UNIVERSITY OF BATH

Innovations in DC Grid Technologies at University of Bath

Dr. Rohit Bhakar

UNIVERSITY OF BATH

THE SUNDAY TIMES

UNIVERSITY OF THE YEAR 2011-12

Rankings

UNIVERSITY OF BATH

2012 *The Guardian* ‘QS top 50 universities under 50’ table for 2012.

The University of Bath is ranked 12th in the world.

2012 the *Times Higher Education* ‘100 under 50’ table.

The University of Bath is ranked 37th in the world.

Outstanding students

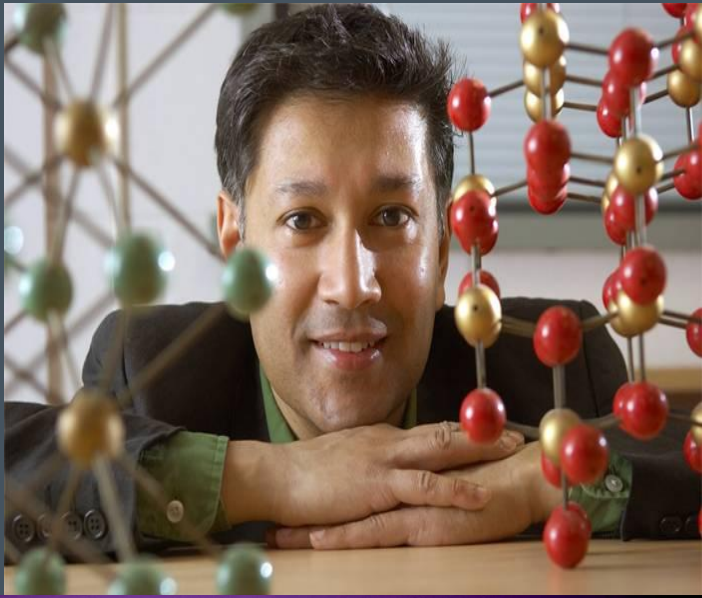
Bath has more than 15,000 students including 3,500 international students from across the globe.

Over 5,000 employers are looking to recruit our students.

We have one of the lowest drop-out rates in the UK - 92% of undergraduates complete their courses.

Outstanding Research Environment

UNIVERSITY OF BATH



World-class academics

Outstanding publication record

Wide-range of well-funded research

State-of-art research facilities

Focused on research with global vision and impact

Addressing the needs of industry, business, government and society both now and for future generations

City of Bath

Population 85,000

UNESCO World Heritage Site

Excellent transport links, near international airport and 160km west of London.

Bath is named after the natural hot springs in the city discovered by the Romans in AD65

Bath is famous for its beautiful architecture

Our campus

Department of Mechanical Engineering

Department of Electronic & Electrical Engineering

All four departments ranked 3rd or higher in The Sunday Times UK University Guide 2013

Department of Chemical Engineering

Department of Architecture & Civil Engineering

Highly ranked and rated programmes

Mechanical Engineering - No.1 for subject area Sunday Times 2013, no. 1 for teaching excellence, Guardian league tables 2013

Electrical and Electrical Engineering – Top 3 for subject area, 91% student satisfaction and top 3 for academic learning and teaching resources, national students survey

Chemical Engineering – 2nd in the UK for graduate employment, unistats.com, top 3 in the UK for subject area, Sunday Times 2013

Civil Engineering – 2nd in the UK, Guardian League tables

Architecture – top programme in the UK (Sunday Times, Guardian league tables and Complete University Guide), 100% graduate employment rate

Strong links with industry and business

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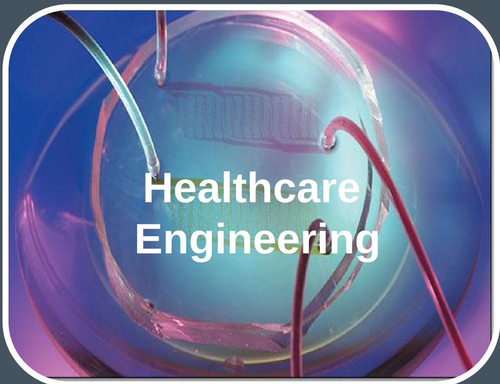
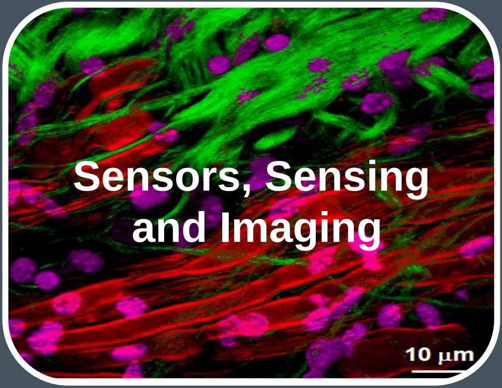
Creating, developing and sustaining industrial and business links is a vital part of our core business

2,500 organisations offer placements to our students

80% of our engineering students are working with industry

Five cross- cutting research themes





Research underpinned by a strong environmental and sustainability agenda

Formal and Developing International Research linkages

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H.I.T., Harbin Institute of Technology	**Fluid Power and Machine Systems**
BeiHang	**Gas Turbine Engineering**
Dalian University of Technology	**Offshore Structures Engineering**
Tsinghua	**Smart Grids, Energy Storage and Automotive Powertrain Engineering**
Purdue	**Gas Turbine Engineering**
NUS	**Engineering Design (teaching and research)**
NTU	**Efficient distributed and collaborative embedded systems for assisted home living and healthcare environments**

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Worldwide **Impact**

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Group: Centre for Sustainable Power Distribution

Prof. Furong Li: Network Pricing, Electricity Markets, Big Data Analysis

Prof. Raj Aggrawal: Power System Protection

Dr. Miles A. Redfern: Power System Protection, Electricity Markets

Dr. Rod Dunn: Power System Stability & Security

Dr. Weijia Yuan: Superconductivity, SMES, Superconducting cables

Dr. Simon Blond: Energy Management in Buildings, Power System Protection

Dr. Min Zhang: Superconducting machines & Fault Current Limiters

Dr. Rohit Bhakar: Network Pricing, Electricity Markets

Dr. Cenghong Gu: Network Pricing, Multi Energy Vector

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Core Group’s Industry Linkage

ofgem

nationalgrid

npower

WESTERN POWER DISTRIBUTION

Serving the Midlands, South West and Wales

HORIZON

NUCLEAR POWER

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EVOLVING RESEARCH OUTLOOK

Power System Restructuring

- Deregulation
- Economics
- DG Integration

Network Pricing

- Transmission Network Pricing
- Distribution Network Pricing

Electricity Markets

- Risk Management
- Generator Bidding Strategies
- Wind Integration in Markets
- System Planning

Energy

- Energy Storage Planning
- Energy System Planning
- Smart Grids & Pricing
- DC Grids
- Wind Forecasting
- Frequency Regulation

2006 → 2010 → 2014

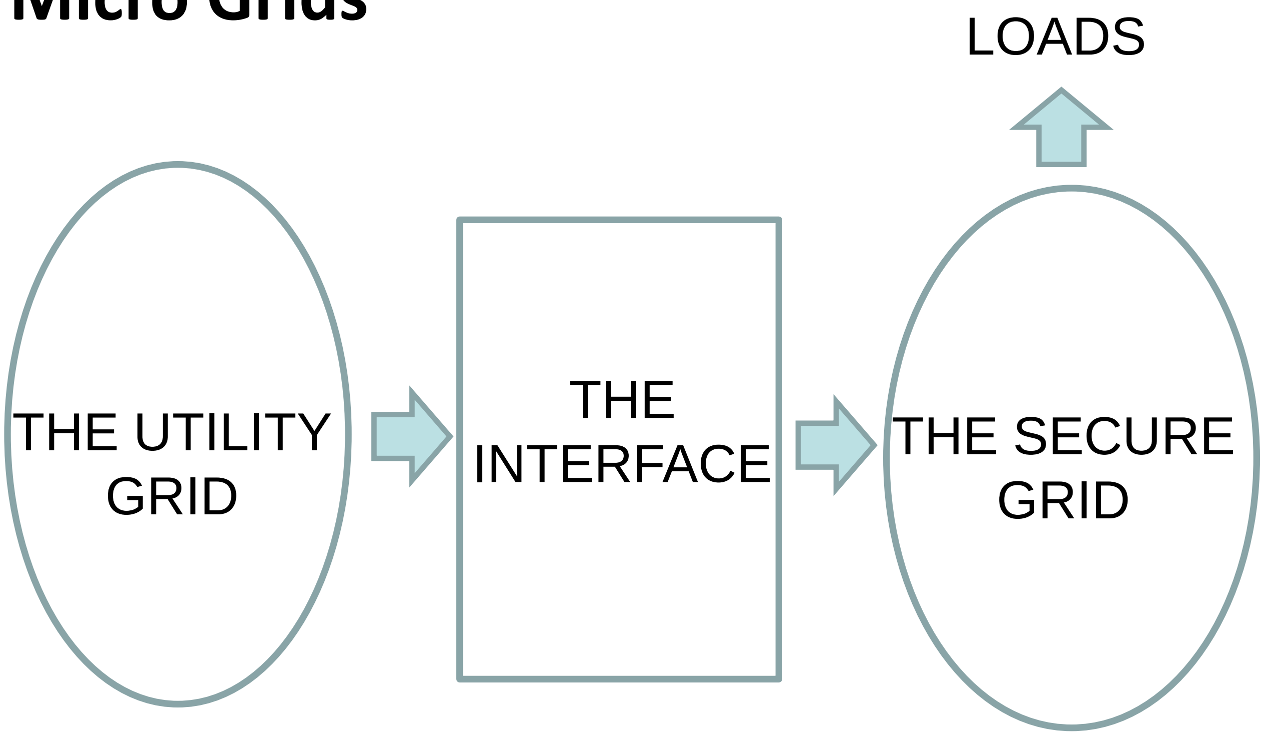
Challenges

- Will the lights go out?
- Recognising this ‘challenge’ is also not new.
- Privatisation, 1989, raised the promise of reduced standards of supply.
- What would the consumers be able to accept?
- How could priority loads be protected?
- What areas of research were required to provide the ‘fixes’.

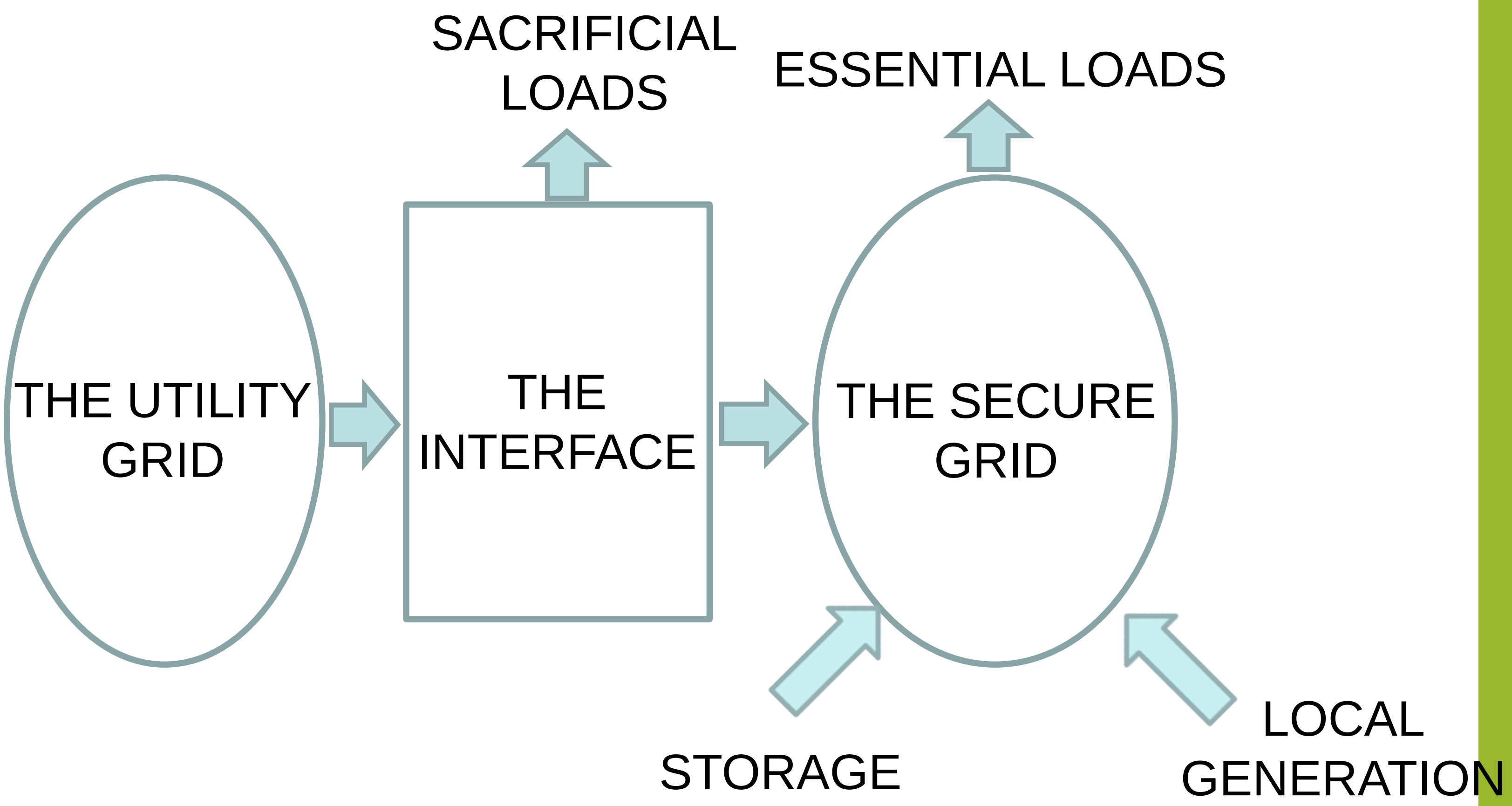
Challenges

- Standard fix of the day was stand-by generation
- Priority loads, hospitals, banks, security operations, supermarkets etc., had stand-by generators which would protect the supply in the event of a disturbance
- These ideas led to the concept of the micro-grid, which could range from small networks or relatively large networks

Micro Grids

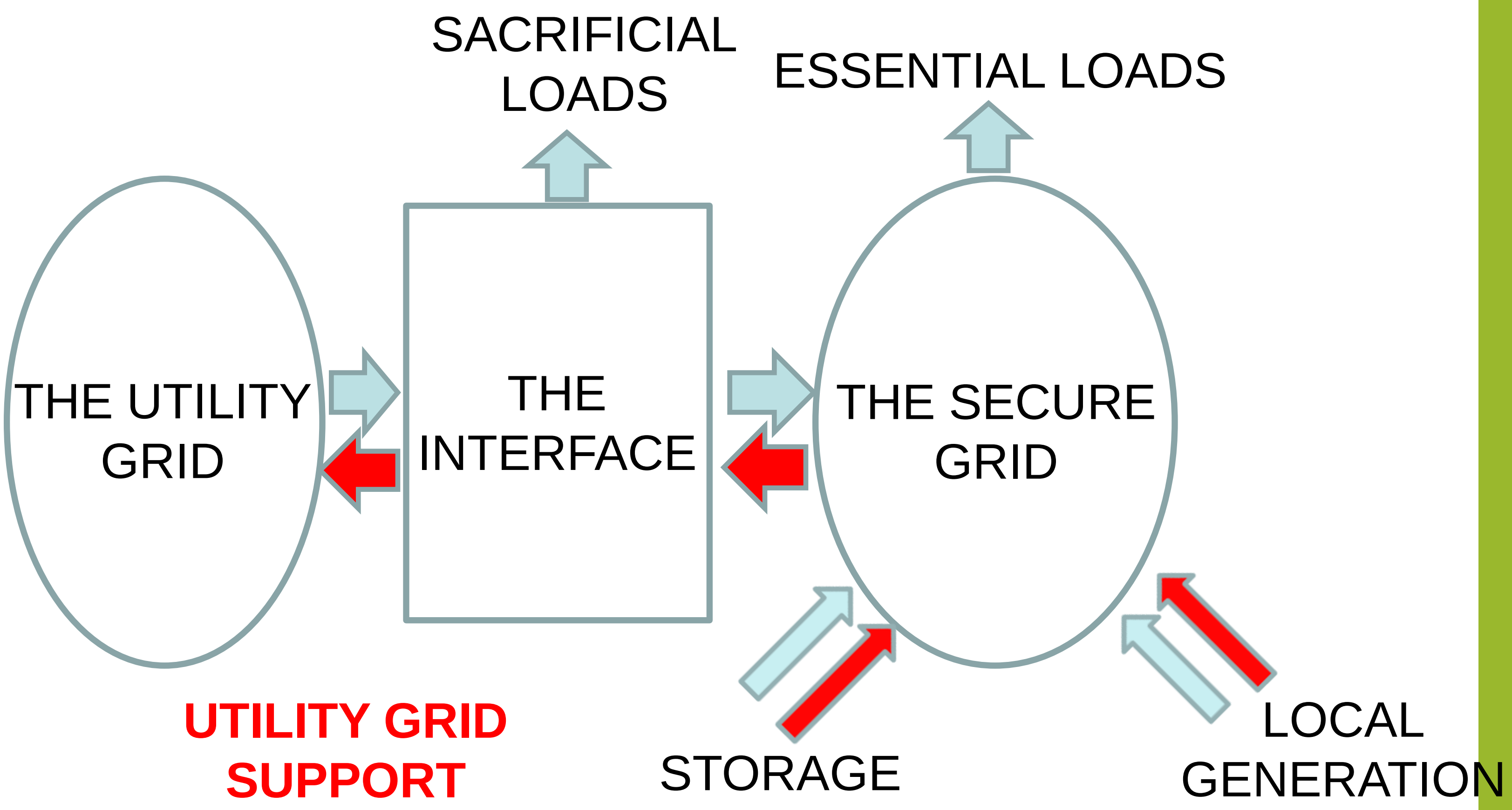


Micro Grids



SACRIFICIAL LOADS
ESSENTIAL LOADS
THE UTILITY GRID
THE INTERFACE
THE SECURE GRID
STORAGE
LOCAL GENERATION

Micro Grids


SACRIFICIAL LOADS
ESSENTIAL LOADS
THE UTILITY GRID
THE INTERFACE
THE SECURE GRID
UTILITY GRID SUPPORT
STORAGE
LOCAL GENERATION

Micro Grids

- At the start of the research, micro-grids were envisaged to be AC
- By 2000, the concepts had developed into DC micro-grids

Essential loads

- Lighting
- Communications
- Entertainment
- Control systems

Sacrificial loads

- Washing machines
- Ovens
- Vacuum cleaners
- Space heaters

DC Micro Grid

- The first implementation of a DC Micro-grid in the University of Bath was Project Edison: Smart-DC
- The "DC library", a low voltage DC micro-grid supporting 50 computers, lighting and incorporated PV renewables
- Project team included Professor R Aggawal, Dr. M Redfern, Ben Williamson & S. Kaushik
- Project funded by RWE nPower & University of Bath

Why DC?

- Advent of modern electronic systems such as computers, mobile telecommunications, digital media and entertainment & LED lighting
- These devices use low voltage direct current
- Require conversion equipment to provide the required DC power

Project Edison: SMART-DC

- Project Edison: SMART-DC investigates benefits of powering these electronic systems from a local DC supply
- This is derived from a centralised AC/DC converter & transmitted over a specially designed localised DC network
- Project designed to demonstrate increased security of supply for consumers, financial and environmental savings and benefits, together with benefits to electricity supplier through a variety of intelligent demand management & smart grid techniques

Project Overview

- Test Site: An entire floor of computers in the UoB's Library
- Existing array of 50 computers, due for renewal, replaced with new DC powered units, together with a centralised AC/DC converter & integral energy storage facility
- An ideal showcase: Available 24 hours a day, with high occupancy
- Some project elements could be demonstrated by modelling & simulation
- Actual implementation provides significant opportunities for experimentation, model validation & real-life data acquisition

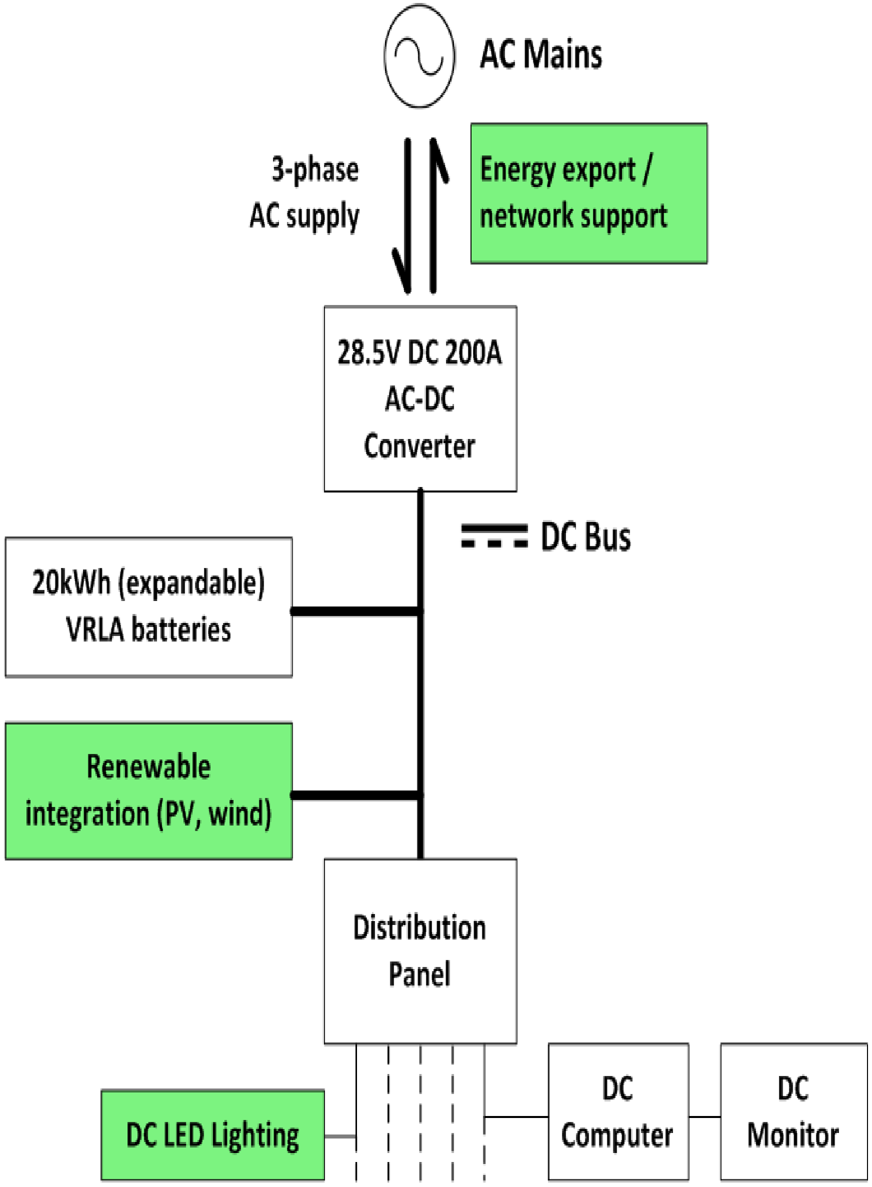
Project Context

- Due to inefficiencies of power supply unit in a computer, significant amounts of energy supplied is turned in to heat
- SMPS have a poor power factor & introduces harmonic distortion: PF correction could be expensive
- PCs consume 35W per workstation (including monitor)
- As they run off DC energy
  - Harmonics & PF normally associated with AC computer power supplies can be managed easily
  - Internal DC/DC converters are energy efficient & quiet

.

The DC Library

- A centralised 3-phase 415V AC/DC rectifier provides 200A continuous (250A peak) 28.5V DC supply
- Large valve-regulated lead acid battery bank provides sustained off-grid power for 8+ hours
- Batteries are always online & maintained on float charge for seamless transition
- A fully protected DC distribution network comprises of over-current circuit breakers
- Power rail on DC/DC converter in each computer also powers 18.5” widescreen LED-backlit LCD monitor
- System has design overhead for future expansion
- New compact workstations created desk space for 17 additional computers
- Power supply has capacity for 100+ additional machines
- Batteries are scalable



Suite of DC computer workstations

Data Acquisition and Analysis

- Continuous monitoring of all aspects of the system
- AC voltage & current across three phases, real & reactive power, power factor & harmonics
- DC energy consumption, charge & discharge of batteries, quality of DC supply including ripple & voltage
- To be able to correlate AC & DC power consumption against computer usage, number of computers switched-on/off, logged-in/out, sleeping/awake, or shutdown/unexpectedly-disconnected is also monitored

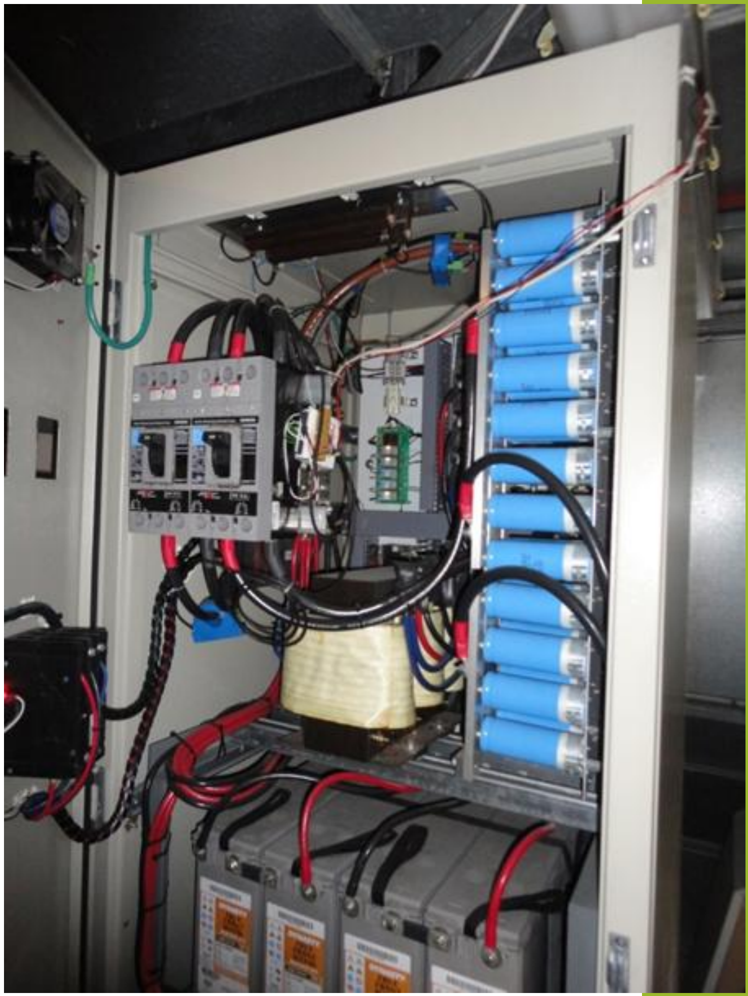
Benefits of the SMART-DC Installation

- Benefits across a wide range of areas
- Fast, quiet & compact computer with a clear, bright monitor
- Reduced heat output, also shifted away from user to converter, thus reducing fan noise & air conditioning use
- Lower energy bill & better environment

AC-DC converter and battery management controller

Security of Supply

- Storage improves security
- Useful for critical systems
- DC power supply units have simpler design, with fewer parts that could fail
- Benefits of peak capacity requirements due to diversity effects, when running many computers off a single power supply



AC-DC power converter and control systems

Harmonics

- SMPS cause waveform distortion & inject current harmonics
- Present AC/DC conversion reduces harmonic distortion, specially the magnitude of 3rd, 5th, & 7th harmonics
  - Saves energy
  - Reduces inefficiencies
  - Enhances life of distribution equipment
  - Reduces level of harmonic filtering required
  - THD reduces from 3.2% to 2.3%

battery storage

Energy Consumption and Efficiencies

- Heat emission reduced by roughly half for DC powered computers
- Multiple energy savings
  - Increased energy efficiency in the equipment
  - Avoiding need to power fans in the computers
  - Reducing use of air conditioning

- https://www.youtube.com/watch?v=9nrsxV69rXI

Modelling

- Extensive modelling to be performed on all aspects of system to be able to predict energy, financial & environmental savings, & to demonstrate benefits of scaling up
- Operating status & efficiency of distribution network to be compared against validated model & voltage drop at each node to be compared to the model to ensure optimum operating conditions
- Models of fault studies, system security & system protection ensure reliability right from the initial design

Modelling

- Modelling of energy use & storage, including demand curves, allow for optimum use of AC supply & DC storage batteries in terms of financial & environmental savings
- Modelling enables an examination of integration of other DC loads and micro-generation sources in later stages to demonstrate the feasibility and benefits of extending loads to include LED lighting and addition of PV or micro-wind turbines to system
- Benefits of larger scale installations to be assessed where the economy of scale means that demand curves are averaged out & operating overhead (base-load) of a single power supply is spread between more users

Project SoLa BRISTOL

- Buildings, Renewables and Integrated Storage with Tariffs to Overcome network Limitations
- Involved installing DC micro-Grids into 30 homes, 5 schools and a commercial office, including battery storage & communications with local sub station
- Project team included Prof. R Aggarwal, Prof. F. Li, Dr. I. Walker, S. Kaushik, Susie Martin, Chen Zhao and others.
- Project funded by OFGEM’s LCNF, WPD & UoB
- Involves Siemens, Bristol City Council, Knowlewest Media Centre & Galomaner

Development Site

- Prototype system installed into Bristol council "ecohome"
- Platform to refine system design
- Provides live demonstration
- Hardware, communications & control trial
- 3.2 kWp PV panel installed

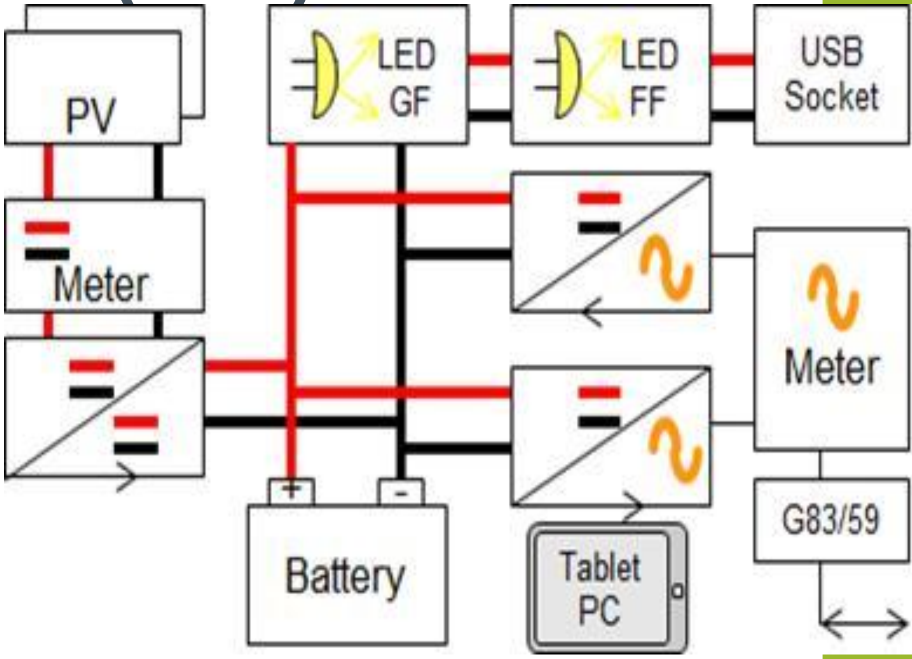
- Three distinct & geographically dispersed sub-systems
  - Sub-Station Equipment (SSE)
  - User Premises Equipment (UPE)
  - Data Repository Equipment (DRE)
- Sub-systems have bidirectional communication utilising both public radio & public-IP networks
- Variance in domestic properties depending on available PV area, family sizes & their life styles, which influences ToU & their total energy needs
- Schools & office installations also vary in their PV plant size, number of loads & level of exported power
- Export power profile is configurable within the system, which assists in studying combined local demand & export potential's influence on distribution network

SUB STATION EQUIPMENT

- SSE designed to provide monitoring capability of supply-side measurements & associated communication of appropriate parameters to the other two sites
- intelligence provided through LV connection manager equipment
- UPE receives configuration & control data
- DRE receives data for storage & future analysis
- Each group of domestic, schools & office installations have their associated SS monitoring equipment

User Premises Equipment (UPE)

- Based on a DC micro-grid which utilises solar PV generated DC for supporting DC appliances, storage & export after conversion to AC
- User interface display device (computer) provides necessary information to domestic user on PV generation, DC power consumption & power exported to grid & their associated financial benefits



Power Flows within the Domestic Installation

DC lighting

- Beneficial to drive loads from DC supply as compared to AC supply
- All AC lighting loads changed to DC lighting loads
- Provides opportunity of time of day load shifting
- Reduces level of harmonics injection & distortion
- Moving all DC lighting loads on to DC micro-grid enabled provisioning power from DC storage system
- Enables direct use of PV
- Delivers demand side load shifting benefits to network and to some extent, grid independence to the user
- Peak tariff period power demand supplemented from stored capacity
- Power for essential services can be maintained during utility disturbances

Power Related Switchgear System

- Combined inverter-charger
- DC-DC charge controller
- Twin PV input strings operating at greater than 300Vdc
- Protection & control switch gear with DC Bus
- Inverter-charger cable, AC mains in-out cable & battery bank isolation handles

Benefits of intelligent, distributed, linked system

- DNO prospective: provides peak time load shifting, time based tariff, effective integration of distributed PV generation & local storage
- User prospective: better light quality, better utilisation of PV generated DC power, reduced bills & visibility of energy usage statistics, & reduced reliance on availability of AC mains grid
- Grid prospective: controlled integration of distributed micro generators & local storage sites effectively reduce overall transmission energy loss
- Environmental benefits of reduced CO2 emission
- Conventional PV installations export all of the available PV DC output to the AC grid at the moment of generation
- Could influence power quality of the network by introducing voltage swells
- Potential for reverse flow in the distribution network under high densities of clustered installations during periods of high solar irradiance

Bidirectional Combined Inverter Charger

- Exports power to grid & provides top-up charging of batteries during both on-peak or off-peak periods
- Highly configurable micro-computer controlled unit, to configure parameters to provide different functions depending on the time of day, controlling the duration of any export, & control output current during export
- Charging parameters and durations can be set. Charging profiles can be configured to be three, four or five stage charging. Battery charging from the grid side can also be triggered based on the DC bus voltage levels.
- Functions can be remotely updated

Battery

- Valve Regulated Lead Acid batteries, due to lower initial capital investment & post installation lower maintenance costs
- Four 12V 100 Ah VRLA batteries used for providing 24V supply with capacity of 200Ah
- Four seasonal profiles for basic charging regimes
- Top-up charging can be provided during off-peak periods to ensure availability of “high” level of charge for peak load periods

CHARGE CONTROLLER

- Provides interfaces between PV strings & DC micro-grid, delivering the DC-DC voltage step down function
- Maximum Power Point Tracking (MPPT) of PV module's DC output
- Custom designed unit to control capability
- Some data collection capability

System Monitoring

- Bidirectional meter for measuring incoming & exported power on ac-grid side
- Internal measurements relating to energy flows are recorded within this system for system use
- System configured to utilise PV output to support DC loads during PV output periods & simultaneously charge batteries for later use
- Surplus exported to AC grid
- Observed parameters battery temperature, battery bus voltage, micro-grid DC current & AC mains current being exported to the Grid
- System configuration also provides for off peak top up charging opportunities, PV supported DC load, exporting to grid while at the same time charging battery & periods when DC loads are supported by storage

Present Status

- Domestic installations are operational
- Immediate return in terms of saving householders money
- They are also “keeping the lights on”

Future Perspectives

- Will the lights go out? YES!
- Will the standards of supply be degraded? MOST LIKELY.
- Can the system evolve to keep the lights? YES!
- Will there be future challenges to address? YES.

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High Energy And Power Density Solutions to Large Energy Deficits

- Model local DC resources as single and multiple service providers, both as
  - Model local DC technologies for single service and assess its efficiencies
  - Model local DC grids to address local power balancing and system security-multiple service and assess its efficiency
- Ultra fast simulation to identify large energy imbalance and security risks
  - Development of Simulation Platform for Static and Dynamic Analyses
  - Identify Key Drivers for Large Energy Deficits in Low Carbon Supply Systems
  - Ultrafast Simulation Platform for Static and Dynamic Analyses
- Address Large Energy Deficits Identified
  - Costs of maintaining system security by the transmission system
  - Modulate DC grids to address large energy
- Develop the Required Innovations for local DC grids
  - Innovation in local DC grid technologies
  - Innovation in commercial arrangements

Opportunities

- Researchers & faculty:
  - Short to medium term visits
  - Joint Publications
  - Research Collaborations
  - Joint Projects
  - Job Opportunities

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Questions