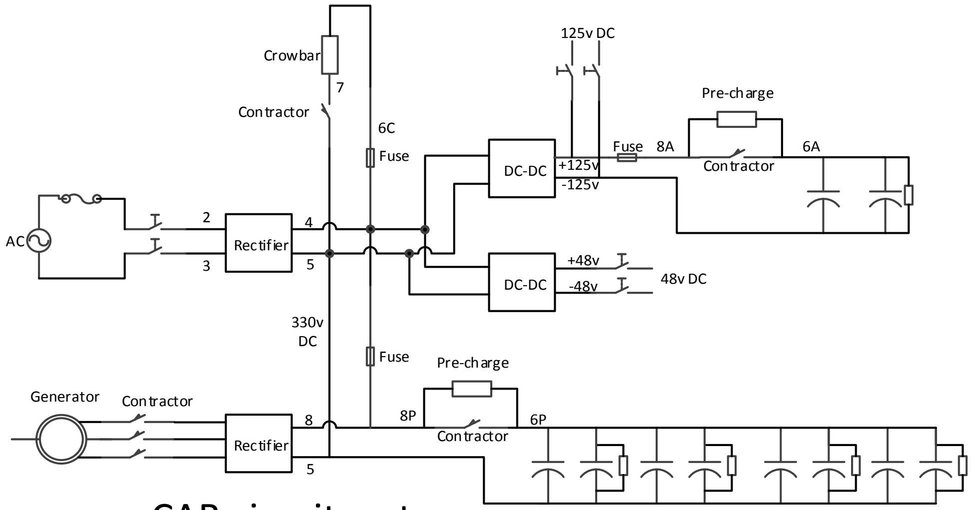


3. Project progress - Integration of CAES to Grid

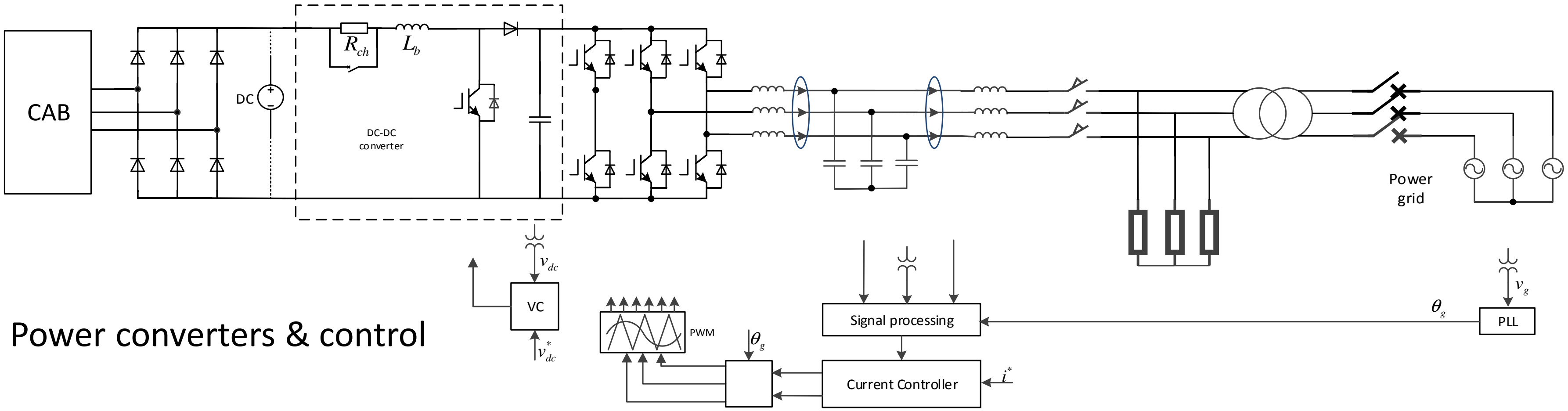
Hardware systems development

Grid-connected inverter development

- CAES test rig tested;
- Schemes of grid-connected inverter designed;
- Hardware components ordered;
- Hardware (PCBs) and software (Opal-RT) partially developed and tested.



CAB circuit system



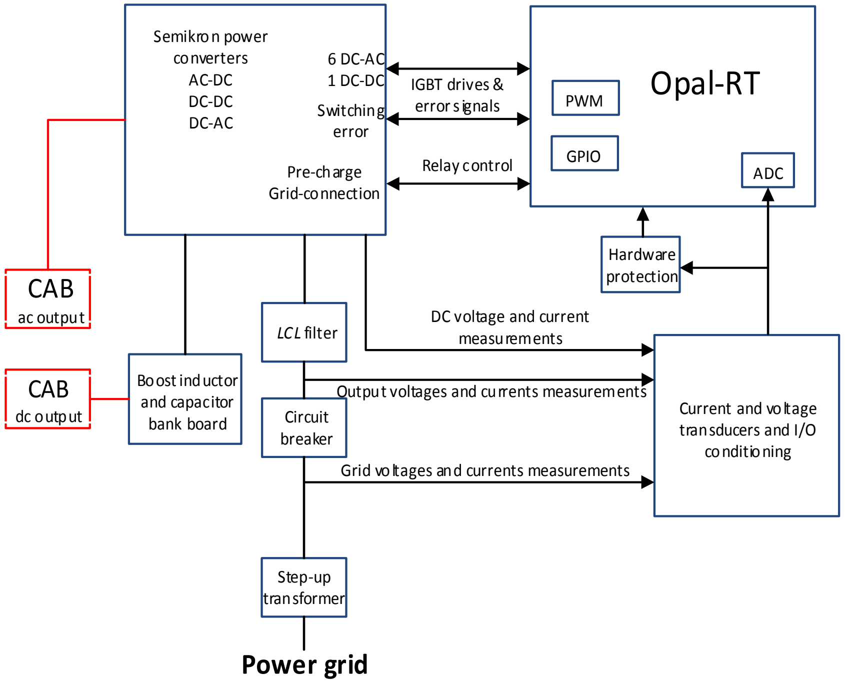
Power converters & control

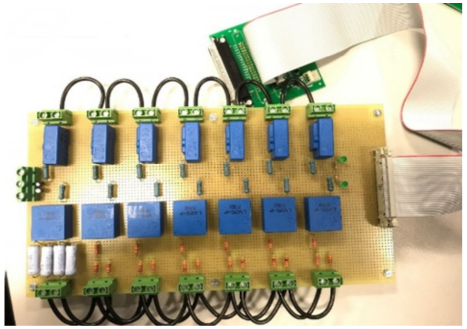
IMAGES

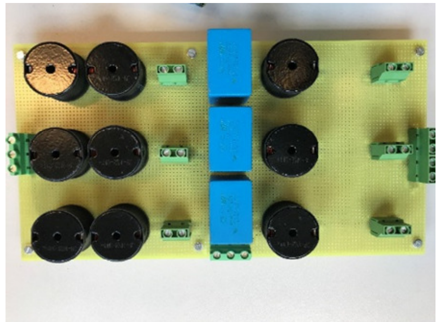
WARWICK

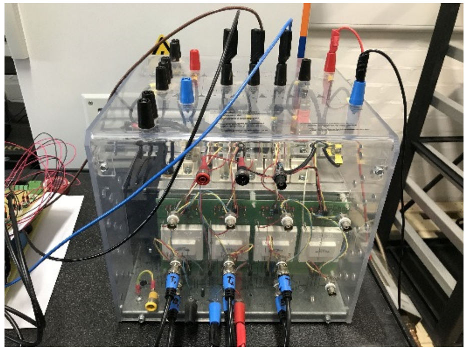
3. Project progress - Integration of CAES to Grid

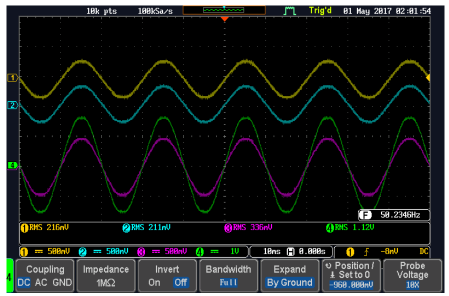
Hardware systems development











Main features

- AC or DC input suitable for CAB;
- Complete hardware and software protection design;
- Condition monitoring;
- High-order low-pass filter, high power quality;
- Decoupled from CAB, each part independently controlled.

3. Project progress - HTTS integration

CCGT-ACAES plant

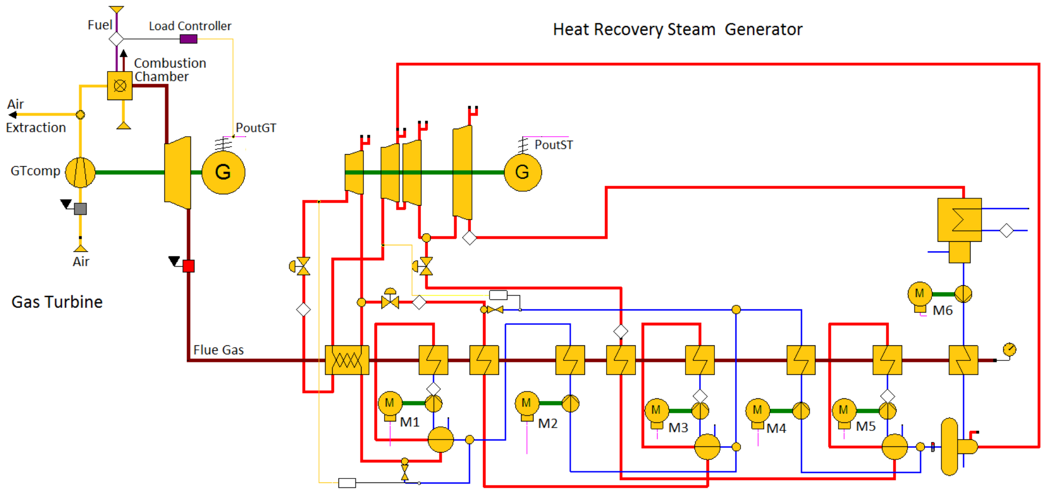


Figure 1. CCGT power plant process cycle.

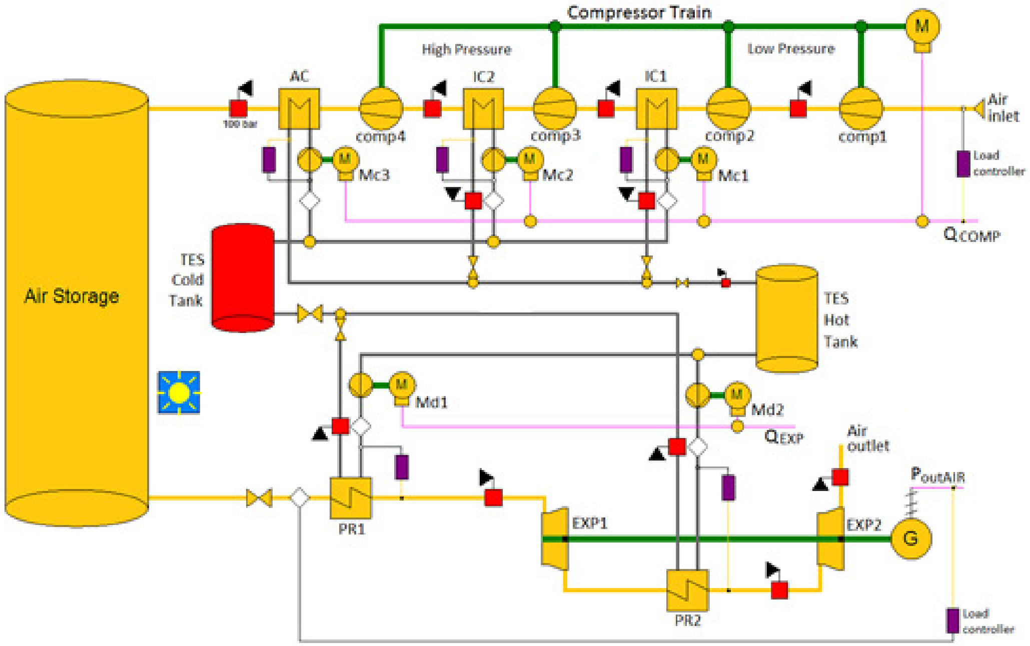


Figure 2. ACAES power plant process cycle.

3. Project progress - HTTS integration

CCGT-ACAES plant

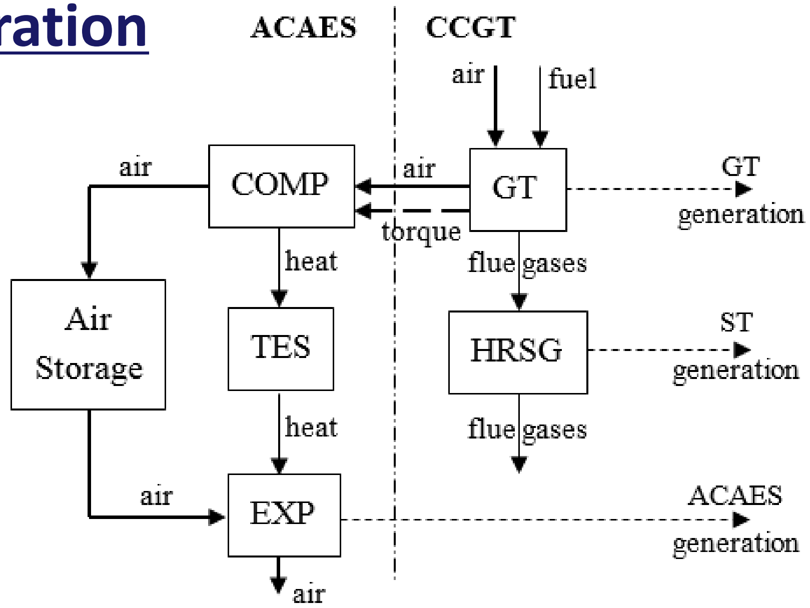


Figure 3. CCGT-ACAES power plant process flowchart.

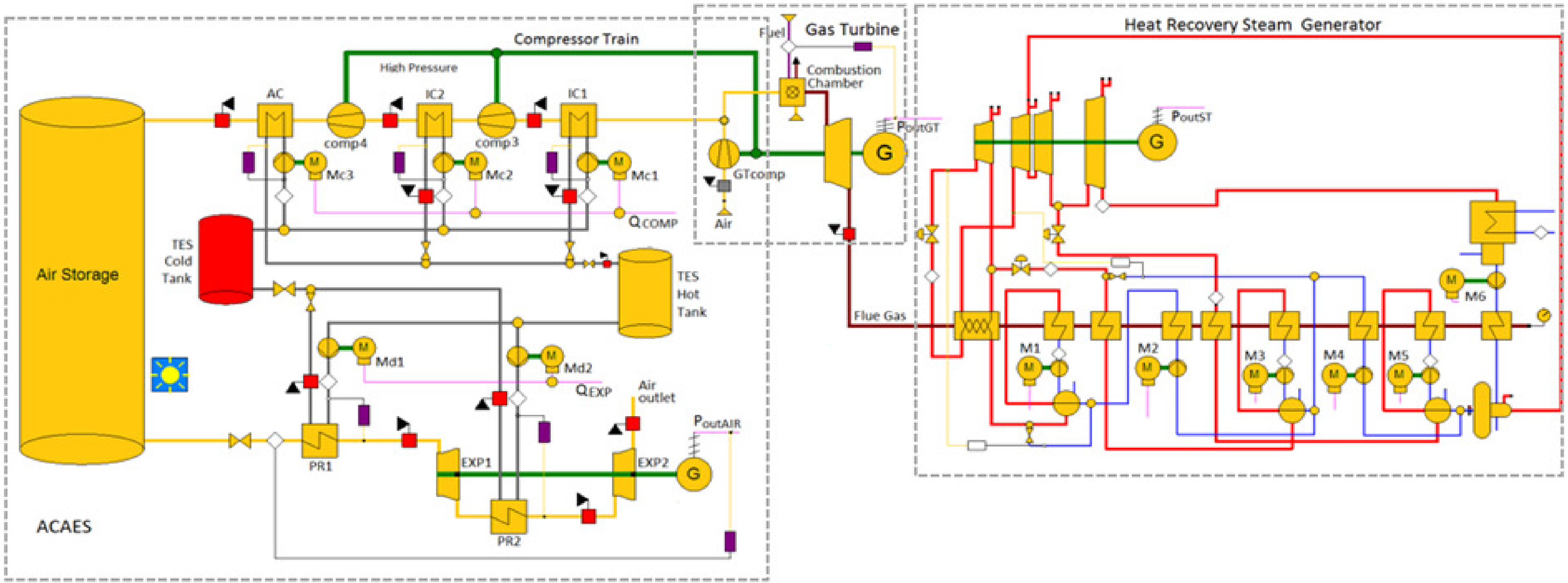


Figure 4. CCGT-ACAES power plant model implementation in EBSILON®Professional.

3. Project progress - HTTS integration

CCGT-ACAES plant

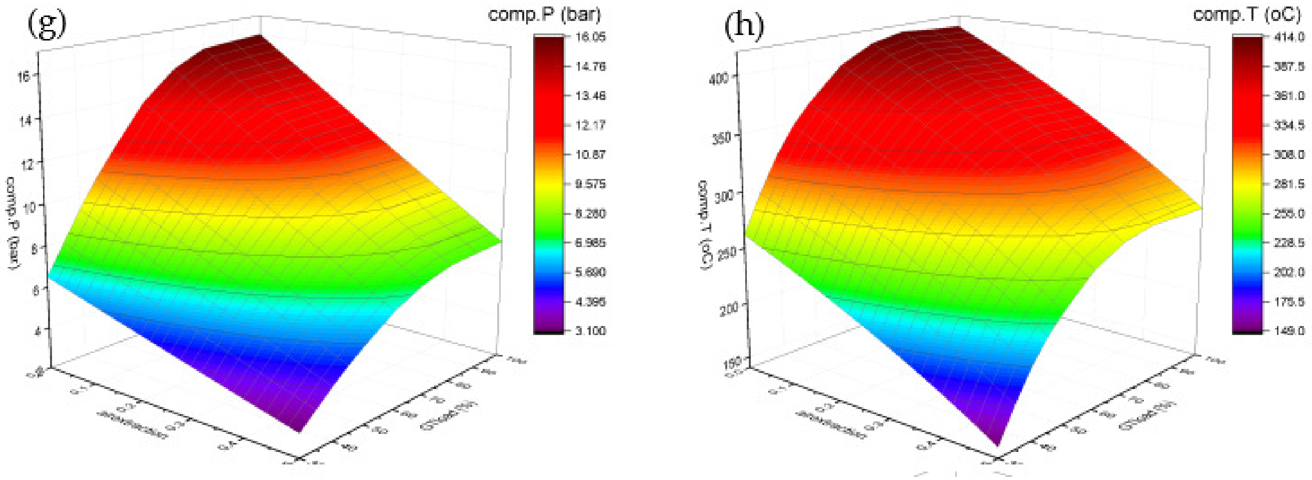


Figure 5. CCGT air extraction experiment results.

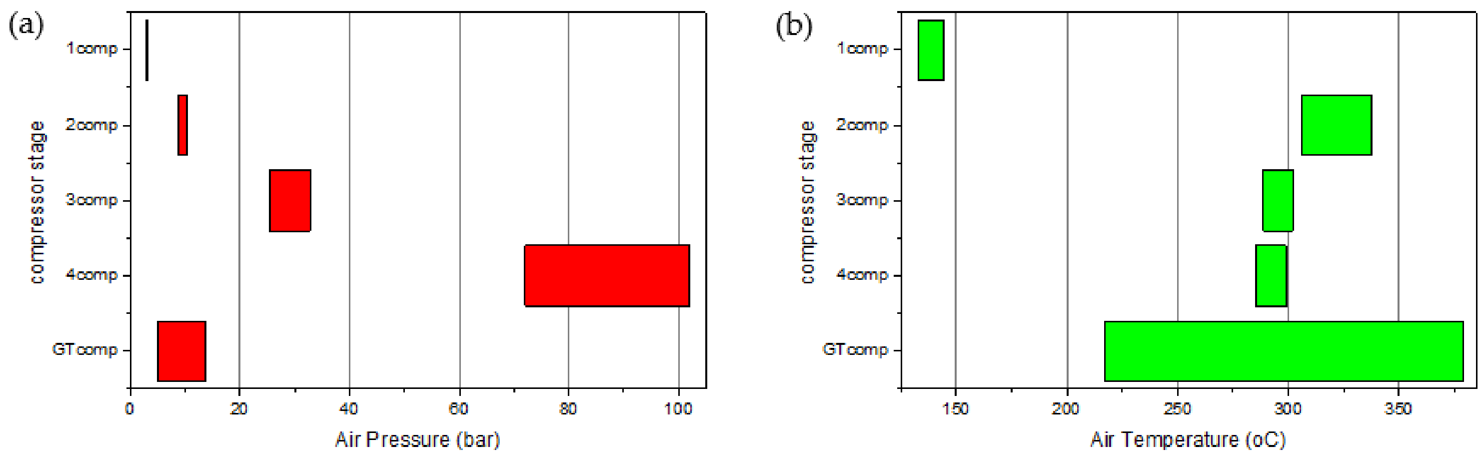


Figure 6. Comparison results for ACAES and CCGT air extraction experiment: a) compressor pressure range; b) compressor temperature range.

3. Project progress - HTTS integration

CCGT-ACAES plant

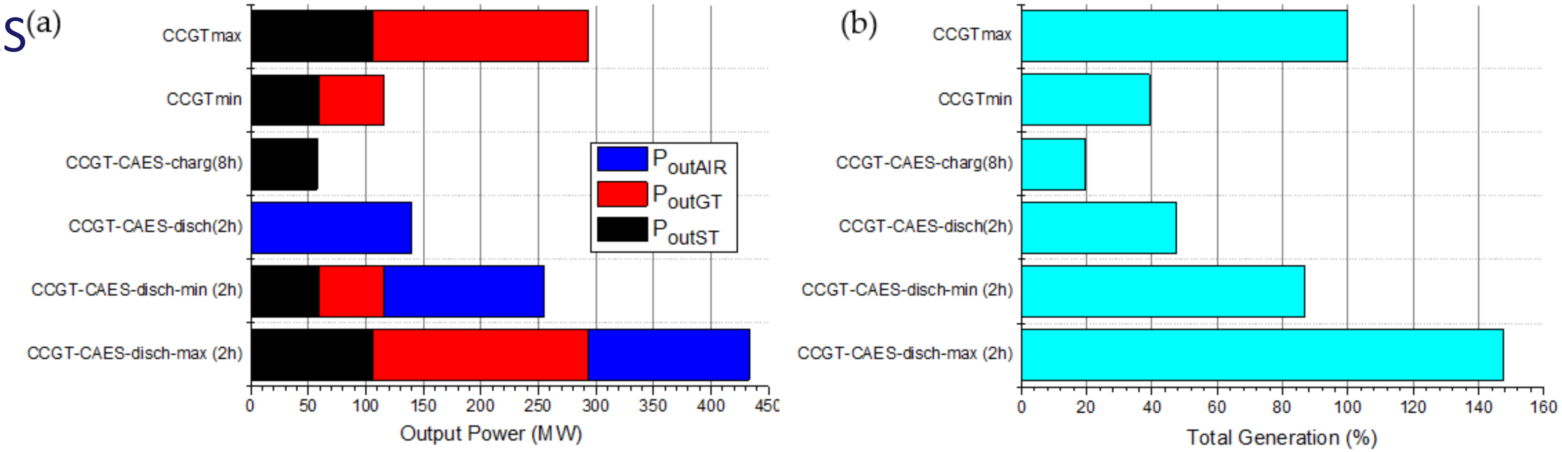


Figure 7. CCGT-ACAES vs CCGT power output for all considering operating modes.

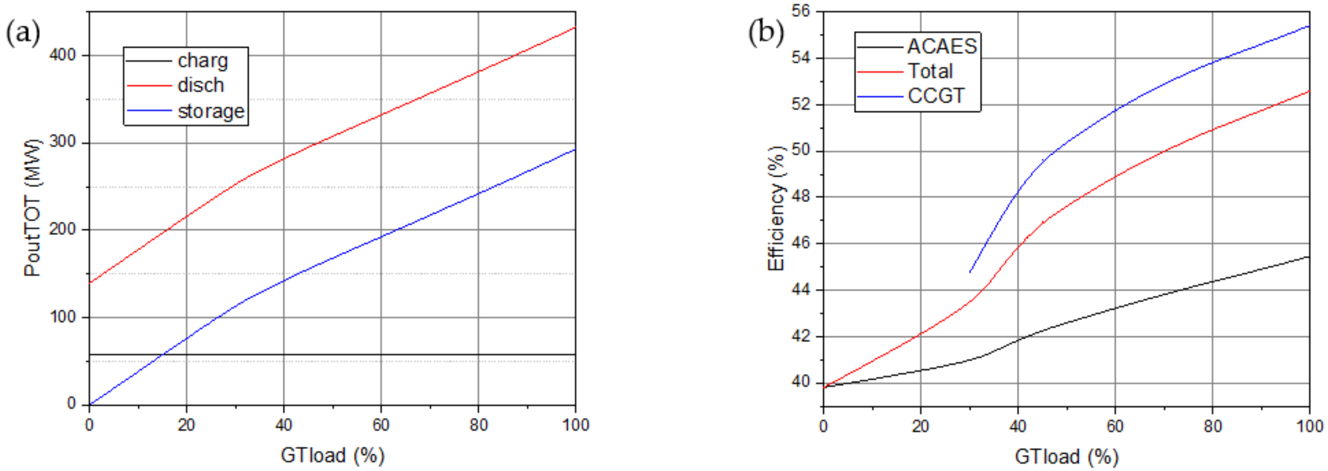


Figure 8. CCGT-ACAES plant model total power generation and efficiency comparison.

J D Wojcik, J Wang: ***Technical feasibility study of Combined Cycle Gas Turbine (CCGT) integration with Adiabatic Compressed Air Energy Storage (ACAES) plant***.

3. Project progress - ES integration

James Lam – PhD candidate

Physics Master's from University of Oxford

- Particular interest in the energy sector
- Master's research in Perovskite PV development

Started PhD in the School of Engineering in May

PhD research aims

- To investigate and optimise the integration of the 50kW battery into the university campus' micro grid system
- To assess the potential benefits of increased interaction with the grid as a VPP

3. Project progress - ES integration

Objectives

- Investigate the interaction between the battery and existing campus assets under varying control scenarios
- Optimise the use of the battery with respect to financial savings and CO_2 emission reduction
- Investigate the potential to use the campus energy system as a VPP, providing grid services and export functionality to the grid

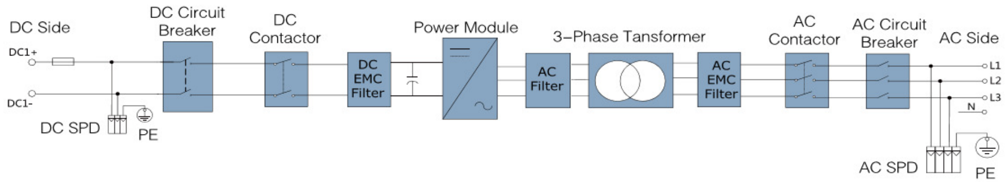
Work

- Use historical metering data to build a model of the campus energy usage
- Compare a range of optimisation algorithms
- Work to implement a control algorithm in the battery unit and investigate the realised changes
- Investigate the potential for combined control of all energy assets with the aim of providing services to the grid as a VPP
- Investigate the expansion of BES on the university campus

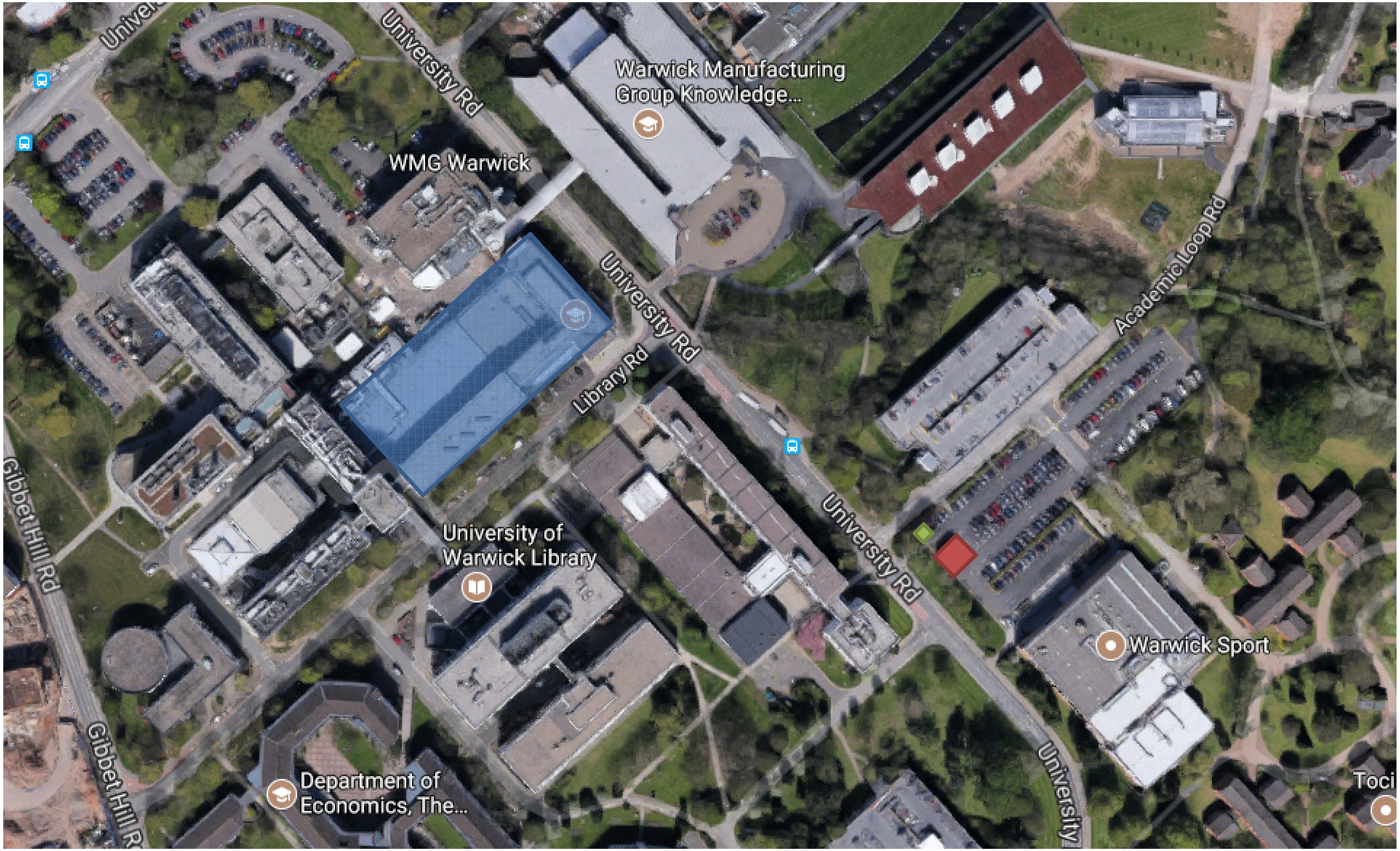
3. Project progress - ES integration

50kW/35kWh Storage System (Li-on battery)

DC Side Parameters	
Max. DC power	670V
working voltage	195~650V
Min. DC voltage	195V
AC Side Parameters	
Nominal power	50kW
Max. AC power	55kVA
Max. AC current	79A
Max. THD	<3%
Nominal grid voltage	400V
Grid voltage range	310~450V
Nominal grid frequency	50Hz
Grid frequency range	47~52Hz
Power factor at nominal power	>0.99
Isolation transforme	Yes
DC current injection	<0.5% at nominal output current
Power factor	0.9 (lagging)~0.9 (leading)
Individual inversion voltage range	370~410V
Individual inversion output voltage distortion	<3% (linear load)
Unbalance load capacity	100%
Individual inversion voltage transition range	Within 10％(resistance load 0%<=>100%)
Efficiency	
Max. efficiency	95.5%
General Data	
Dimensions (W*H*D)	806×1884×636mm
Weight	730kg
Operating Temperature	-30~+55℃
Power Consumption at Stop	<40W
Cooling Method	Temperature-controlled forced air cooling
Protection Degree	IP21
Relative humidity (no condensing)	0~95%，(Non-condensing)
Max. working Altitude	6000m (operation with derating above 4000m)
Display	Touch screen
Dispatch communication	RS485, Etherne
BMS communication	RS485、CAN
Communication protocol	Modbus / IEC104



3. Project progress - ES integration



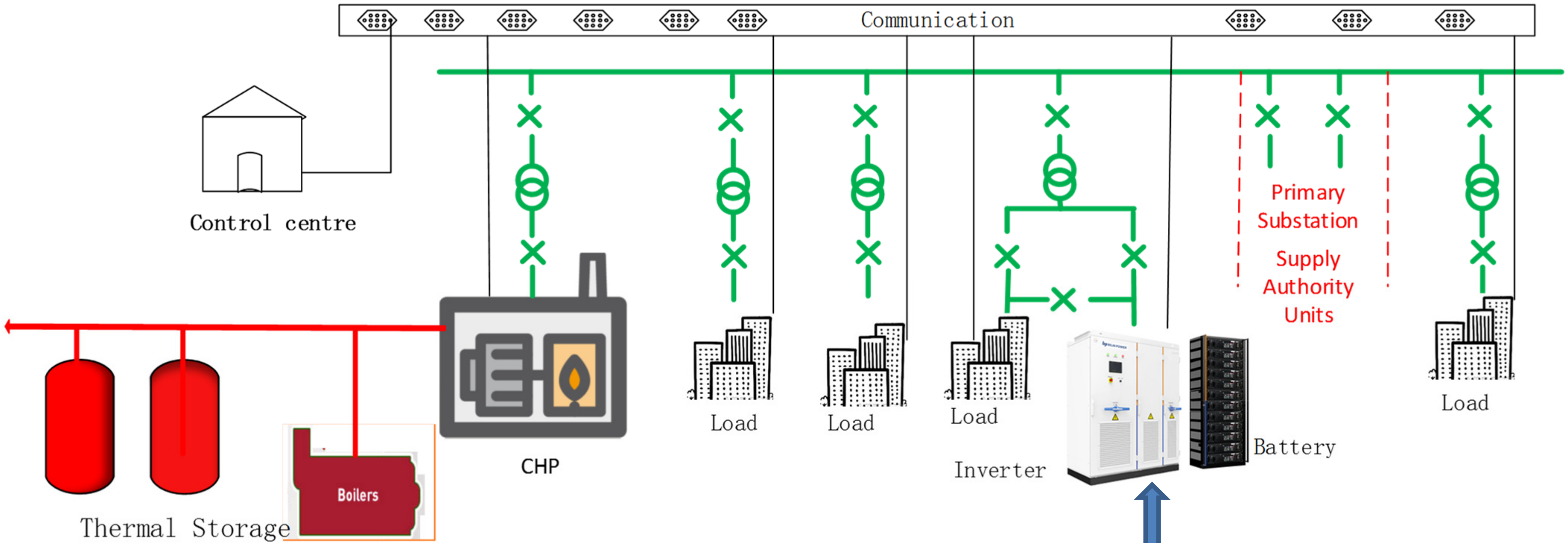
3. Project progress - ES integration

Cooperation Company

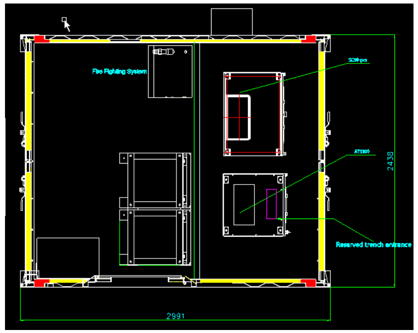
POWER X

3. Project progress - ES integration

University CHP system:



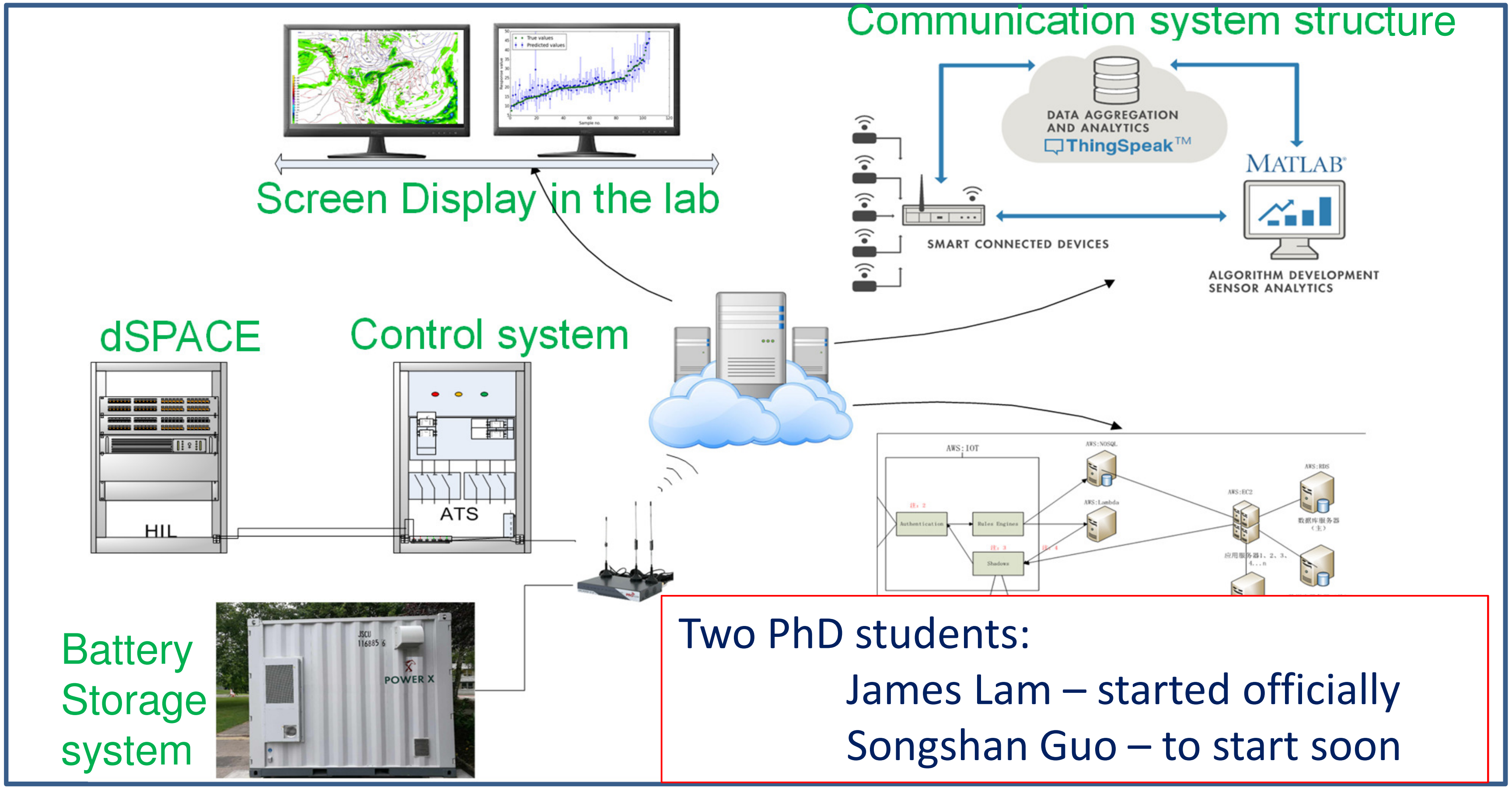
Structure of battery container



3. Project progress - ES integration

New lab for Power and Control Systems Research Laboratory

We will move to a new location in July. The new lab is in the process of refurbishment. The picture is shown below. The new lab has a large open space.



Two PhD students:

James Lam – started officially

Songshan Guo – to start soon

4. Future Work

- To continue working on development of CAES-TES simulation tool – Web (will integrate this task with JUICE project).
- To continue WP1.4 Task 2. CAES specific opportunities in the UK (to support BGS' work?).
- To complete the grid tied inverter to CAES test rig to study its dynamic characteristics when it is connected to grid.
- To extend and improve the grid model simulation block and to study dynamic performance of CAES connecting to grid.
- To extend the project work to study of University CHP integration with energy storage to operate as a Virtual Power Plant in the broad context of grid operation (PhD students, will be continued to JUICE project).
- To conduct feasibility study on integration of CAES to thermal power plant operation process (Jacek).