EPSRC

IMAGES

Research Councils UK Energy For a Low Carbon Future

Integrated Market-fit and Affordable Grid-scale Energy Storage & Compressed Air Energy Storage

Professor Jihong Wang

Power and Control Systems Research Laboratory

School of Engineering, University of Warwick

Coventry CV4 7AL, UK

International Workshop on Energy Storage in the Grid: Low, Medium and Large Scale Requirements

Barcelona, Spain, 10 Jan 2014

WARWICK

PACSR Lab Power and Control Systems

Outline

- The University of Warwick
- IMAGES Research Project
- Overview of Compressed Air Energy Storage

Location

- In Coventry, very central – at the “heart of England”
- In the centre of the manufacturing region
- 60 minutes from London by train

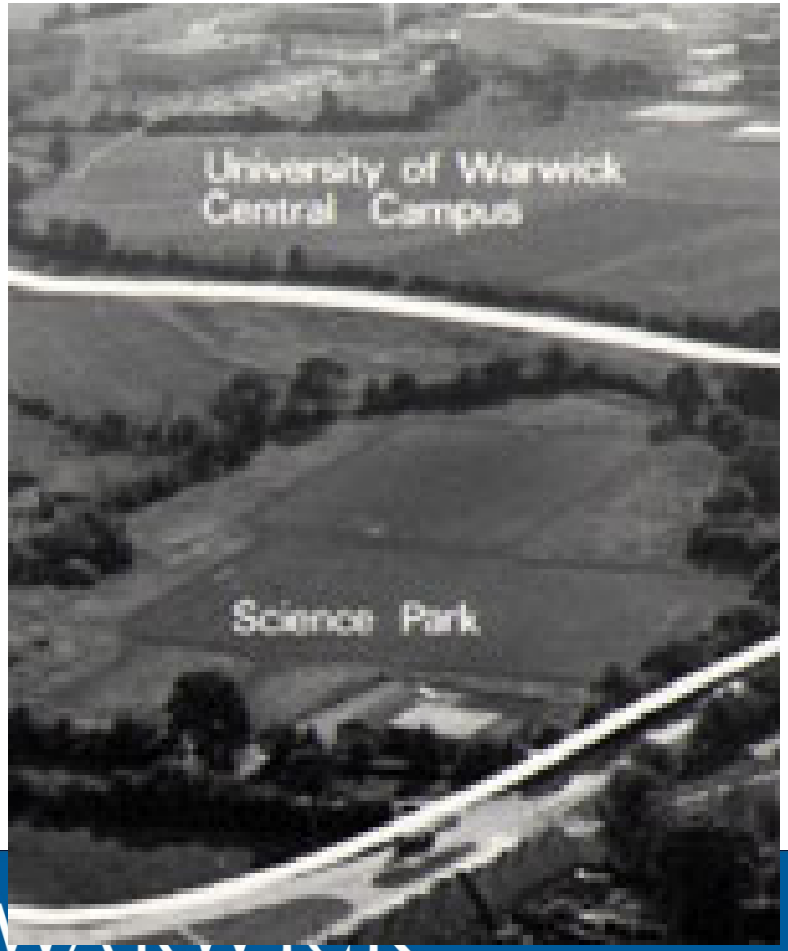
WARWICK

PACSR Lab

History of the University

Established in 1965

First student intake: 450



The University – fact

Consistently ranked in the **top 10** of UK universities:

5th - The Times Good University Guide, June 2012
8th - The Times Good University Guide, June 2013

The results of the 2008 Research Assessment Exercise (RAE) reiterate Warwick's position as one of the UK's leading research universities, with Warwick ranked at **7th overall in the UK**. 65% of Warwick's research is 'world-leading' or 'internationally excellent' (Quality level of either 3* or 4*)

The best <u>modern</u> university in the UK!

Outline

- The University of Warwick
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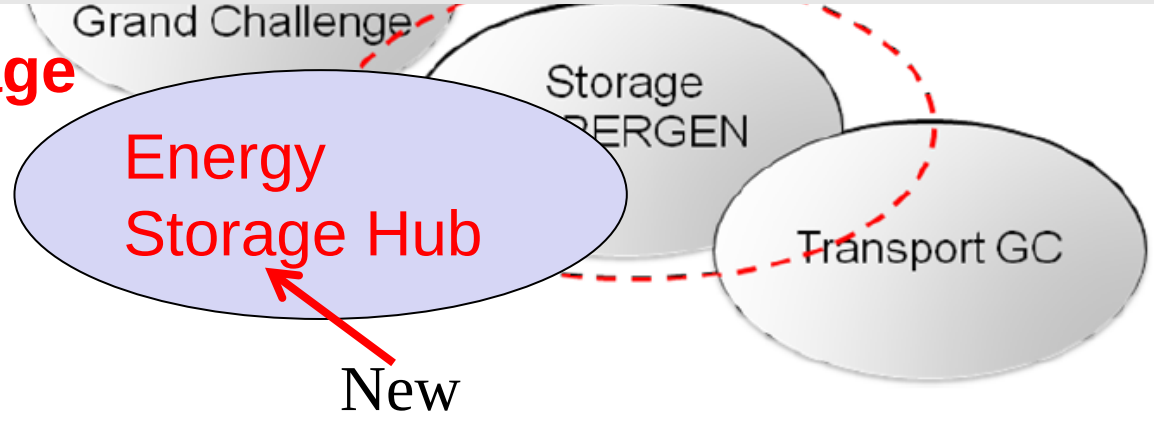
Overview of EPSRC Energy Storage Research in the UK

Two Grand Challenge Programme Projects:

1) Energy storage for low carbon grid (led by Imperial College London)

2) Integrated market-fit and affordable grid scale energy storage (IMAGES, led by Warwick)

Energy Storage for Grid 2013



Integrated Market-fit and Affordable Grid-scale Energy Storage

IMAGES

The Consortium (Total Funding (FEC)3.7m from EPSRC UK)

THE UNIVERSITY OF WARWICK — J Wang, M Waterson, R MacKay, M Giullietti, P Mawby, R Critoph

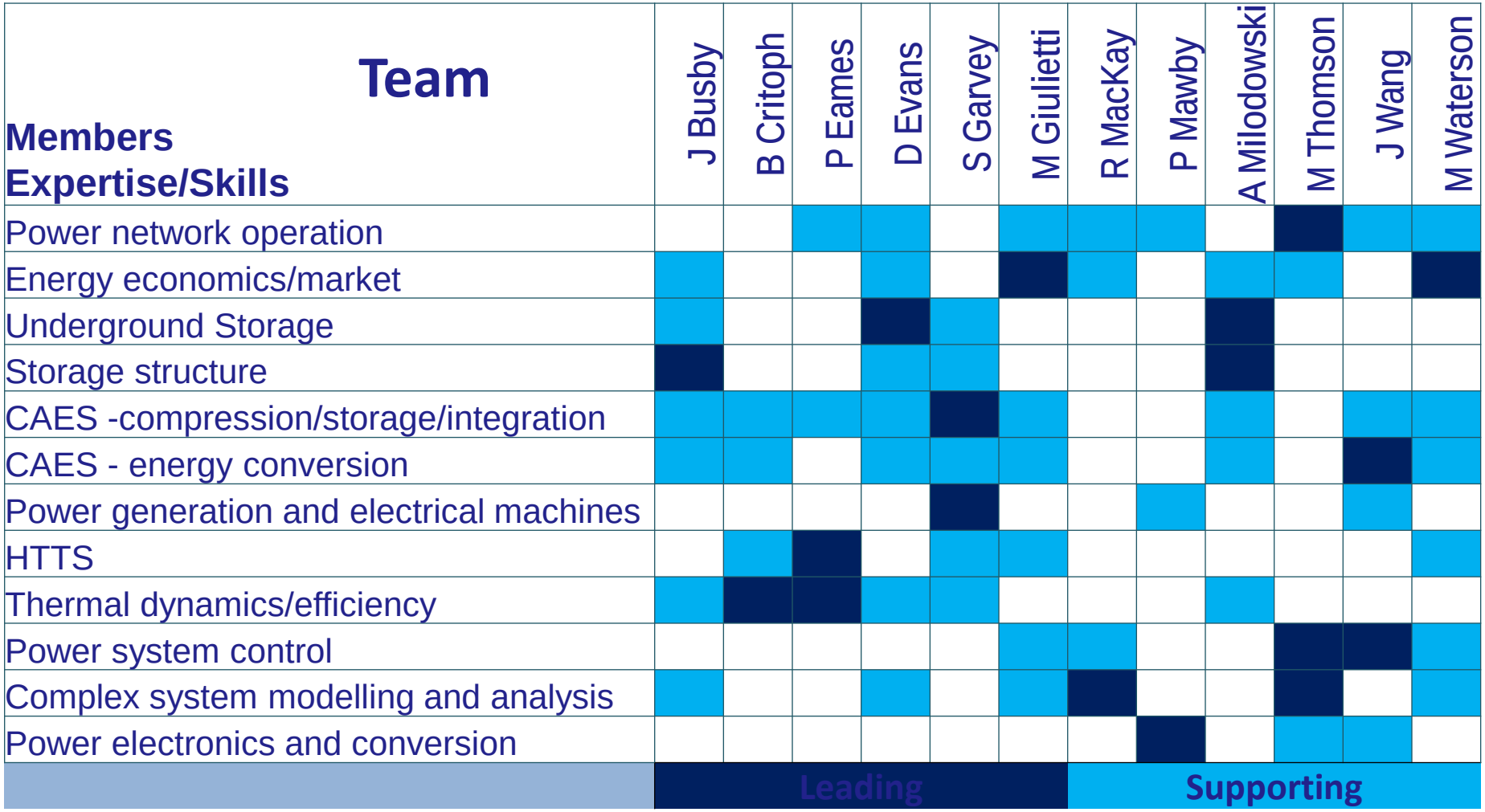
The University of Nottingham — S Garvey

Loughborough University — P Eames, M Thomson

BGS 1835 British Geological Survey, NATURAL ENVIRONMENT RESEARCH COUNCIL — D Evans, J Busby, A Milodowski

The Consortium

The Team


Team
Members
Expertise/Skills
J Busby
B Critoph
P Eames
D Evans
S Garvey
M Giulietti
R MacKay
P Mawby
A Milodowski
M Thomson
J Wang
M Waterson
Power network operation
Energy economics/market
Underground Storage
Storage structure
CAES -compression/storage/integration
CAES - energy conversion
Power generation and electrical machines
HTTS
Thermal dynamics/efficiency
Power system control
Complex system modelling and analysis
Power electronics and conversion
Leading
Supporting

Industrial Partners

ALSTOM Grid

nationalgrid

e·on

GE

Rolls Royce

Gaelectric
POWER FROM NATURE

COSTAIN

Gateway

Pnu Power
An Energetix Group Company

Eni Saipem s.a.

INEOS Enterprises

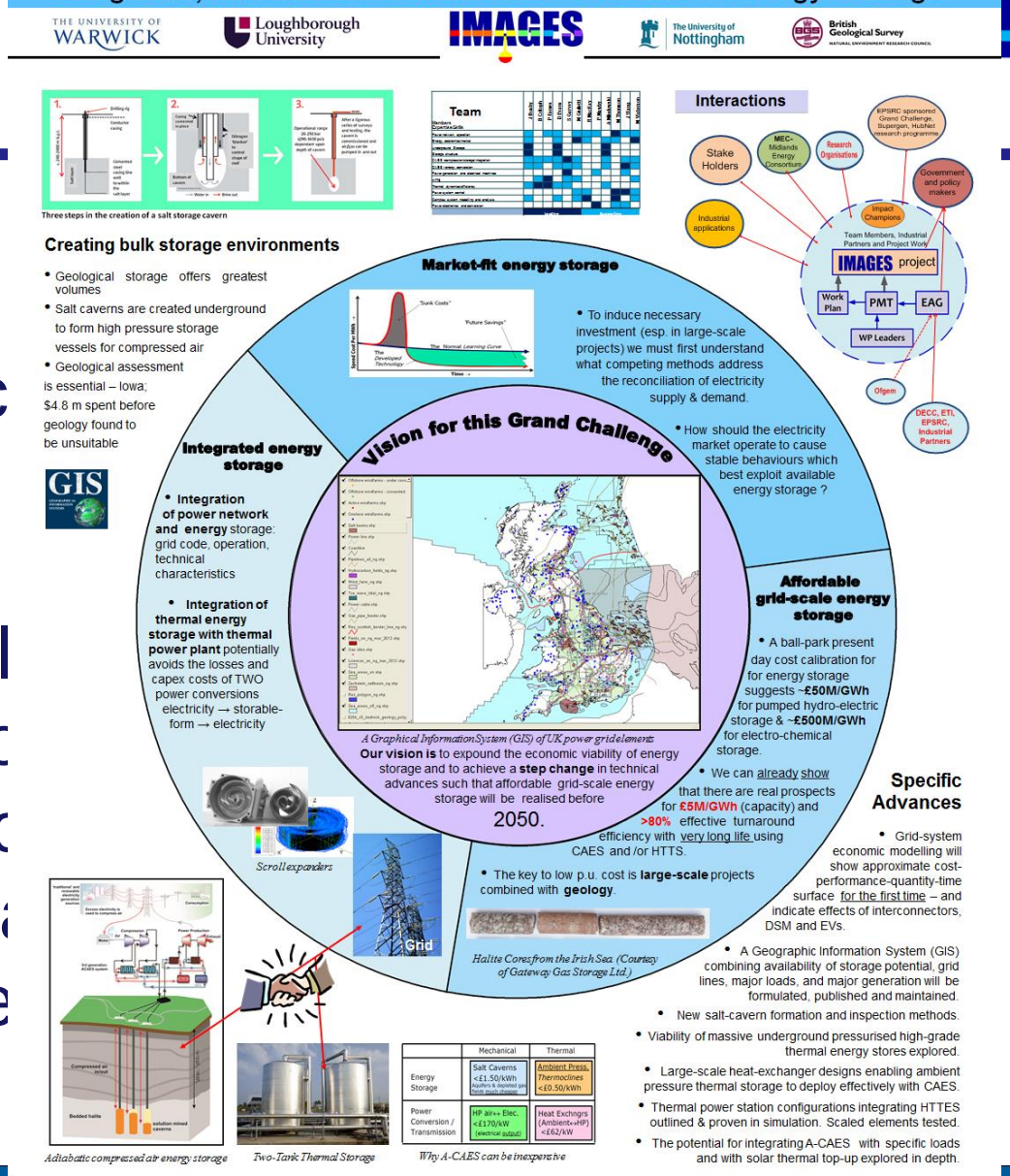
Atlas Copco

Highview Power Storage

IMAGES Project Brief

Vision :

- to expound the ec storage
- to achieve a step required technical storage for techno
- to pioneer technic affordable grid-sca will be realised be



WARWICK

CSR Lab

What we aim to achieve :

Economic analysis :
- to reveal the multi-dimensional true values of ES
- to identify the way for maximising the value of ES

Support → Policy makers, Investors

Network analysis:
- to clarify the role of ES from demand and supply balance
- to exam network operation rule for ES integration

→ Regulations, Operators

Support

Techno-economic-network analysis:
- to derive a matrix of performance/cost of ES
- to exam technical characteristics for network integration

Support → Guidance for technology development

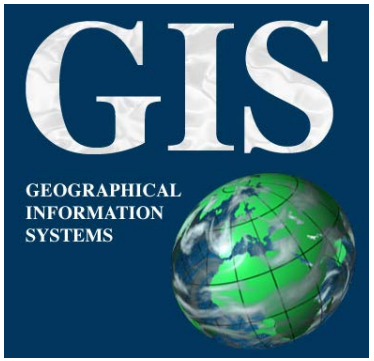
To provide essential information to government policy makers and regulation bodies
To support UK industry for technology development

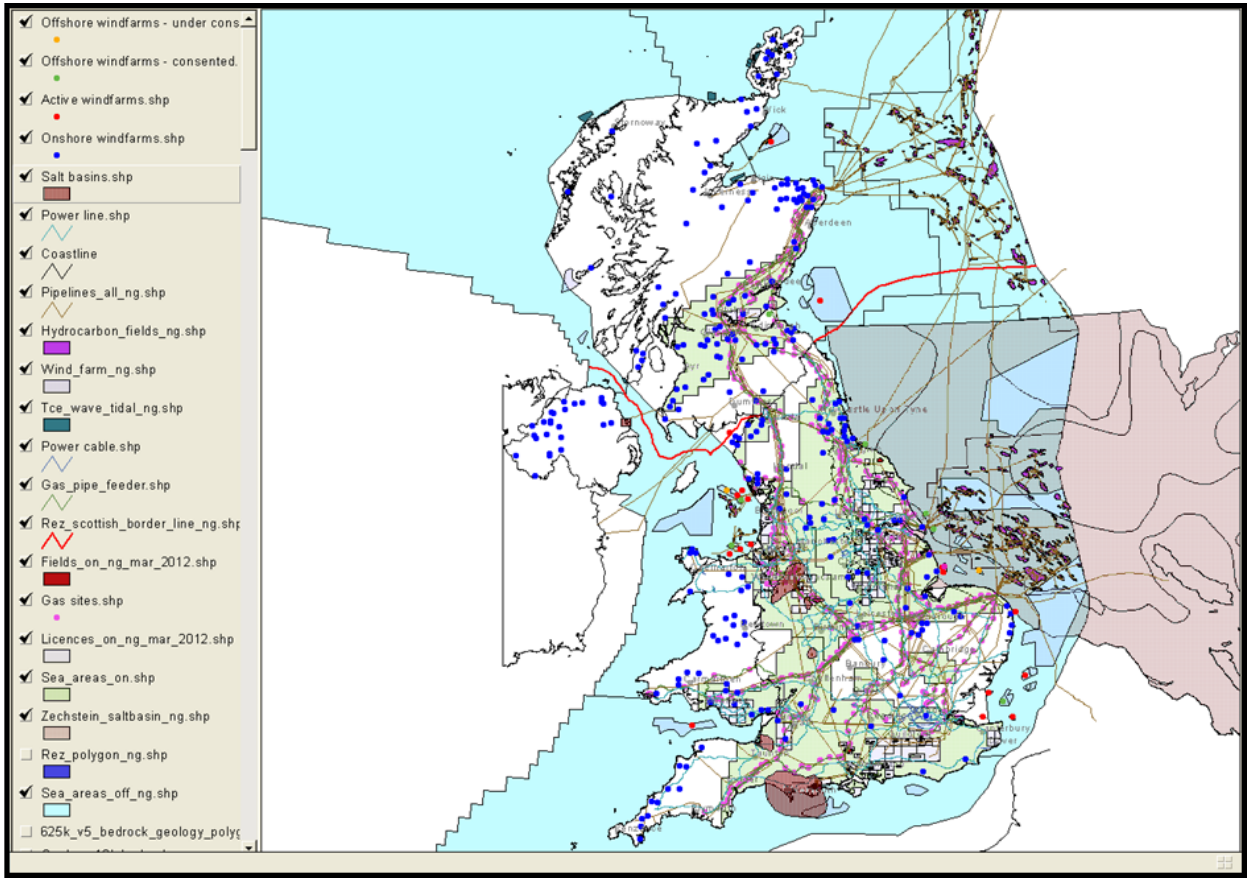
What we aim to achieve :

- to gain a clear picture of national storage resources (CO2, Compressed Air, Gas, H2, Thermal etc) and its map to the renewable power generation locations

Support → Energy system planning and policy

The information will be available from GIS





What we aim to achieve :

Technology breakthrough –

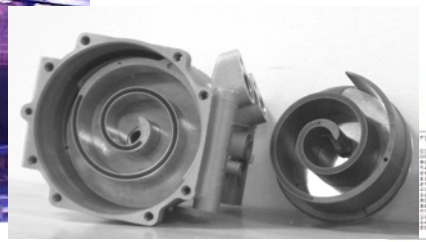
Technology for potential deployment

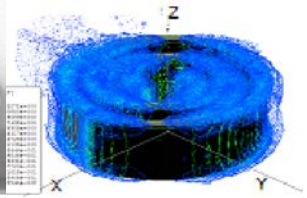
Compressed Air Energy Storage

- 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

Support →

To maximise renewable energy penetration





What we aim to achieve :

Technology innovation –

Technology for potential deployment

High Temperature Thermal Storage:

- 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

Support → To turn inflexible CCS and nuclear plants to flexible plants

IMAGES Project Brief

- Kick-off: Oct. 2012
- Four reports are drafted for comments within the team members:
  - An overview of electricity network operation (Dr Lisa Flatley)
  - Overview of electrical energy storage technologies (Dr Xing Luo, J Wang and J Clarke)
  - Revenues from storage in a competitive electricity market (M Giulietti, L Grossi, M Waterson)
  - EERA report: Overview of current development of compressed air energy storage (X Luo and J Wang)
- Project progress:
  - three patents filed
  - the first version of simulation tool for CAES is developed to be completed soon
  - etc
- Project website

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About Us | News and Events | Project Infomation | Contact Us | Team Intranet

File Share » Review Meeting on the 30/05/13

Review Meeting on the 30/05/13

Maps to First floor Seminar Romm in Energy Technologies Building (ETB), Nottingham University

Nottingham University Jubilee Campus Map

Energy Technologies Building 1st floor map

Details of the Review Meeting on the 30/05/13

Web Address: http://www2.warwick.ac.uk/energystorage

Actuator Dynamics - S G Garvey

BGS Progress Report - D Evans, J Busby, A Milodowski, L Field and D Parke

The economic value of energy storage - L Flatley

University of Warwick Progress Report - X Luo

(old infomation)

Maps to C25 in the Coates Building, Nottingham University

Nottingham University Campus Map

Coates building 3rd floor map with C25

IMAGES Proje
School of Engineering
University of Warwick
Coventry
CV4 7AL, UK
email: J.H.A.Clarke@w

Personal Summary

Details of the Review Meeting on the 30/05/13

PACSR Lab

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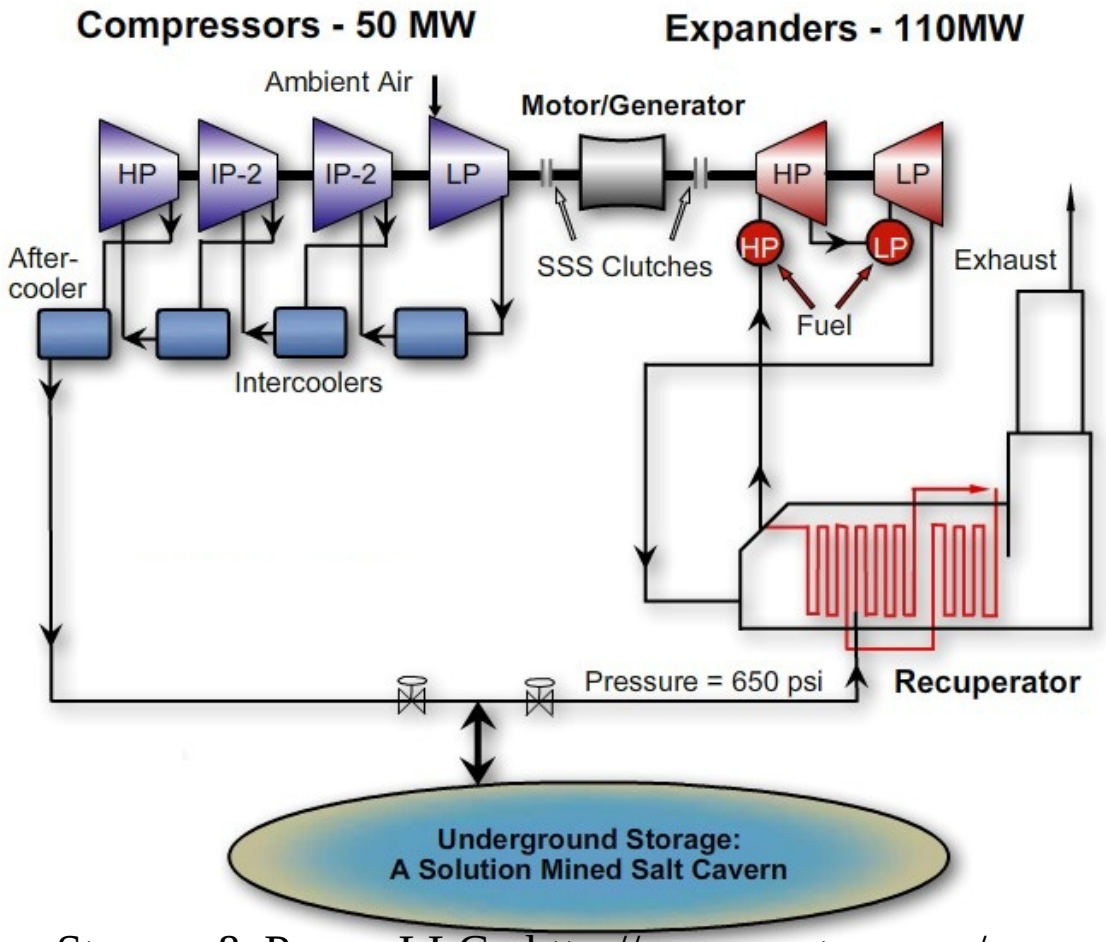
Compressed Air Energy Storage – Grid Scale

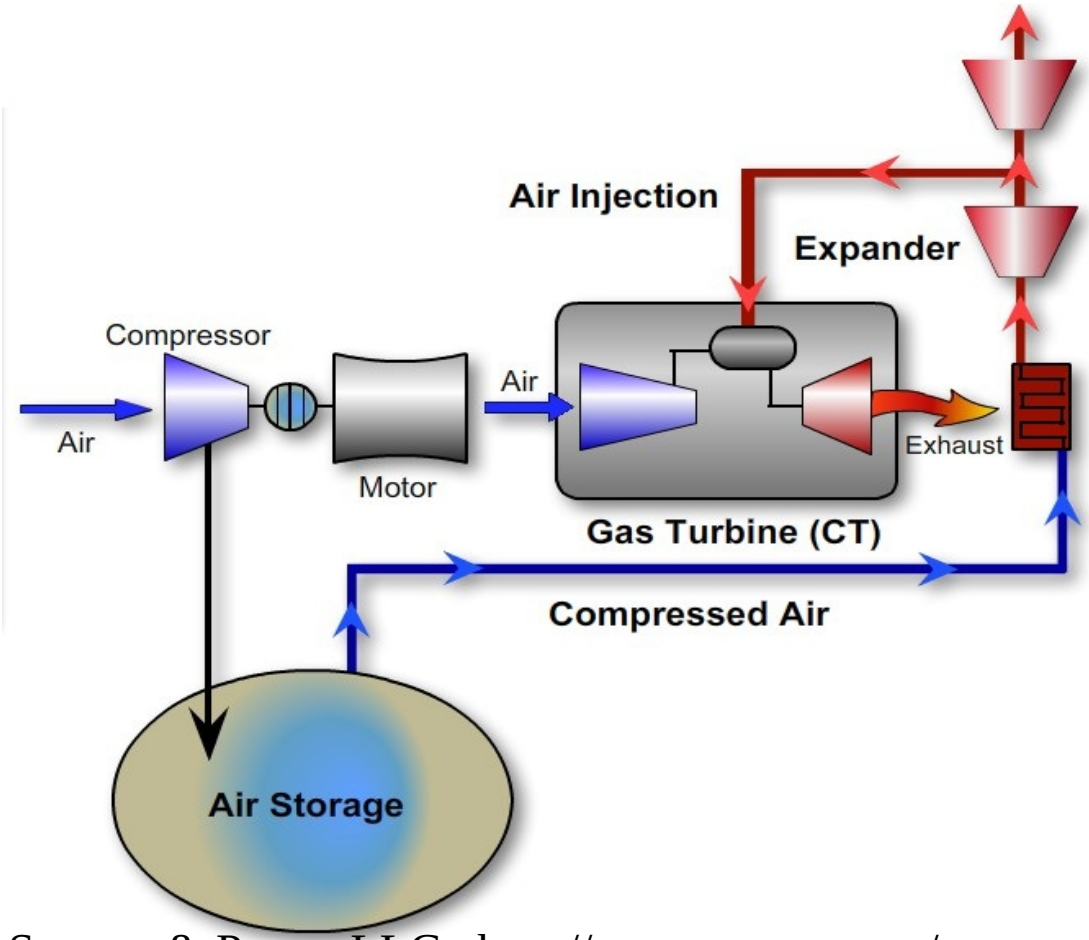
First generation CAES system



Courtesy to Conven Energy Storage & Power LLC, http://www.enstpo.com/

Compressed Air Energy Storage – Grid Scale

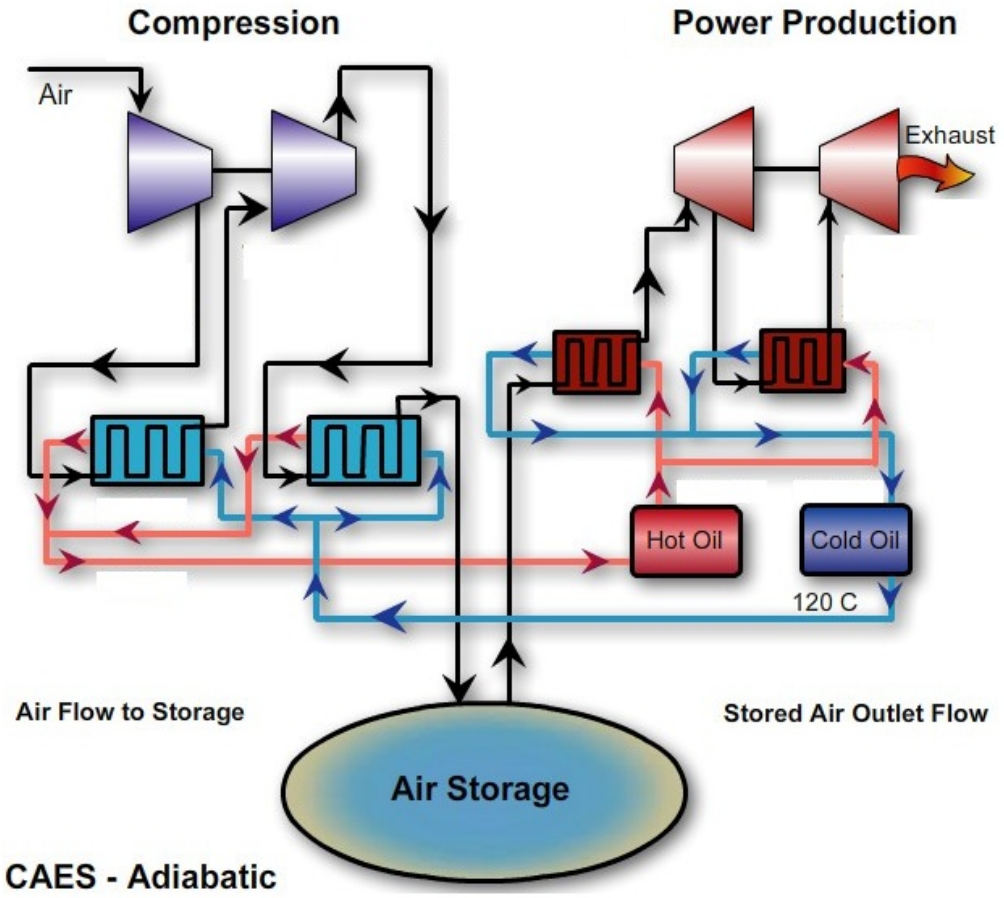
Second generation CAES system



Courtesy to Conven Energy Storage & Power LLC, http://www.enstpo.com/

Compressed Air Energy Storage – Grid Scale

Third generation CAES system



Courtesy to Conven Energy Storage & Power LLC, http://www.enstpo.com/

Compressed Air Energy Storage – Grid Scale

Today world-wide two plants exist:

1. Huntorf, Germany built in 1978, charging power 60 MWe (8 hrs), discharge power 321 MWe (2 hrs)

2. McIntosh, USA built in 1991, charging power 60 MWe (45 hrs), discharge power 110 MWe (26 hrs)

Compressed Air Energy Storage – Grid Scale

ADELE – Adiabatic compressed-air energy storage (CAES) for electricity supply (RWE) in development

Compressed Air Energy Storage – Grid Scale

LTA - Low Temperature Adiabatic CAES

Figure 3:
energy st

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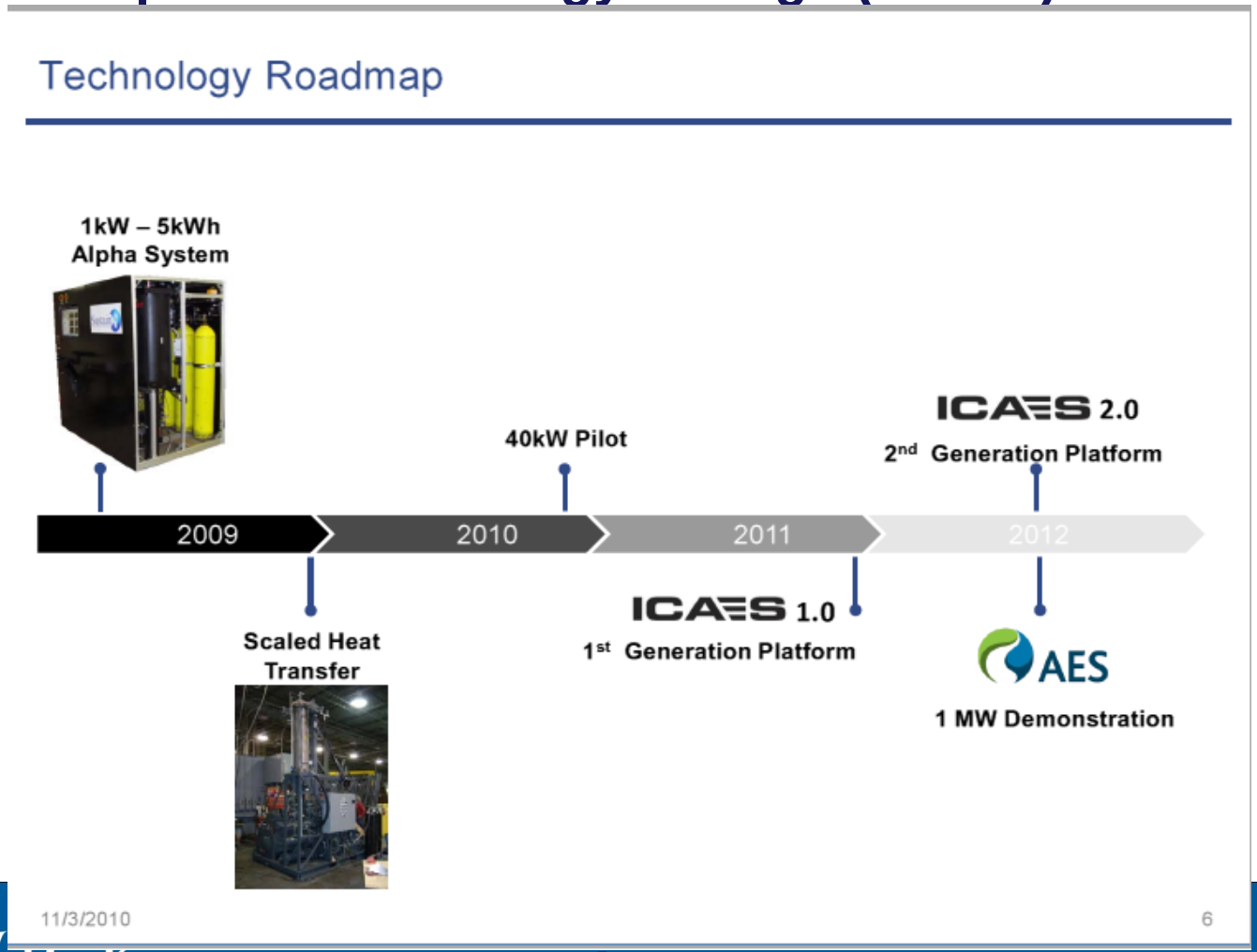
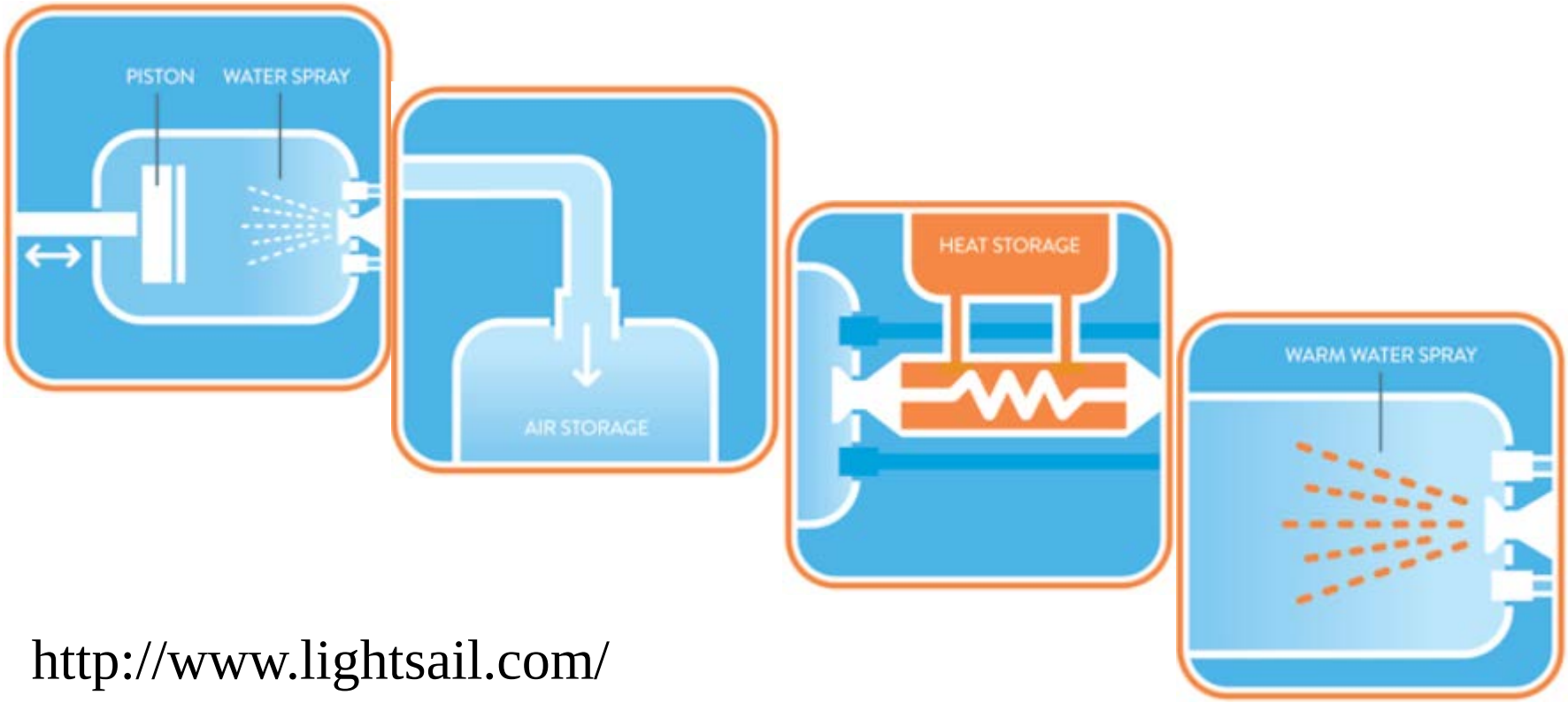
Compressed Air Energy Storage – Grid Scale/Small Scale

Isothermal compressed air energy storage (ICAES) – SustainX



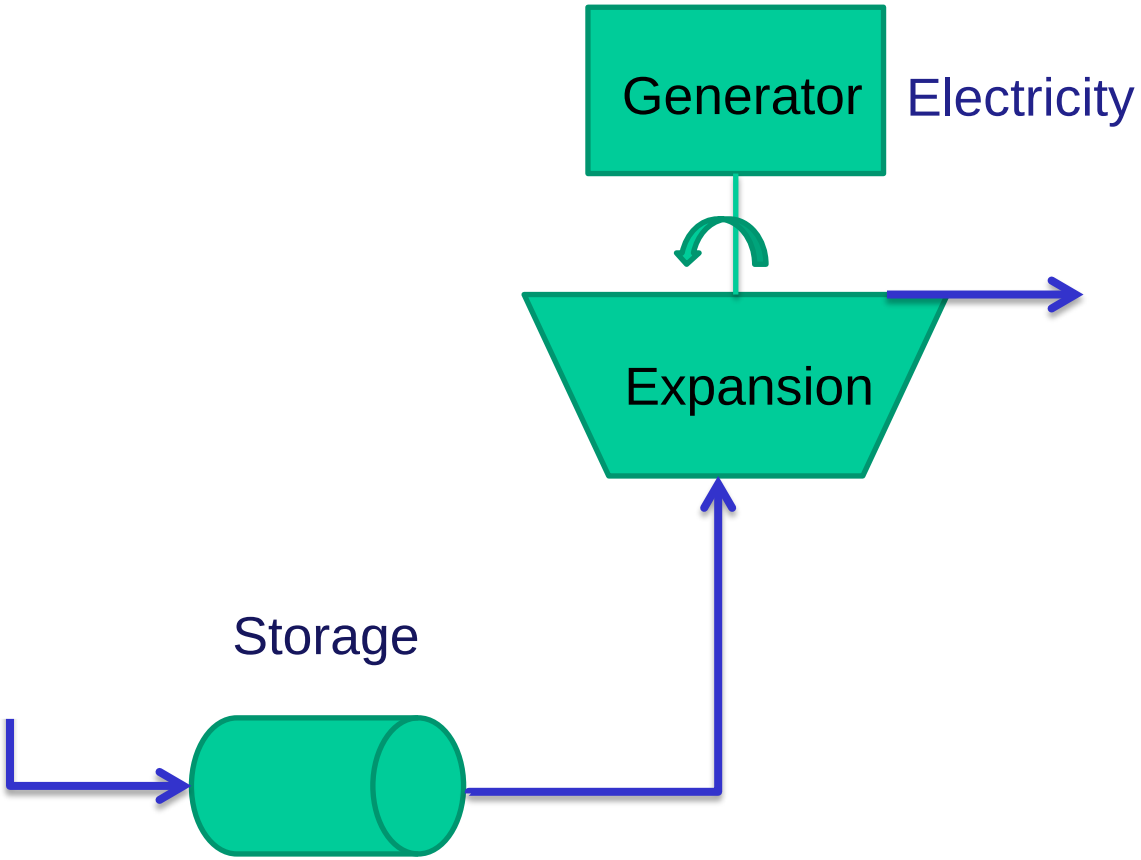
Compressed Air Energy Storage – Grid Scale/Small Scale

Technology of LightSail Energy



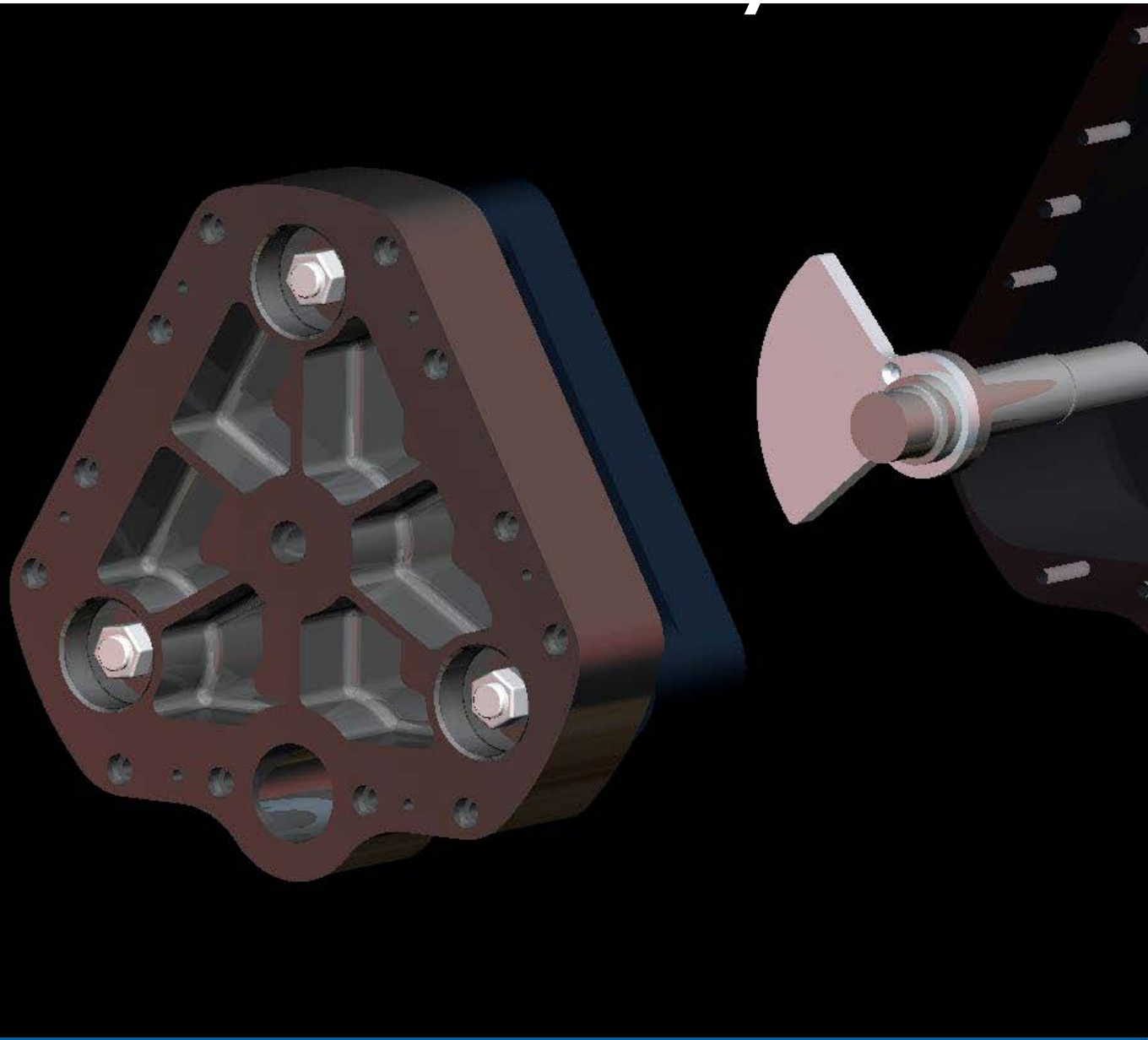
http://www.lightsail.com/

Compressed Air Energy Storage – Battery



Pnu Power
An Energetix Group Company

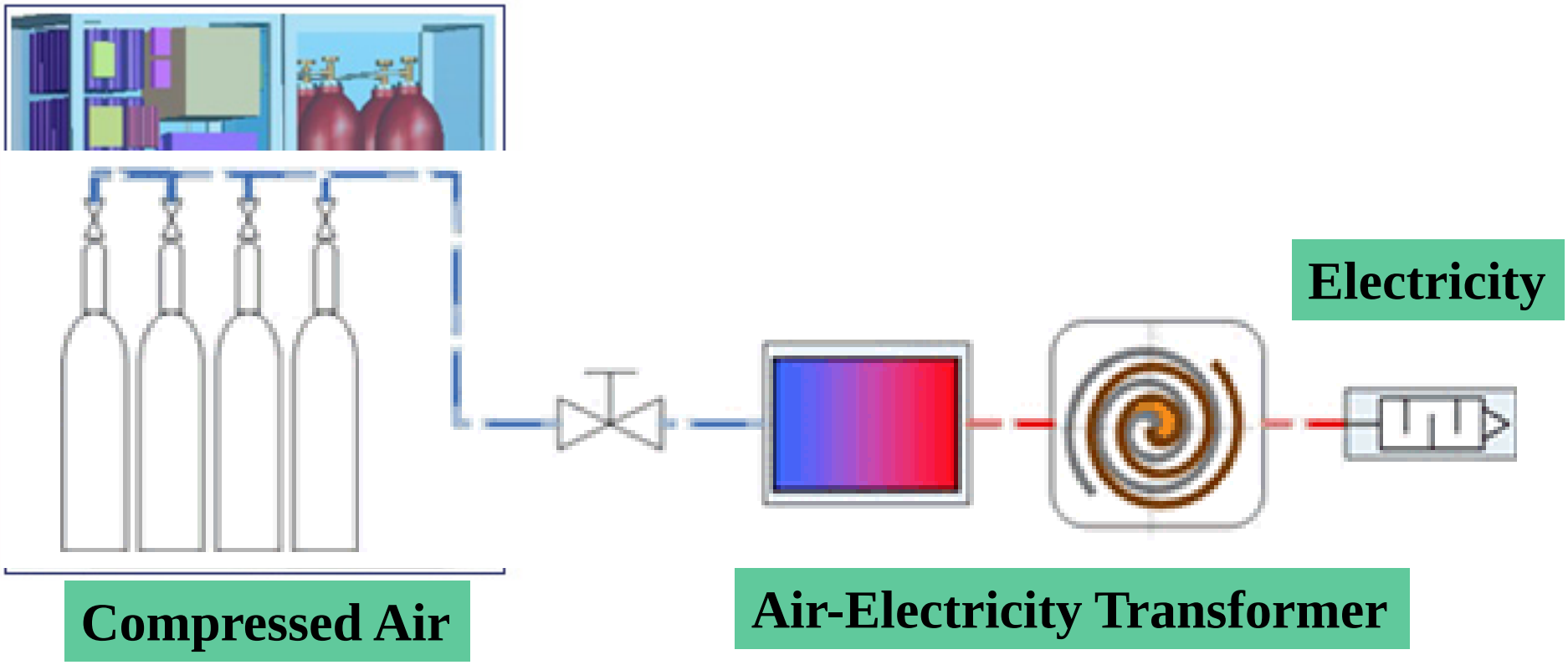
flowbattery
Performance Standby Products



WARWICK

Compressed Air Energy Storage - UPS

Project: 2005-2007 (with Energetix Group)



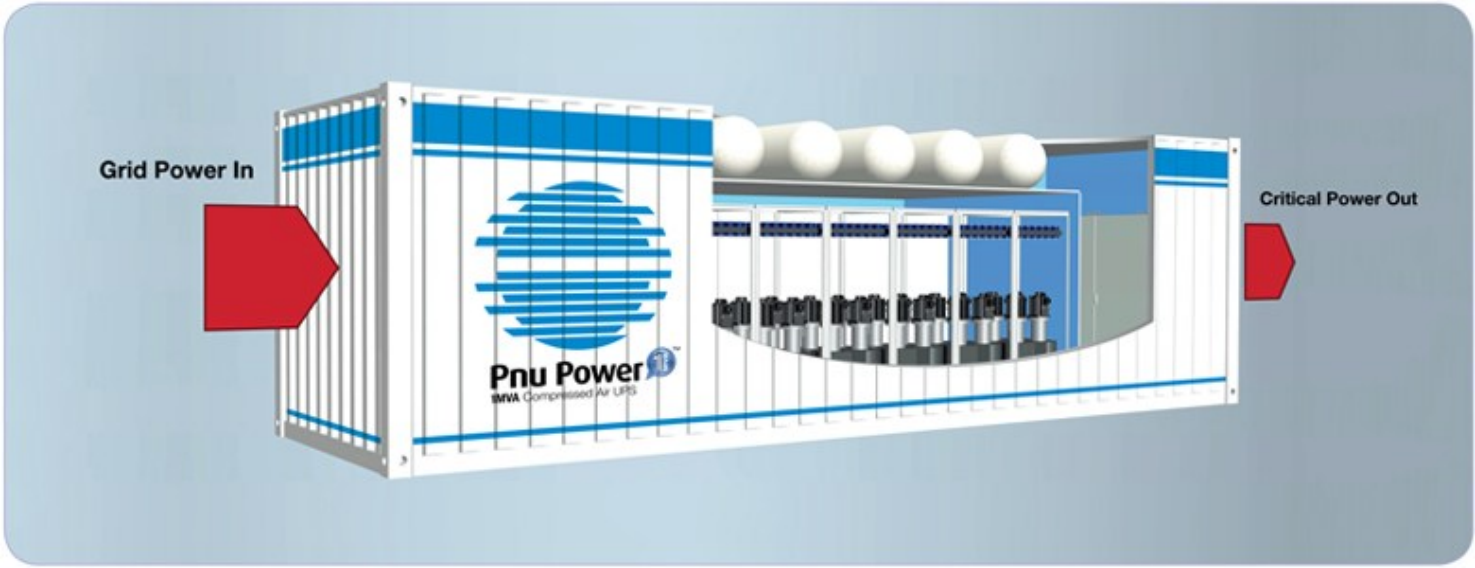
Courtesy to Pnu-Power

Compressed Air Energy Storage - UPS

100/200kW

10kW

3kW



nationalgrid

- National Grid UK – Capenhurst, Cheshire - June 2009
- Utility Switching 400 / 235kV Substation
- 8kW peaking unit for 6 hours backup
- No issues, no maintenance in 4 years

flowbattery
Performance Standby Products

Military – Energy Recycling - Application

- ATK Thiokol – Utah, USA – October 2009
- Grid Connect Peak Shaving – Energy Recycling from waste (?) compressed air
- 40kW Parallel System

flowbattery
Performance Standby Products

The co-operative financial services

Broadcast Application

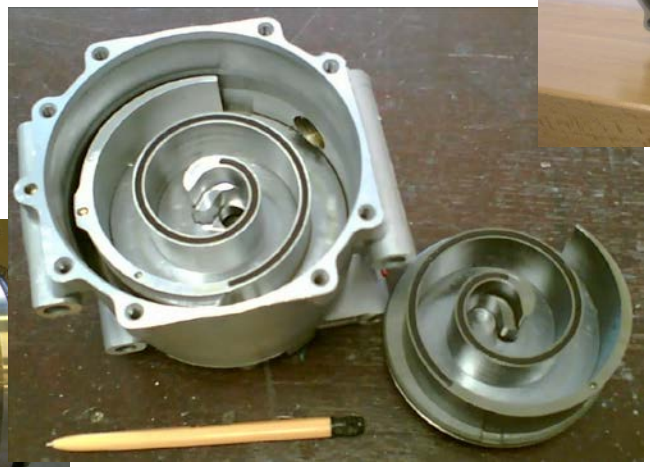
“ good with air ”

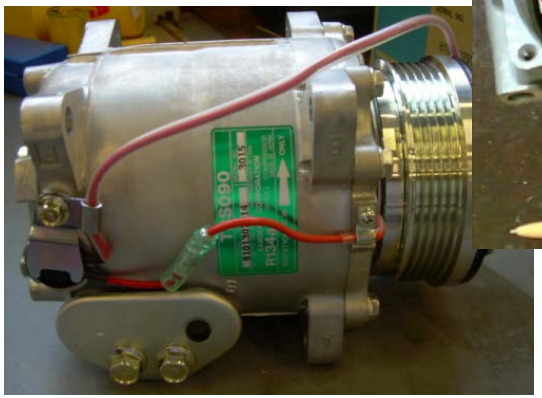
- CFS – Kings Valley Pyramid, Stockport, UK – April 2012
- 300kW unit – ride through to generator start
- Data Centre application

flowbattery
Performance Standby Products

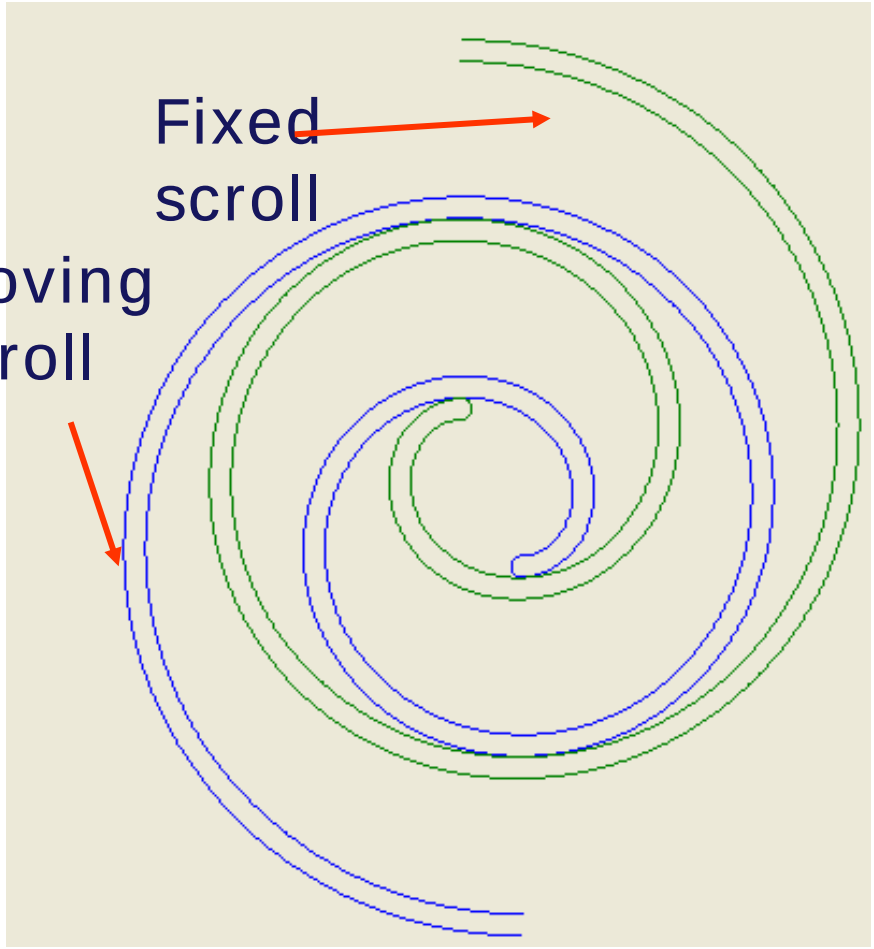
Compressed Air Energy Storage

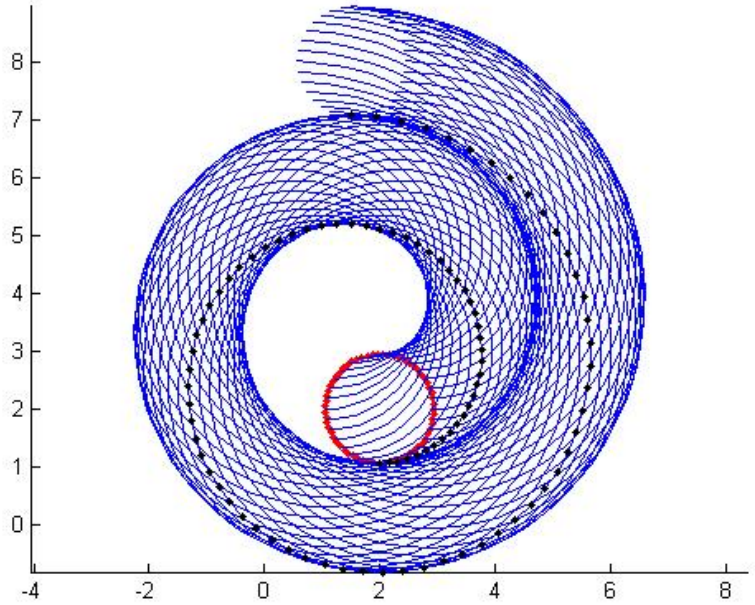
Key Component: Scroll Expander





Compressed Air Energy Storage



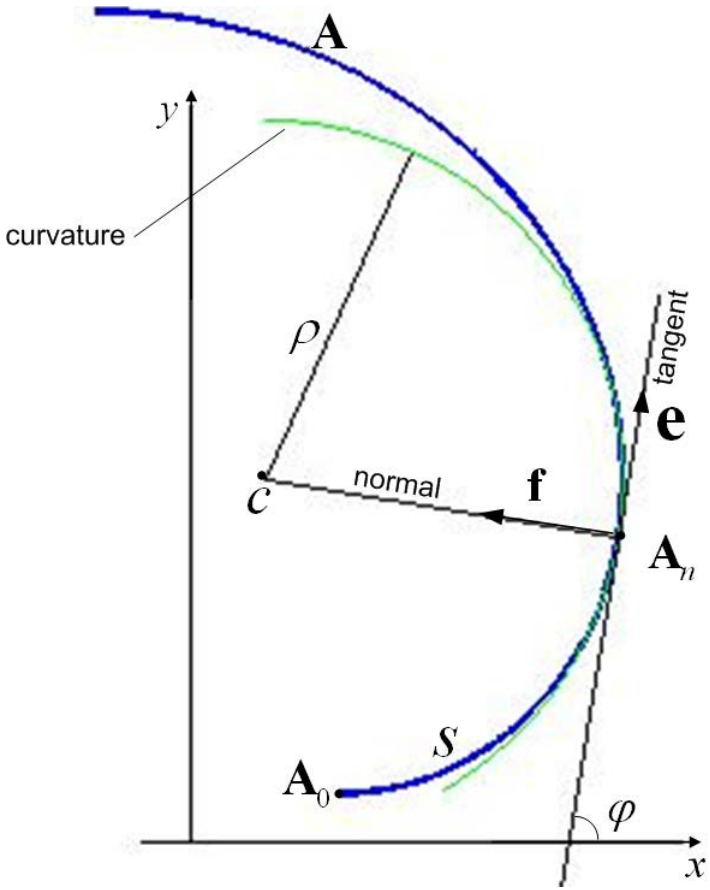


Scroll 1

Scroll 2

Scroll 3

Mathematical model of the scroll air motor



Basic geometry of a scroll

A : the scroll

c : the centre of the curvature

e : unit vector that is tangent to the curve

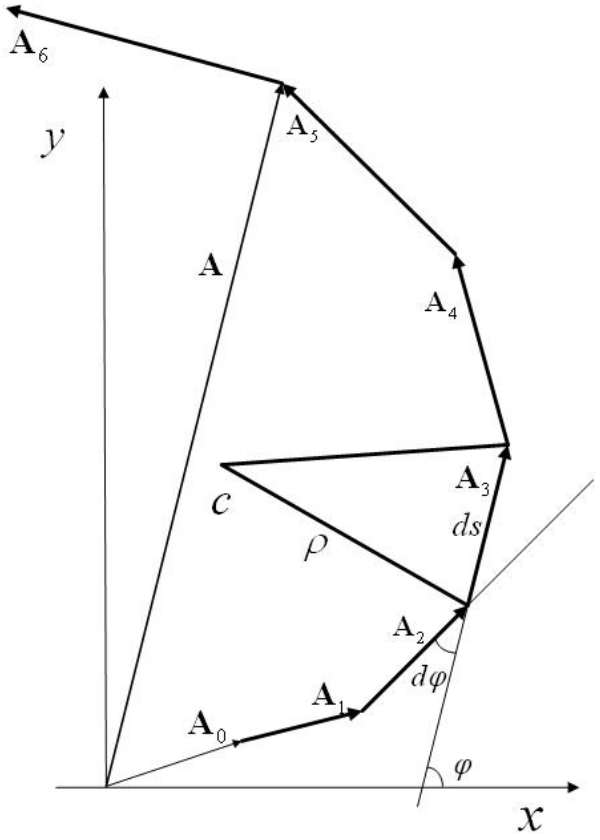
f : unit vector that is perpendicular to the curve

s : length of the arc between $\mathbf{A}_0$ and $\mathbf{A}_n$

φ : tangential angle

ρ : radius of curvature

Mathematical model of the scroll air motor



Equations for scroll geometry

$$\text{Q } \mathbf{A}_i = ds(\cos\varphi, \sin\varphi) \text{ and } ds = \rho(\varphi)d\varphi$$

$$\therefore \mathbf{A} = \sum_{i=1}^{n} \mathbf{A}_i = \int_0^{\varphi} \rho(\varphi)(\cos u, \sin u)du$$

$$\rho = \rho_0 + k\varphi$$

$$\rho' = k$$

Mathematical model of the scroll air motor

Volume calculation of a sealed chamber

According to Green's Theorem

The area of yellow region

$$Area = \frac{1}{2}\int_{\alpha}^{\alpha+\pi} -y_A(\varphi)d\left(x_A(\varphi)\right) + x_A(\varphi)d\left(y_A(\varphi)\right)$$

$$+\frac{1}{2}\int_{\alpha-\pi}^{\alpha} -y_B(\gamma)d\left(x_B(\gamma)\right) + x_B(\gamma)d\left(y_B(\gamma)\right)$$

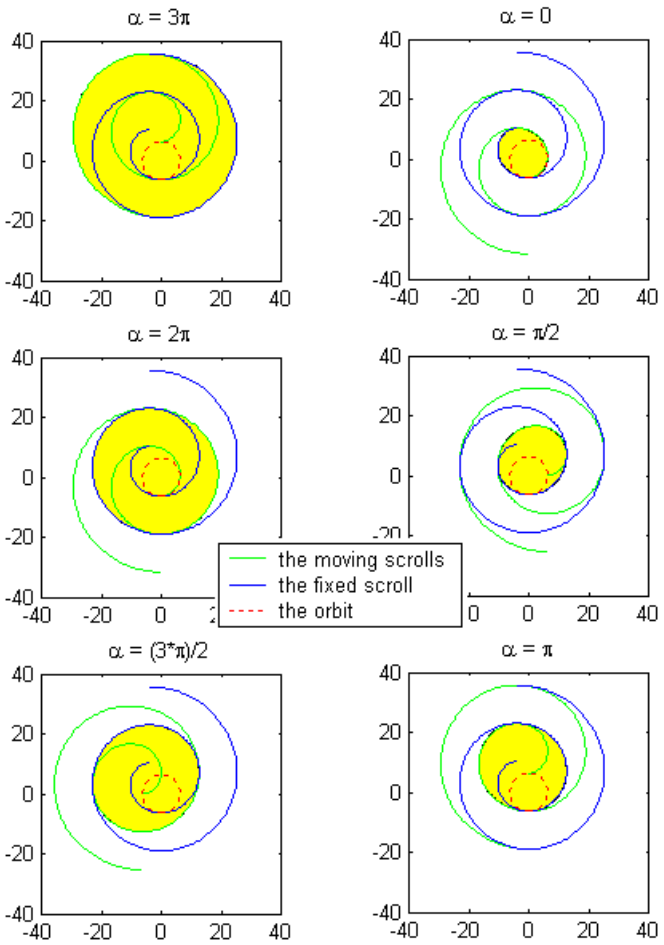
x, y: horizental, vertical coordinates

A,B: subscription of the moving, fixed scroll

α: orbit angle

φ: tangential angle of the moving scroll

γ: tangential angle of the fixed scroll



Mathematical model of the scroll air motor

(1) $\dot{x}_1 = x_2$

(2) $\dot{x}_2 = \frac{1}{J}\left(\tau - M_f x_2\right)$

(3) $\dot{x}_3 = -\frac{\dot{V}_c}{V_c}\gamma x_3 x_2 + \frac{1}{V_c} R\gamma c_0 c_d c_k \sqrt{T}\, p_s XX_{\max} f\left(p_s / x_3\right)$

(4) $\dot{x}_4 = -2k\gamma x_4 x_2 / \left(r + 2\rho_0 + 2k\pi + 2kx_1\right)$

(5) $\dot{x}_5 = \begin{cases} -2k\gamma x_5 x_2 / \left(r + 2\rho_0 + 2k\pi + 2k\left(x_1 + 2\pi\right)\right) & \alpha \in [0,\pi] \\ p_{\text{atm}} & \alpha \in (\pi, 2\pi) \end{cases}$

Dynamic process

$$\tau = \begin{cases} zr[(2\rho_0 + 2k\alpha + k\pi)(x_3 - x_4) \\ +(2\rho_0 + 2k\alpha + 5k\pi)(x_4 - x_5) \\ +(2\rho_0 + 2k\alpha + 9k\pi)(x_5 - P_{\text{atm}})] & \alpha \in [0,\pi] \\ zr[(2\rho_0 + 2k\alpha + k\pi)(x_3 - x_4) \\ +(2\rho_0 + 2k\alpha + 5k\pi)(x_4 - P_{\text{atm}})] & \alpha \in (\pi, 2\pi) \end{cases}$$

x_1: orbit angle

x_2: angular speed

x_3: pressure in the central chamber

x_4: pressure in the first side chamber

x_5: pressure in the second side chamber

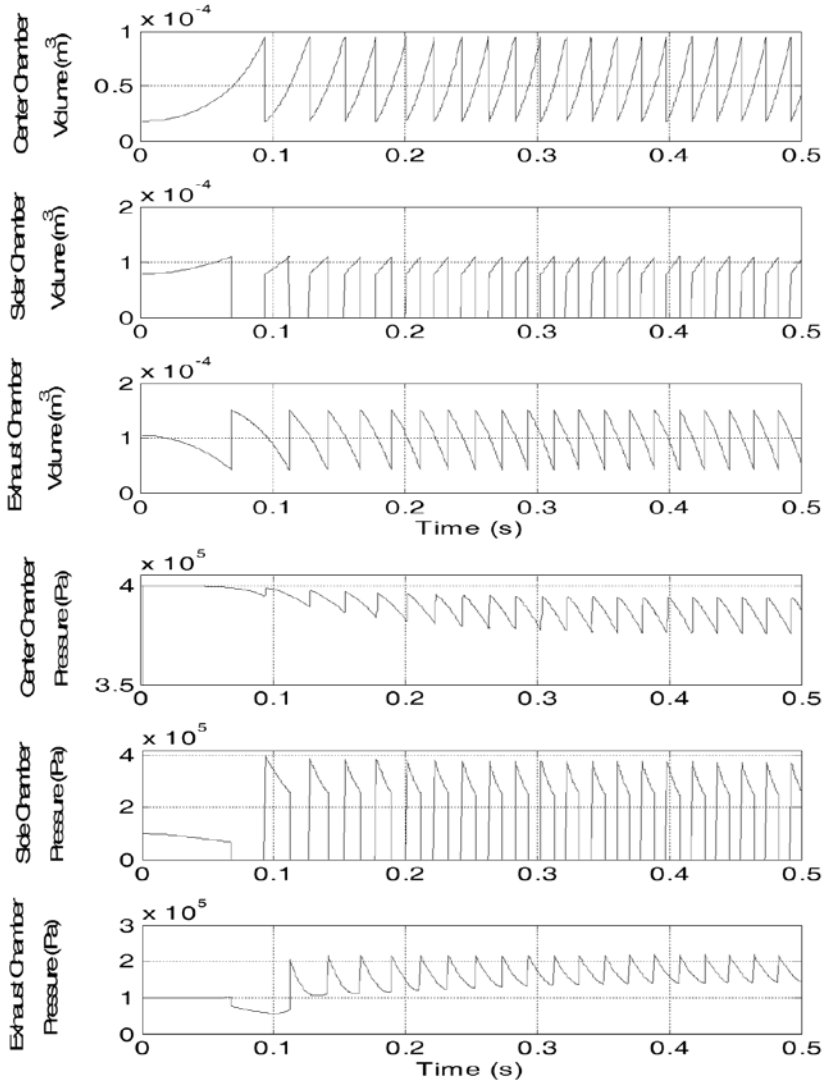
Mathematical model of the scroll air motor

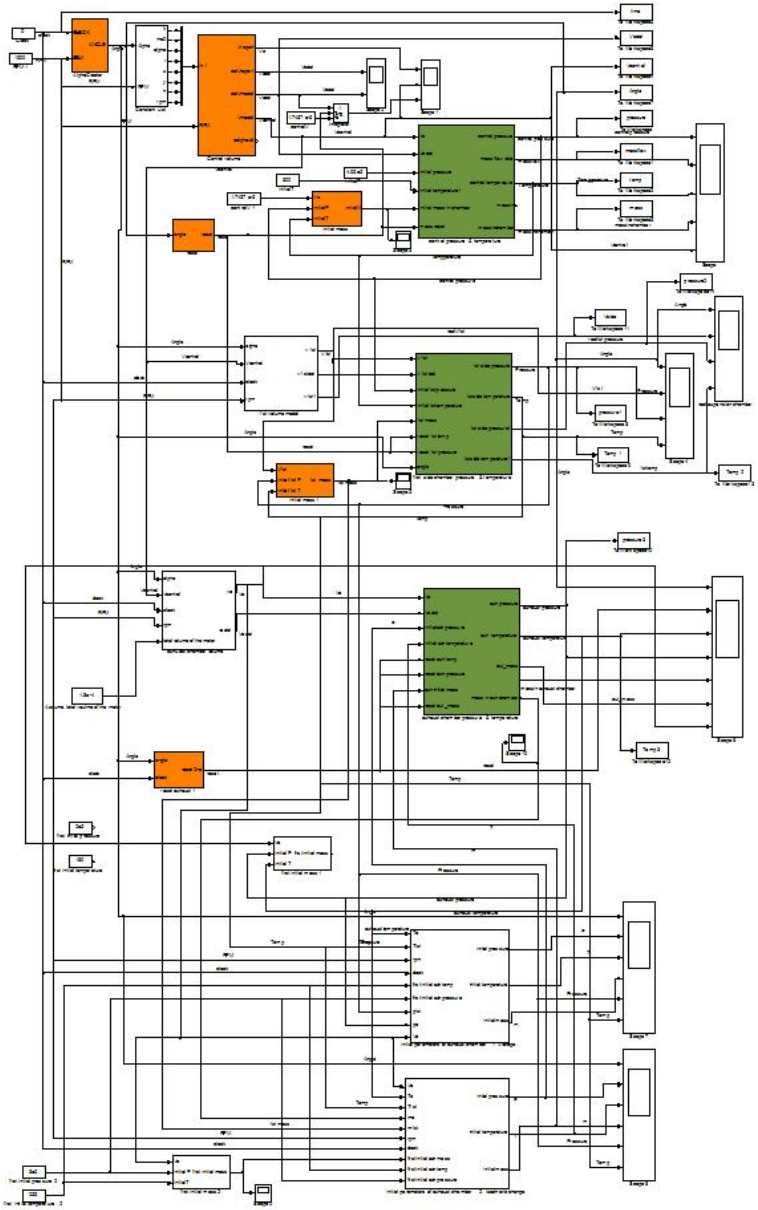
Considering the thermal process, the model is modified

$$[\dot{X}_{air}] = \frac{d}{dt}\left(\frac{n}{V}\right) = \frac{\dot{n}}{V} - \frac{\dot{V}n}{V^2} = \left(\frac{\dot{m}}{M}\right)/V - \frac{\dot{V}}{V^2} \times \frac{m}{M}$$

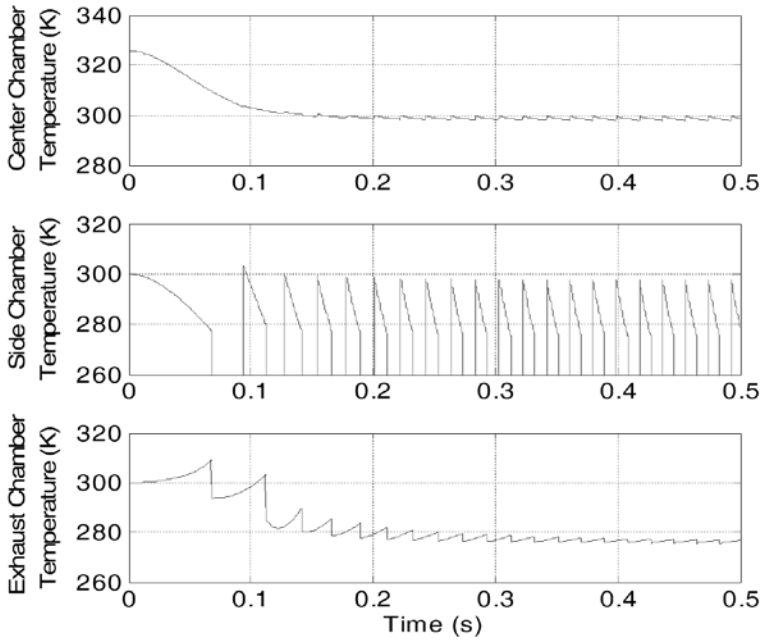
$$\dot{T}_c = \frac{(\dot{m}_{in} h_{in}/V_c) - (\dot{V}_c/V_c)([X_{air}]\hat{h}_c) - [\dot{X}_{air}]\hat{h}_c + P_c[\dot{X}_{air}]/[X_{air}]}{[X_{air}]C_{p,air}(T_c) - P_c/T_c}$$

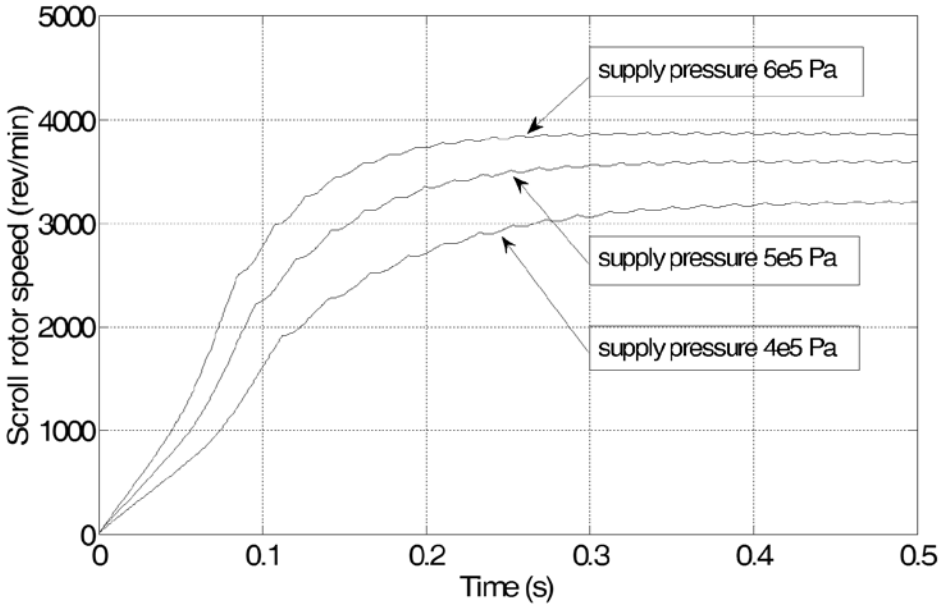
Simulation


Center Chamber Volume (m3)
x 10^-4
Side Chamber Volume (m3)
x 10^-4
Exhaust Chamber Volume (m3)
x 10^-4
Time (s)
Center Chamber Pressure (Pa)
x 10^5
Side Chamber Pressure (Pa)
x 10^5
Exhaust Chamber Pressure (Pa)
x 10^5
Time (s)



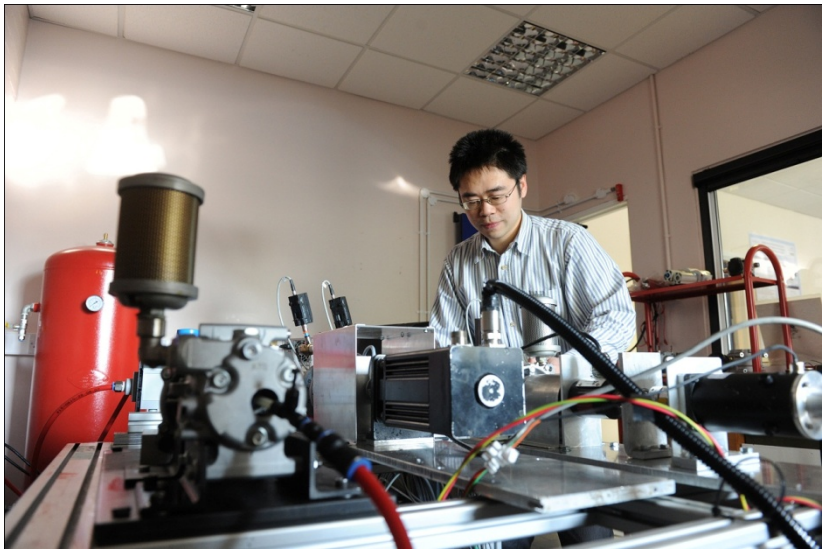
Simulation

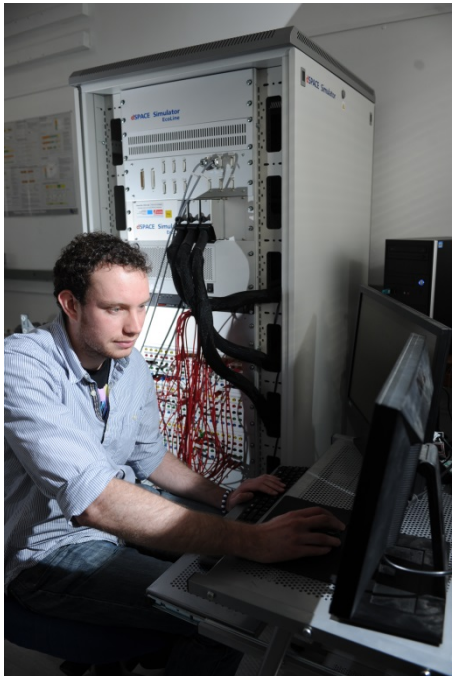

Center Chamber Temperature (K)
340
320
300
280
0
0.1
0.2
0.3
0.4
0.5
Side Chamber Temperature (K)
320
300
280
260
Exhaust Chamber Temperature (K)
Time (s)

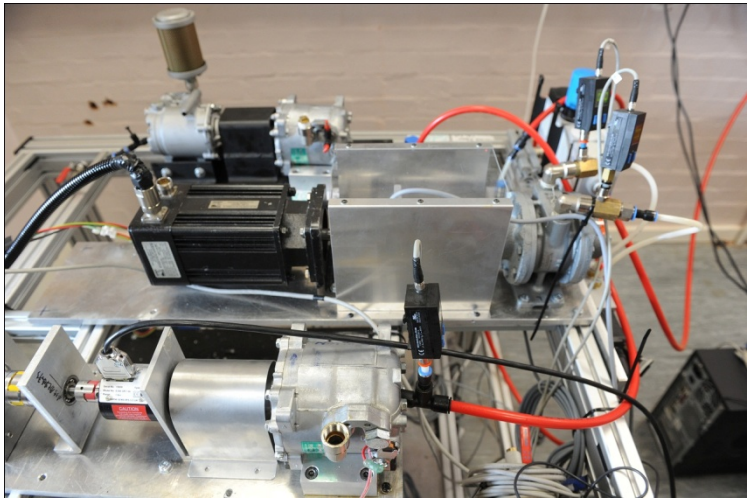

Scroll rotor speed (rev/min)
5000
4000
3000
2000
1000
0
0.1
0.2
0.3
0.4
0.5
Time (s)
supply pressure 6e5 Pa
supply pressure 5e5 Pa
supply pressure 4e5 Pa

Mathematical model of the scroll air motor

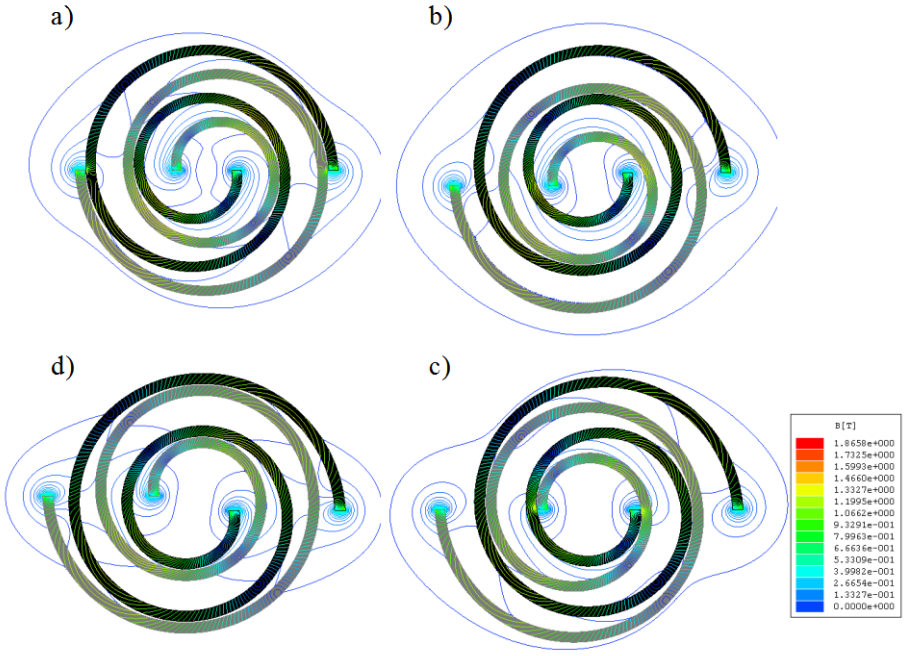
Test:

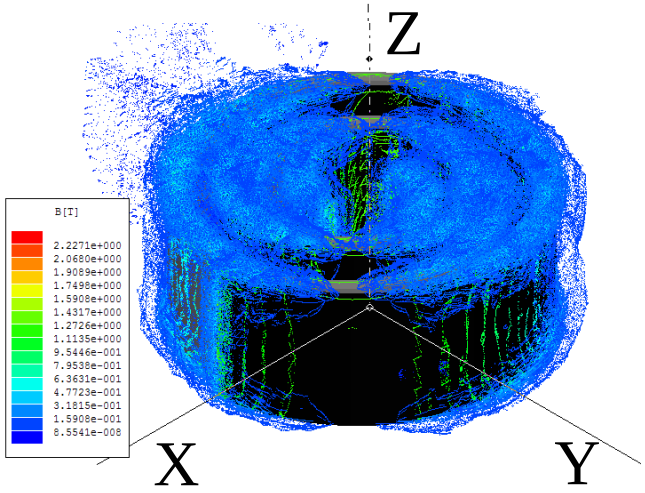


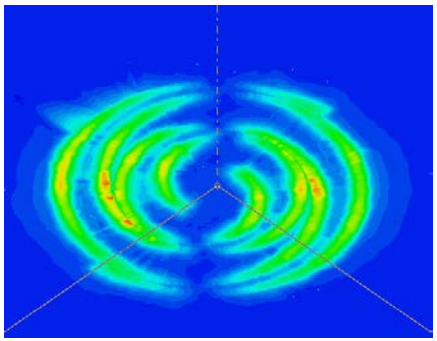


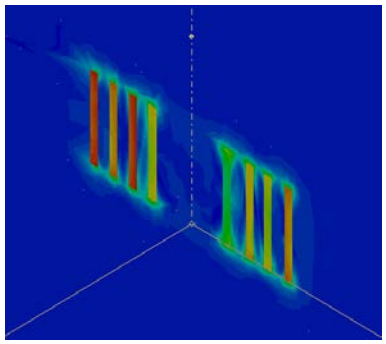


New type of scroll air expenders

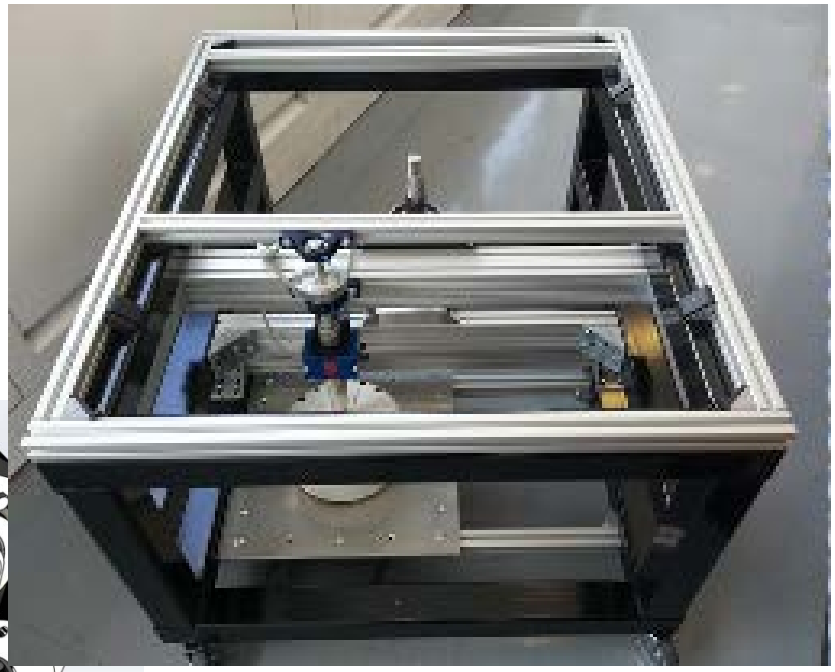








Hybrid Connection with Wind Turbines



Challenging Research Questions:

- Optimizing design of system devices
- New types of air turbines/expanders
- Energy efficiency – heat and cold recovering
- Grid scale or distributed small scale
- Cost reduction
- Geological location for large scale storage

Thank you!

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