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Section 1

Intro to Distribution Networks

EEEN60352 *Smart Grids and SES*

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The University of Manchester – April, 2024

Outline

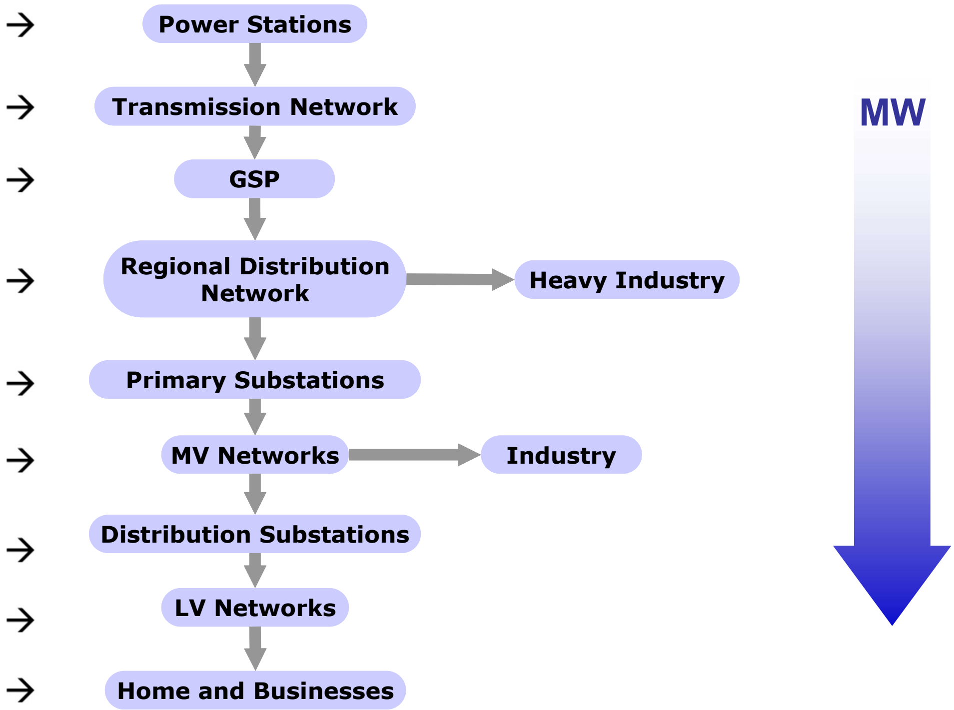
- Electric Distribution Systems and Networks
- Overhead Lines and Cables and Network Configurations
- Load profiles/Characteristics
- Low Voltage Design and Regulation
- Voltage Drop Calculations

Text Books

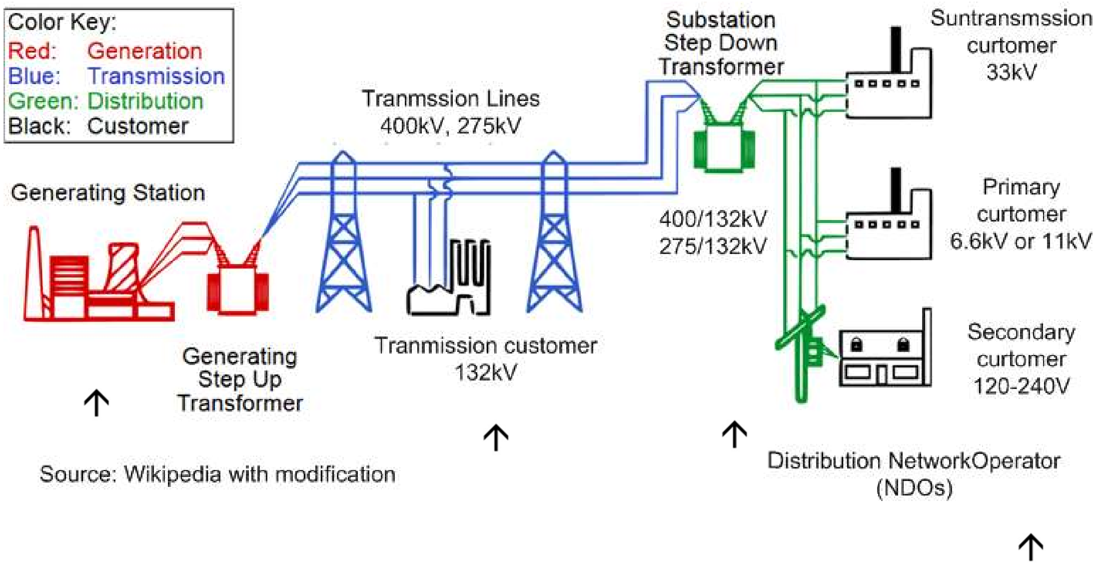
- Electricity distribution network design - Lakervi, E., Holmes, E. J., 1995
- Electric power distribution system engineering - Gönen, Turan, 2008
- Load profile in the UK: www.elexon.co.uk/reference/technical-operations/profiling/
- Energy Networks Association (ENA), http://www.energynetworks.org/electricity/
- UK Statutory Instruments No.2665, “The electricity safety quality and continuity regulation”, 2002.
- British Standard EN 50160: 2010 “Voltage characteristics of electricity supplied by publics electricity networks”

Electric Distribution Systems and Networks

Traditional Power System



Electric Power System



Electric Power System:

Generation, transmission networks, distribution networks & customers

UK Conventional Electricity Value Chain

Large-scale Traditional Generation → Transmission → Distribution → Consumers

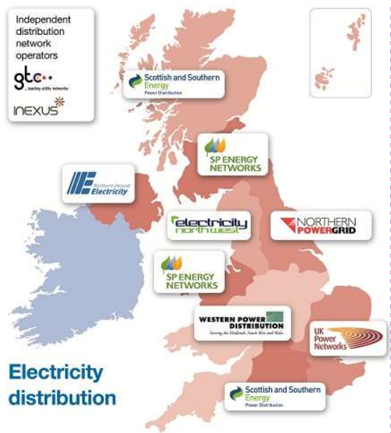
Large-scale Traditional Generation

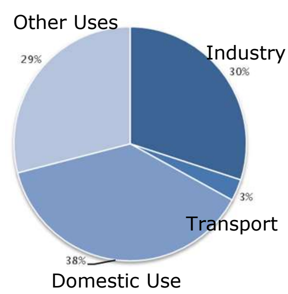
Transmission
- TNO
- GBSO

Distribution
- DNOs

Supply
- Utilities (ESCOs)

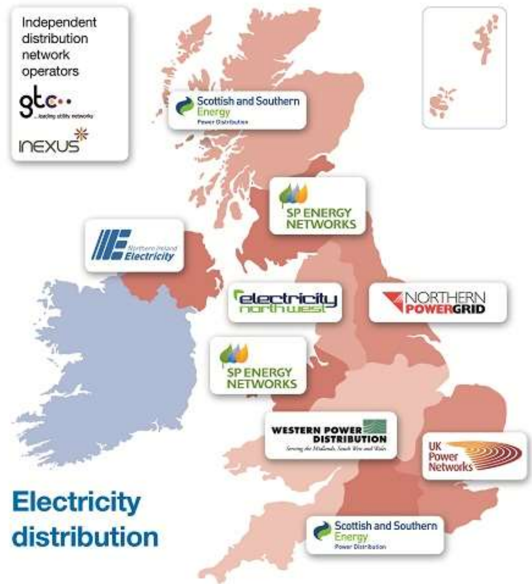
Consumers





The UK Context for Distribution

- Perhaps the most competitive electricity market in the world (full unbundling)
- 9 Distribution Network Operators (DNOs)
- Business regulated by Ofgem
- Assets in <132kV (LV and HV) account for 50%+ of the value of GB electricity networks
- A significant part of the assets installed during the 1950s and 60s



Electric Distribution Networks

Electric Distribution Systems

- Generation from transmission networks
- Primary substation, secondary substations
- Voltage 132kV, 33kV, 11kV and 6.6kV
- Low voltage networks - 3Φ pole mounted transformers

  11kV/400V -> 230V
- Customer/Loads

Distribution Networks

- Primary substations & Primary transformers
- Primary feeders
- Secondary Distribution – pole mount transformers
- Low voltage (LV) feeders
- Service/Needs – Meter/Loads

Electric Distribution Networks

According to the figure

Transmission

EHV > 300kV

HV 36-300kV

Distribution

EHV 36 – 300kV

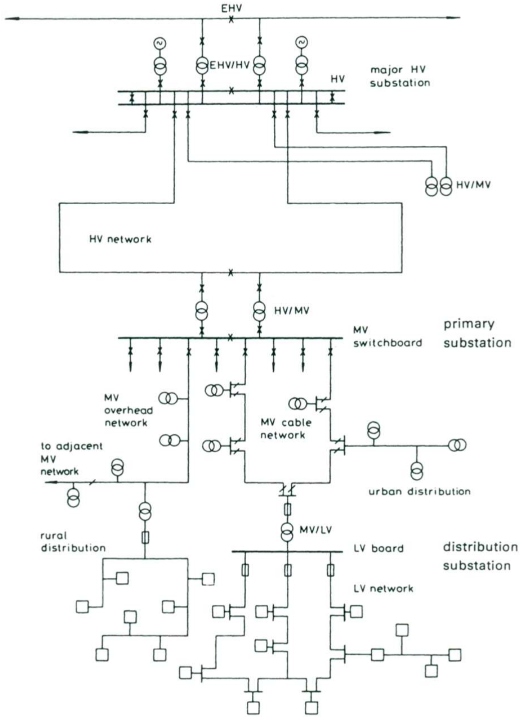
HV/MV 1-36kV

LV < 1kV

→ EHV/HV

→ HV/MV

→ LV

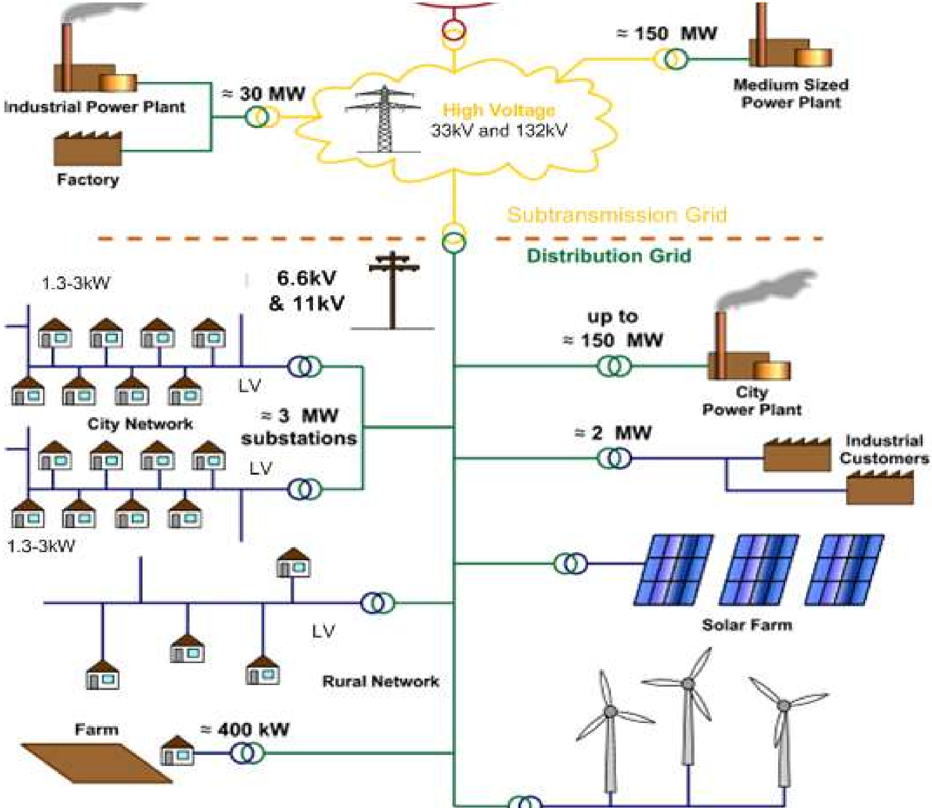


EHV/HV/MV/LV network arrangements

UK distribution

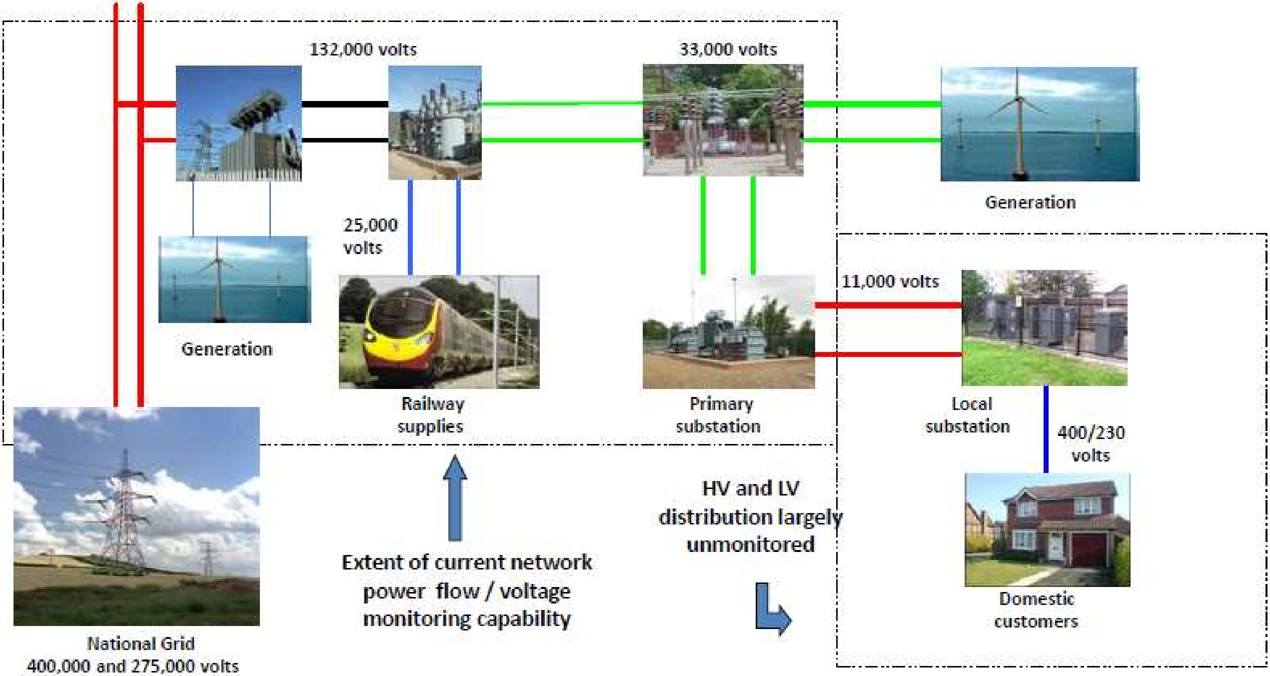
Terminology: EHV, HV, LV

Current and future Distribution Networks



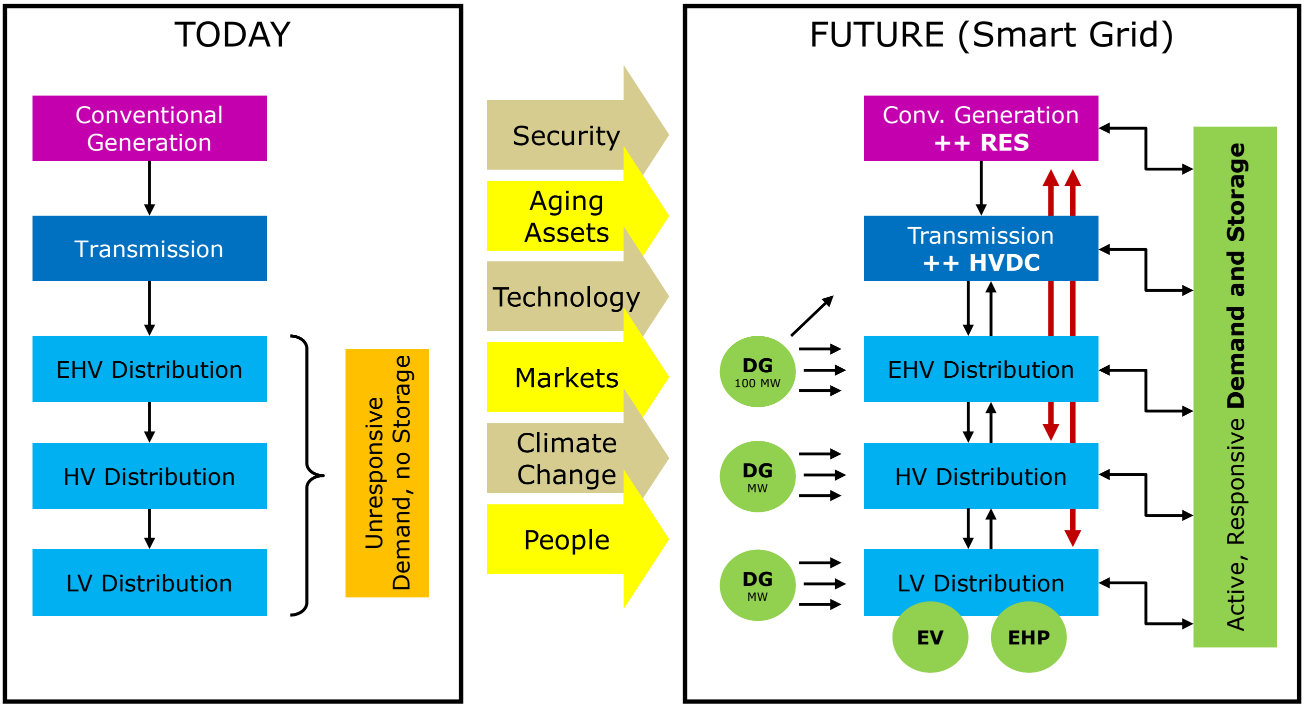
Source: Wikipedia with modification

Current UK Distribution Networks

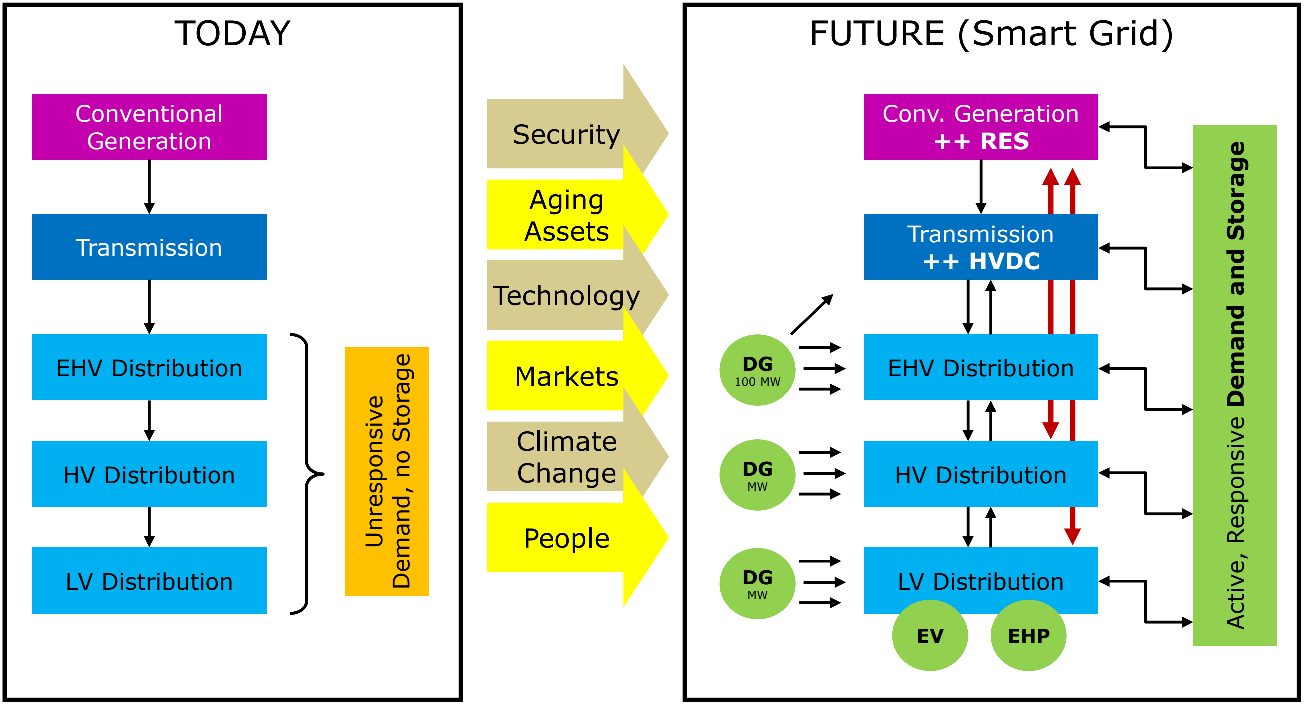


Source: Energy Networks Association

Drivers for Change in T&D Networks



Drivers for Change in T&D Networks



The Challenges

- LV Distribution Networks (400V)
  - Voltage rise due to PV panels (drops due to EVs?)
  - Thermal limits: Are the wires fit for purpose?
  - More unbalances? etc.
- HV Distribution Networks (11kV and 33kV)
  - Voltage rise due to wind power (rural networks)
  - Increase in short circuit level (urban underground)
  - Power quality, "Islanding" and Protection
  - Increased energy losses? Variability?
- EHV Distribution Networks (132kV)
  - Thermal limits
  - Stability and reserve requirements
  - Variability?

Observability

Controllability

Voltage Management

...

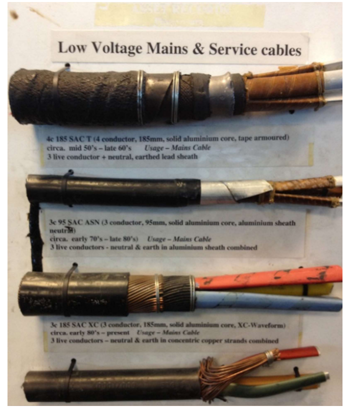
Thermal, Fault Mgmt

Integration of Solutions

Network Lines, Cables and Configurations

Overhead Lines and Underground Cables

- Decision is based on planning mandates, technical aspects and cost
- In rural areas it is common to have overhead lines
- Depending on the country/region, it might be common for urban areas to use underground cables



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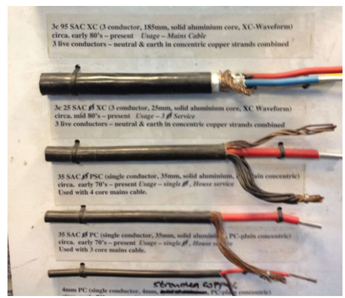
Over-head lines



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Overhead Lines and Underground Cables

- Ratio of underground cables to overhead lines costs at each voltage level (these are very broad values)

EHV	HV	MV(a)	MV(b)	LV(a)	LV(b)
15 to 25:1	10:1	5:1	2:1	5:1	1.5:1

(a) in built up areas ; (b) in normal soil conditions

- Percentage of circuit kilometres of overhead lines and underground cable in England (1993!)

	EHV	HV	MV	LV	Total
OHL (%)	1.2	3.4	27.5	9.8	41.9
UGC (%)	0.1	0.5	20.0	37.5	58.1
OHL/UGC	16:1	7:1	1.4:1	0.3:1	0.7:1

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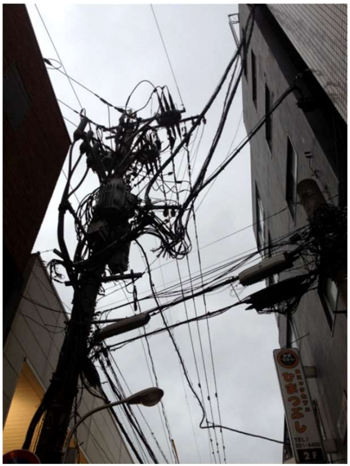
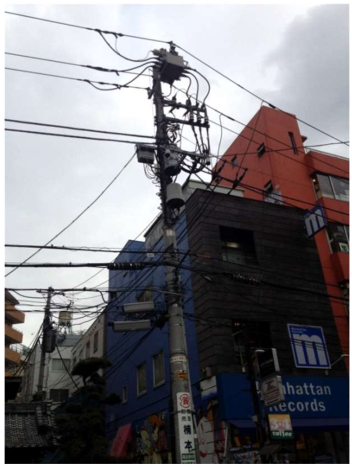
Tokyo, Japan

- However in many other country, overhead /cable is very different, such as overhead lines/cables Tokyo, Why?





Examples of LV Networks in the UK

- Topology of urban networks (Courtesy of ENWL)

Examples of LV Networks in the UK

Landgate

Edge Green

Haward Street, Salford

Dunton Green, Stockport

Greenside, Openshaw

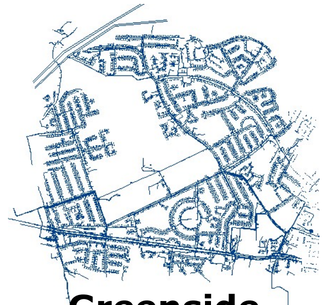
Leicester Av, Altrincham

Examples of LV Networks in the UK

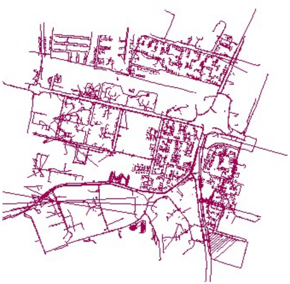
- Courtesy of Electricity North West Limited (ENWL)

Dunton Green

Edge Green



Greenside

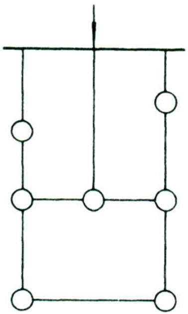


Howard St

Landgate

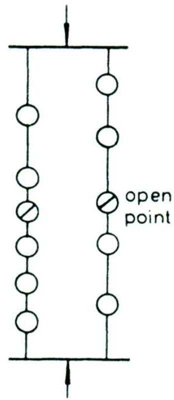
Leicester Av

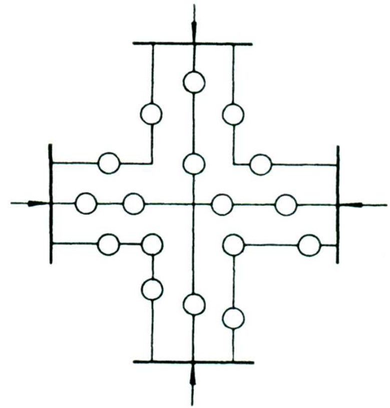
Network Configurations



Mesh/Meshed Network

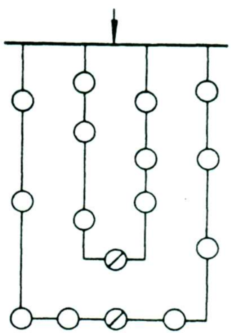
Link Arrangement



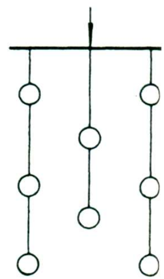


Interconnected Network

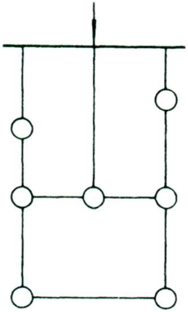
Open Loop



Radial System



Network Configurations



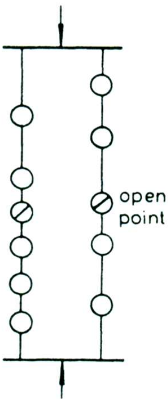
Mesh/Meshed Network

Pros:

- More reliable, used in higher voltages

Cons:

- More lines, protection scheme more complex, more cost
- Lower asset utilisation



Link Arrangement

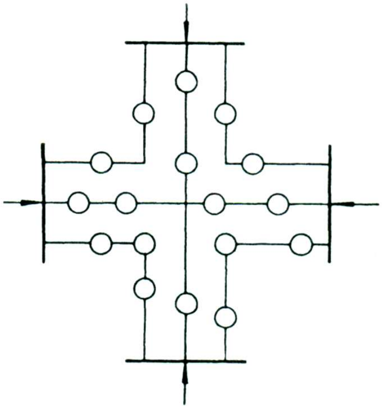
Pros:

- More reliable, two in-feeds
- Less assets, better asset utilisation than mesh,
- Simplicity (topology, protection)

Cons:

- Require high cost distribution automation for the remote open points

Network Configurations



Interconnected Network

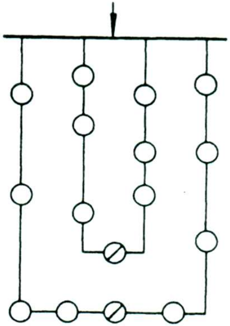
Pros:

- Very high reliability

Cons:

- Very expensive
- Low asset utilisation
- Complex protection, voltage regulation

Network Configurations



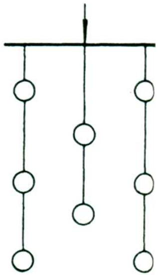
Open Loop

Pros:

- Cheaper, Simple protection

Cons:

- Less reliable
- Require distribution automation



Radial System

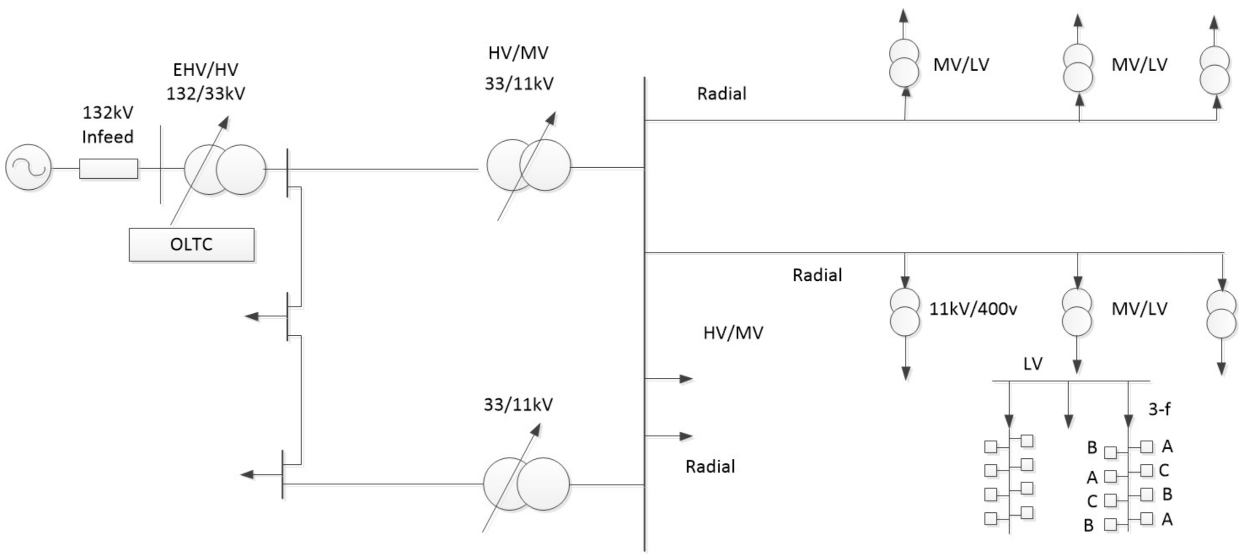
Pros:

- Simplest, Cheapest

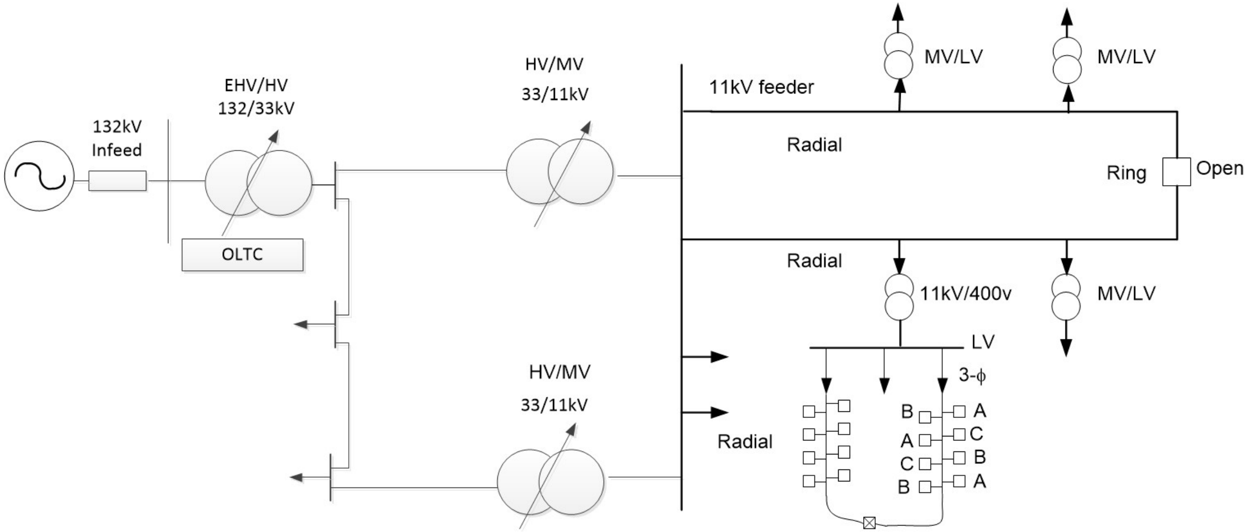
Cons:

- Least reliable,

Distribution Mesh and Radial Configurations



Distribution Mesh and Ring Network Configurations



Some Conclusions

OHL and UGC

- The use of OHL or UGC highly depends on the technical, economic and planning requirements of a given area
  - Aesthetics / Cost / Practicality

Network Topology

- The usage of a given network topology also depends on technical and economic requirements
  - The ability to restore power supply after a fault is a key aspect

Load Profiles Definition and Calculations

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Load Profiling in the UK

- In the UK, a Load Profile represents the pattern of electricity usage by day and by year for the average customer in one of eight Profile Classes (PCs).
- Profile Classes 1 and 2 are for domestic premises and Classes 3 to 8 are for non-domestic premises.
- Elexon (they do balancing and settlement in GB) creates profiles for each of these Profile Classes by randomly selecting sites and installing half-hourly meters at these sites. This data is seen as representative of all meters in this Profile Class.
- More info:
  - www.elexon.co.uk/reference/technical-operations/profiling/

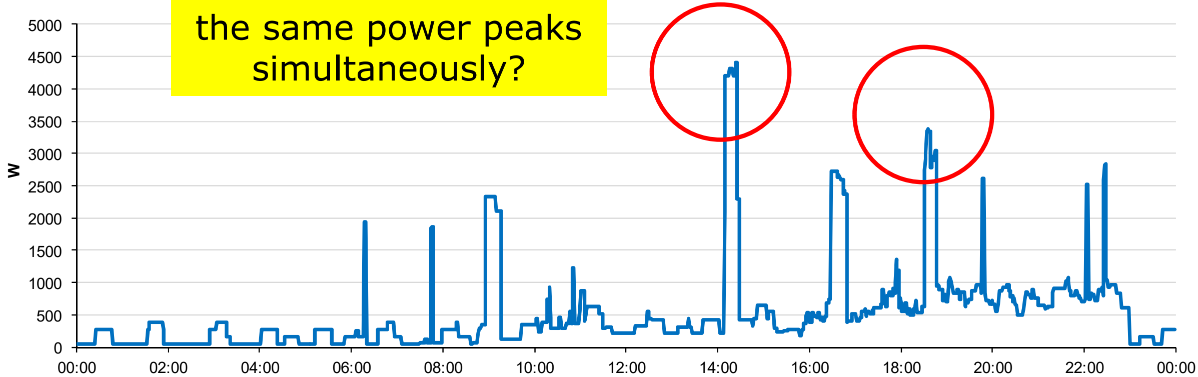
Load Profiling in the UK

- Profile Classes
  - Profile Class 1 – Domestic Unrestricted Customers
  - Profile Class 2 – Domestic Economy 7 Customers
  - Profile Class 3 – Non-Domestic Unrestricted Customers
  - Profile Class 4 – Non-Domestic Economy 7 Customers
  - Profile Class 5 – Non-Domestic Maximum Demand (MD) Customers with a Peak Load Factor (LF) of less than 20%
  - Profile Class 6 – Non-Domestic Maximum Demand Customers with a Peak Load Factor between 20% and 30%
  - Profile Class 7 – Non-Domestic Maximum Demand Customers with a Peak Load Factor between 30% and 40%
  - Profile Class 8 – Non-Domestic Maximum Demand Customers with a Peak Load Factor over 40%

Single Household (PC1) Load Profile

- 3 people, weekday in March
  - Minute by minute
  - CREST Demand Tool
    - https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/5786

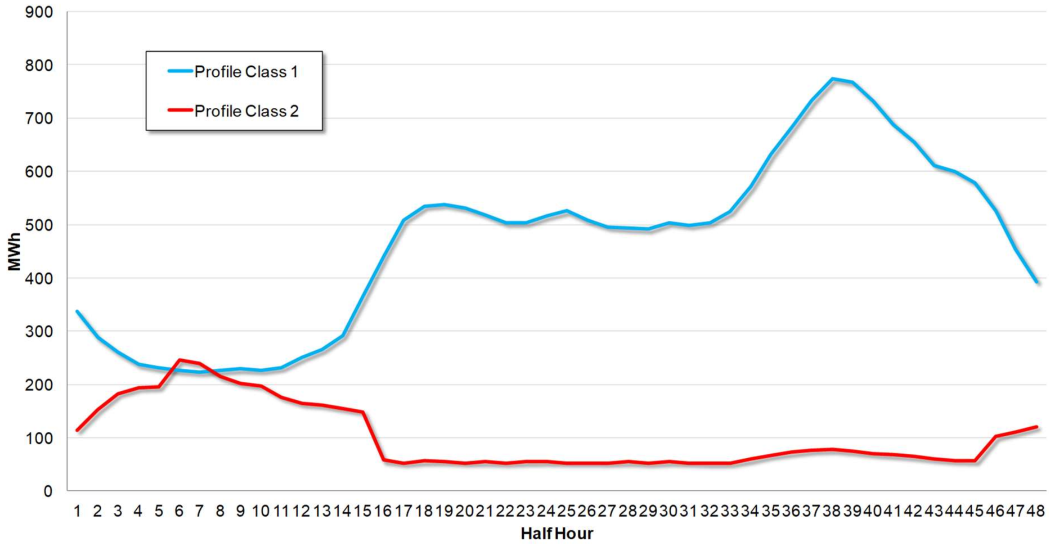
Will all customers have the same power peaks simultaneously?



What would happen with a PV panel or an EV?

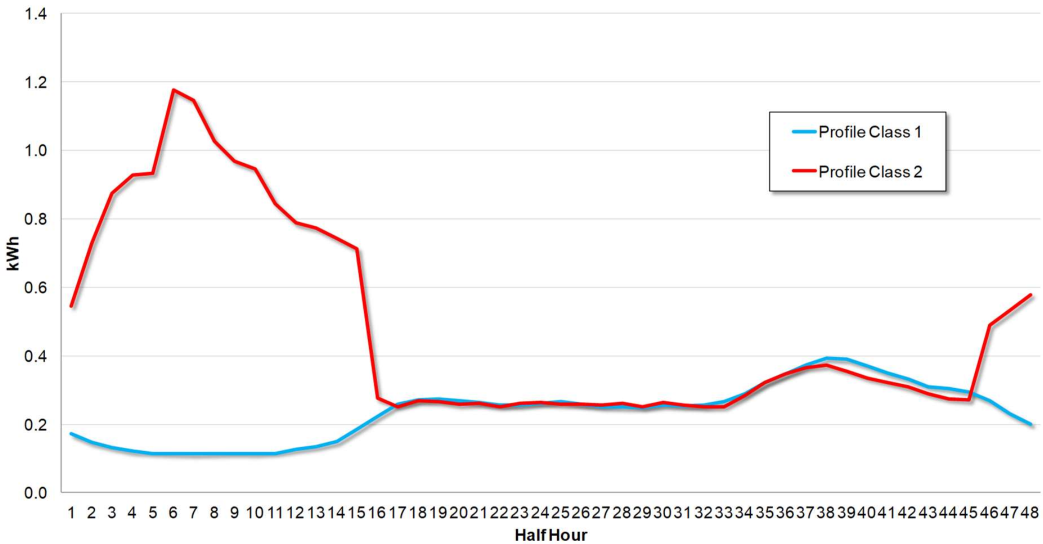
Load Profiling in the UK

- Overall Profiles, 12^{th} March 2015 (ENWL)
  - 1.9 million PC1(Unrestricted) , 0.2 million PC2 (economic 7)



Load Profiling in the UK

- Average/diversified Profiles, 12th March 2015 (ENWL)
  - 1.9 million PC1, 0.2 million PC2



Calculate the power peaks. Why are they important?

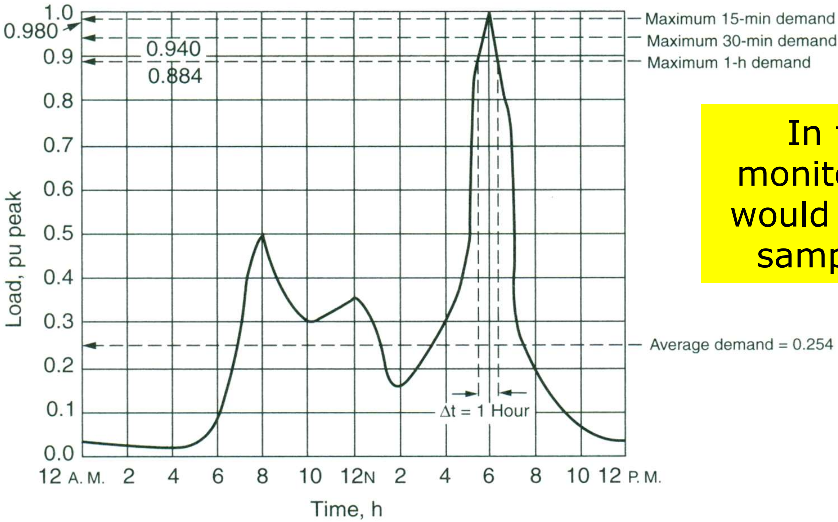
Load Characteristics

- Demand
  - "The demand of an installation or system is the load at the receiving terminals averaged over a specified interval of time" (kW, kVar, kVA, kA, A, etc.)

- Demand Interval
  - The period over which the load is averaged. Δt period may be 15 min, 30 min, 1h, etc.
  - The demand statement should express the demand interval Δt used to measure it
  - The selection of both Δt and total time t is arbitrary

Load Characteristics

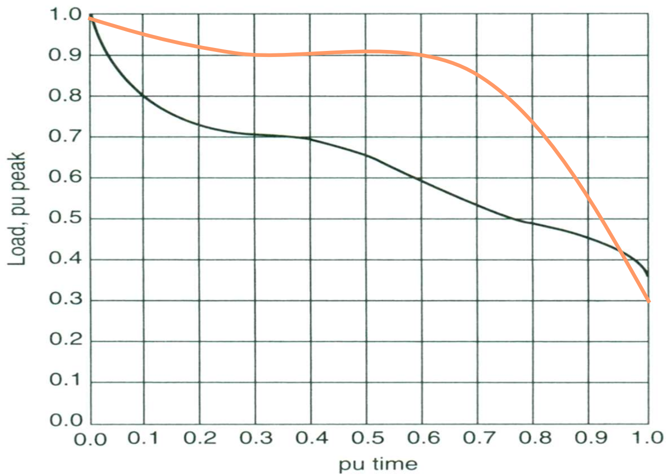
- Daily demand variation curve or **load curve** (pu of peak)
  - Max 15-min demand: 0.98pu
  - Max 1-h demand: 0.884pu



In terms of monitoring, what would be the best sampling rate?

Load Characteristics

- **Load duration curve** (LDC)
  - Maximum demand points connected by a curve (but not in the order they occurred)
  - It can be daily, weekly, monthly or annual



What does this tell us?

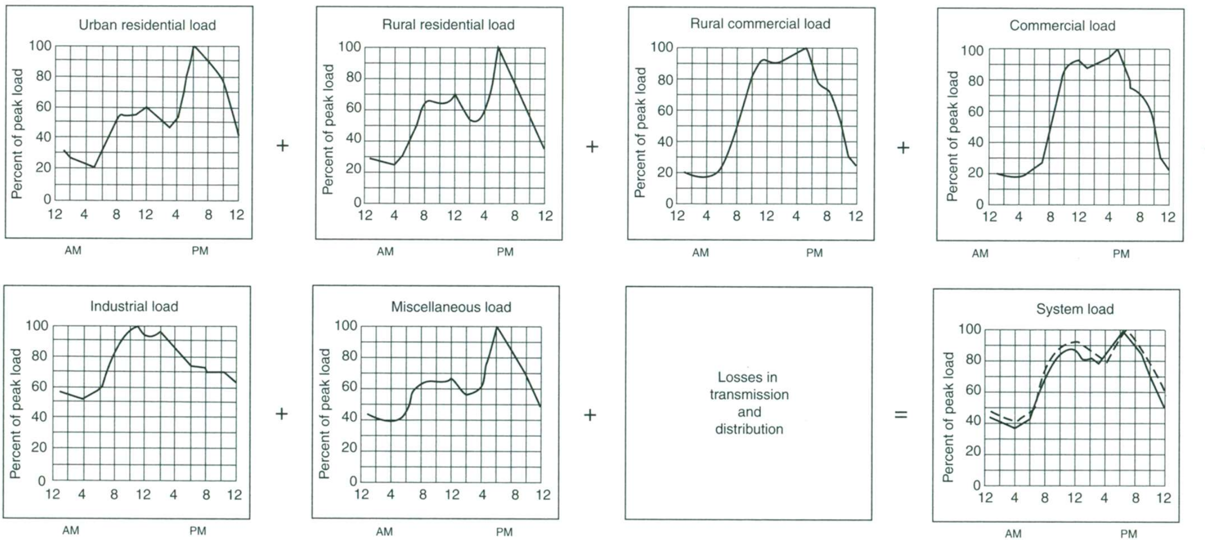
Load Characteristics

- Maximum/Peak Demand
  - Greatest of all demands which have occurred during the specified period of time (e.g., daily, weekly, etc.)
- Diversified/Coincident Demand
  - Demand of a composite group of (somewhat) unrelated loads over a specified period of time
  - The maximum diversified demand is important for <u>planning</u>
- Demand factor
  - Ratio of the maximum demand of a system to the total connected load of the system

$$DF = \frac{\text{maximum demand}}{\text{total connected demand}}$$

Load Characteristics

- If the load curves are aggregated, the system load curve can be developed



Load Characteristics

- Load factor
  - Ratio of the average load (over a designated period of time) to the peak load (occurring on that period)

$$F_{LD} = \frac{\text{average load}}{\text{peak load}} = \frac{\text{average load} \times T}{\text{peak load} \times T} = \frac{\text{units served (kWh)}}{\text{peak load} \times T}$$

Is this >1 or <1?

- Diversity factor
  - Ratio of the sum of the individual maximum demands of the various subdivisions of a system to the maximum demand of the whole system

$$F_D = \frac{\text{sum of individual maximum demands}}{\text{coincident maximum demand}} = \frac{D_1 + D_2 + \cdots + D_n}{D_C} = \frac{\sum_{i=1}^{n} D_i}{D_C}$$

Is this >1 or <1?

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Load Characteristics

- Coincident factor
  - Ratio of the maximum coincident total demand of a group of consumers to the sum of the maximum power demands of individual consumers

$$F_C = \frac{\text{coincident maximum demand}}{\text{sum of individual maximum demands}} = \frac{D_C}{\sum_{i=1}^{n} D_i} = \frac{1}{F_D}$$

Is this >1 or <1?

- Loss factor
  - Ratio of the average power loss to the peak load power loss during a specified period of time

$$F_{LS} = \frac{\text{average power loss}}{\text{power loss at peak load}}$$

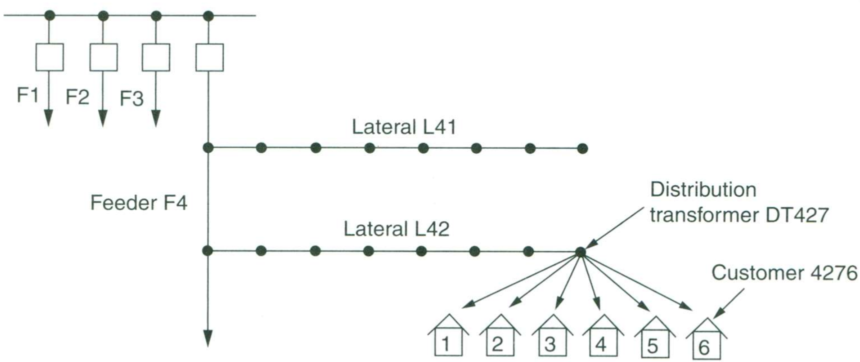
Example 1.1

- Assume that annual peak load of a primary feeder is 2000kW (measured hourly) at which power losses are 80kW. Assuming an annual loss factor of 0.15, determine
  - The average annual power losses
  - The total annual energy losses

A:

Example 1.2

- There are six residential customers connected to a distribution transformer (DT). Assume that the connected load is 9kW per house and that the demand factor and diversity factor for the group of six houses are 0.65 and 1.10, respectively. Determine
  - The diversified demand of the group of six houses on DT427



Low Voltage Design and Voltage Regulation

Low Voltage Design Procedure

- LV networks are typically three-phase in European countries (differently from the single-phase design in the USA).
- The network design is traditionally determined using the After Diversity Maximum Demand (ADMD) method. In general, the following tasks are carried out to design a urban LV network (without considering protection aspects, voltage flicker, etc.)
  - Evaluation of the total load to be supplied.
  - Evaluation of the supply capacity of the existing network.
  - Determination of the number of substations required (and practical locations).
  - Design of the layouts for the LV main corridors (also called distributors) and LV service cables.
  - Determination of the cross sectional area for the main corridors (and sub sections).

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Low Voltage Design Procedure

- DNOs will adopt different ADMD for each customer according to its type (e.g., non-electric heating, electric heating, etc.). The most economic cable is then selected for which the voltage drops at the customer connection points are within the statutory limits.
- Assessment of ADMD for a group of customers

$$\text{Maximum demand} = \left(a \times N + P\right)\text{kW}$$

where

a, average ADMD (kW) per customer

N, number of customer in the group

P, load allowance (kW) for loss of diversity

Low Voltage Design Procedure

Property Type	ADMD per customer (kW)	
	Day	Night
→ Small Non-Electric Non-Detached	1.0	0.4
→ Non-Electric Detached	1.4	0.6
→ Electric Heating (installed in each of a group of average-sized properties). (This takes account of the large diversity, where electric heating is not subject to a restricted-hour tariff.) See 4.2.3 below regarding high density housing.	3.4	2.4
→ Off-peak Tariff, eg E7, (where substantial heating load is switched to take advantage of low 'off-peak' rates)	1.5	0.8 (aggregate installed water and storage heating capacity kW) + 0.5
→ Off-peak Tariff with afternoon boost (where substantial storage heating load is switched to take advantage of low or 'off-peak' rates)	3.4	0.8 (aggregate installed water and storage heating capacity kW) + 0.5
→ Two Rate Tariff, eg E10 with afternoon, evening and night cheaper rates (where the tariff provides an incentive to concentrate usage in the cheaper periods, notably in the evening)	0.6 (maximum space heating available 07:00 to 24:00 plus water heating kW) + 2 *	0.6 (maximum space heating available 00:00 to 07:00 plus water heating kW) + 0.5 *
→ Air conditioning (where installed in each of a group of properties)	Taking account of the likely operating regime, it may be appropriate to add a fraction (say 50%) of the installed cooling load to the above daytime ADMD values.	

Voltage Regulation

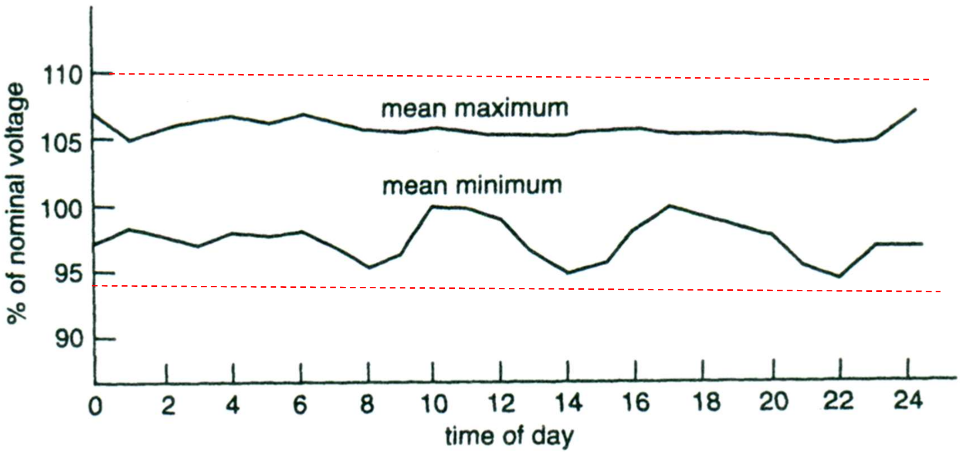
- Voltage Regulation
  - The percent voltage drop of a line with respect to the receiving-end voltage

$$\%\,\text{regulation} = \frac{\left|\overline{V_s}\right| - \left|\overline{V_r}\right|}{\left|\overline{V_r}\right|} \times 100$$

- Voltage drop
  - The difference between the sending-end and the receiving-end voltages of a line
- Nominal voltage
  - The nominal value assigned to a line or apparatus or a system of a given voltage class
- Rated voltage
  - The voltage at which performance and operating characteristics of the apparatus are referred

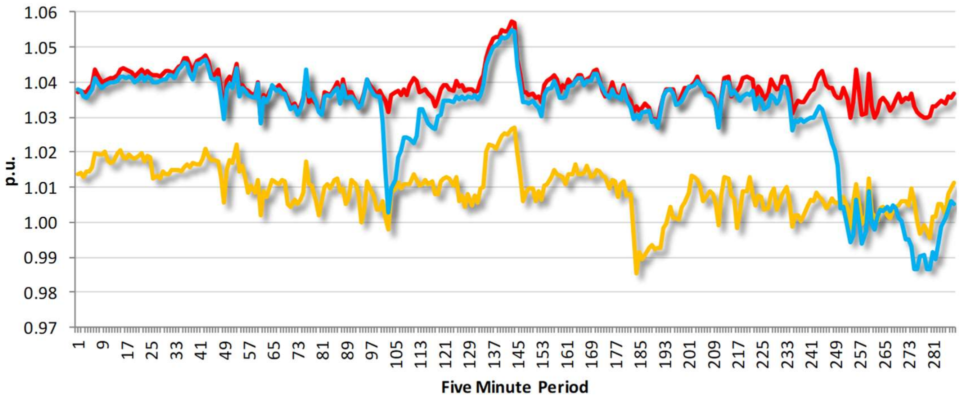
Voltage Regulation

- 24-hour voltage profile for residential customers
- In the UK (400V line-to-line) limits are +10%/-6%



Voltage Regulation

- 5min average 24-hour voltage profile for residential customers
  - Line-to-neutral, 10th October 2012 (ENWL)
  - Busbar of LV network with 3 feeders and 180 consumers



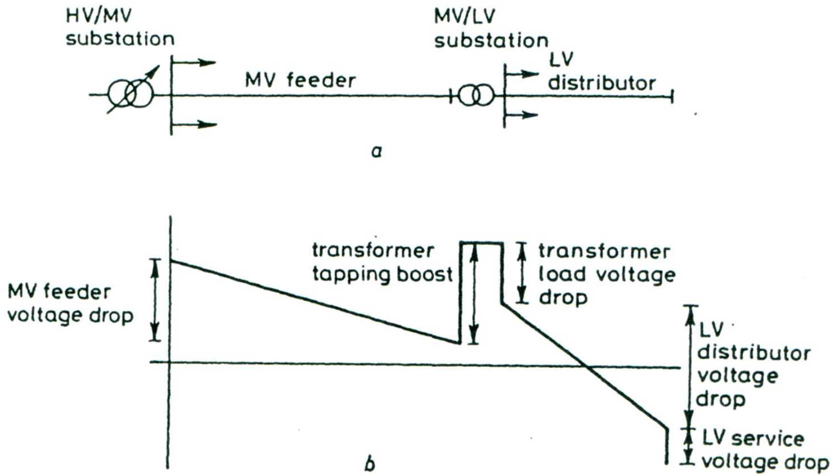
What matters? 5min? 15min? 30min? 1h?

Voltage Regulation

- UK Statutory Instruments No. 2665, “The Electricity Safety, Quality and Continuity Regulations”, 2002
  - Low voltage (400V): +10%, -6% of declared voltage supply
  - Below 132kV: +/- 6%
  - 132kV and above: +/- 10%
- British Standard EN 50160: 2010 “Voltage characteristics of electricity supplied by public electricity networks”
  - For UK distribution, in (at least) a week:
    - at least 95% of the 10 min mean rms values of the supply voltage shall be below the upper limit +10%; and
    - at least 95% of the 10 min mean rms values of the supply voltage shall be above the lower limits of -10%; and
    - none of the 10 min mean rms values of the supply voltage shall be outside the limits ± 15 %

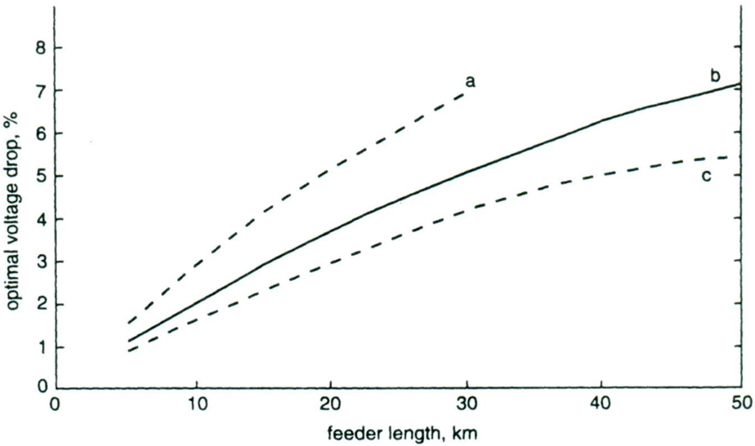
Voltage Regulation

- Voltage regulation on MV and LV networks
  - (a) Simplified distribution network diagram
  - (b) MV and LV network voltage variation



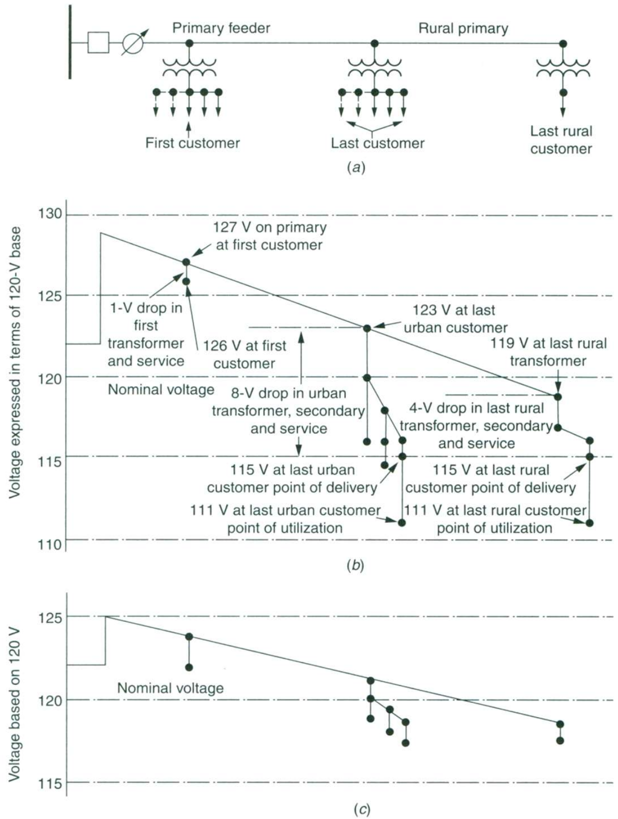
Voltage Regulation

- Optimal voltage drop for a 20kV overhead line as a function of the feeder length
  - (a) Typical urban feeder
  - (b) Mixed urban/rural feeder
  - (c) Typical rural feeder



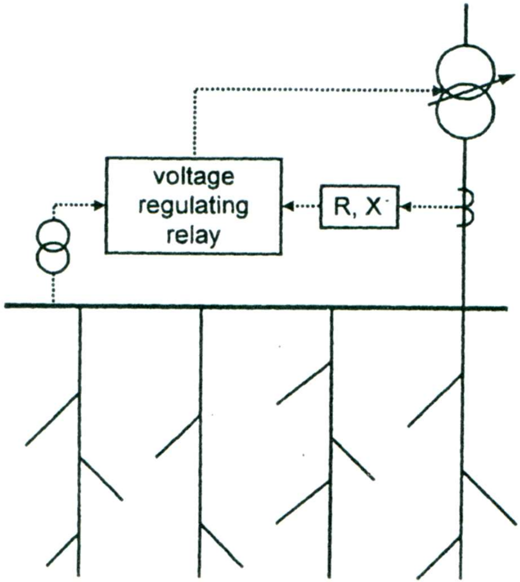
Voltage Regulation

- Voltage spread on a radial primary feeder (USA)
  - (a) one-line diagram of a feeder
  - (b) voltage profile at peak load conditions
  - (c) Voltage profile at light load conditions



Voltage Regulation

- On load tap changer (OLTC)
  - Schematic of line drop compensation



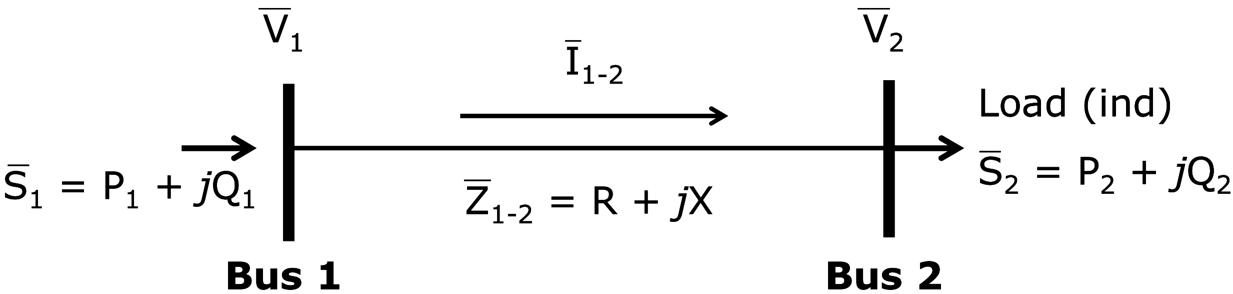
Voltage Regulation

- On load tap changer (OLTC)
  - 33kV/11kV Scottish Power (SP) Power Systems


Voltage Drop Calculations and Examples

Voltage Drop Calculations

- Complex Calculation



$$\Delta\overline{V}_{1-2} = \overline{V}_1 - \overline{V}_2 = \overline{Z}_{1-2} \cdot \overline{I}_{1-2}$$

$$\Delta\overline{V}_{1-2} = \left(R + jX\right) \cdot \overline{I}_{1-2}$$

$$\overline{I}_{1-2} = \left(\frac{\overline{S}_1}{\overline{V}_1}\right)^* = \left(\frac{\overline{S}_2}{\overline{V}_2}\right)^*$$

Typically, loads and V_1 are known (to some extent).

Voltage Drop Calculations

- Complex Calculation
  - If S_1 and V_1 are known, then it is straightforward

$$\overline{V}_1 - \overline{V}_2 = (R + jX) \cdot \left(\frac{\overline{S}_1}{\overline{V}_1} \right)^*$$

  - If S_2 and V_1 are known, then we have a quadratic complex equation

$$\overline{V}_1 \cdot \overline{V}_2^* - \left| \overline{V}_2 \right|^2 = (R + jX) \cdot \overline{S}_2^*$$

If somehow the line complex losses were known, the process would be easier ($S_1 = S_2 + S_{losses}$)

Voltage Drop Calculations

- Simplified Calculation
  - Arithmetic difference between the sending and receiving ends

$$V_{drop} = \left|\overline{V}_1\right| - \left|\overline{V}_2\right| \cong \mathrm{Re}\left\{\overline{Z}_{1-2} \cdot \overline{I}_{1-2}\right\}$$

$$V_{drop} = \mathrm{Re}\left\{(R + jX) \cdot \left(\frac{\overline{S}_1}{\overline{V}_1}\right)^*\right\}$$

$$V_{drop} = \mathrm{Re}\left\{\frac{(R + jX) \cdot (P_1 - jQ_1)}{\overline{V}_1^*}\right\} = \mathrm{Re}\left\{\frac{(R \cdot P_1 + X \cdot Q_1) + j(X \cdot P_1 - R \cdot Q_1)}{\left|\overline{V}_1\right|}\right\}$$

Voltage Drop Calculations

- Simplified Calculation

$$V_{drop} = \left|\overline{V}_1\right| - \left|\overline{V}_2\right| = \frac{R \cdot P_1 + X \cdot Q_1}{\left|\overline{V}_1\right|}$$

  - This is the typical simplified formulae. However, we still need the power values at the sending end.
  - If network losses are not considered to be significant, then

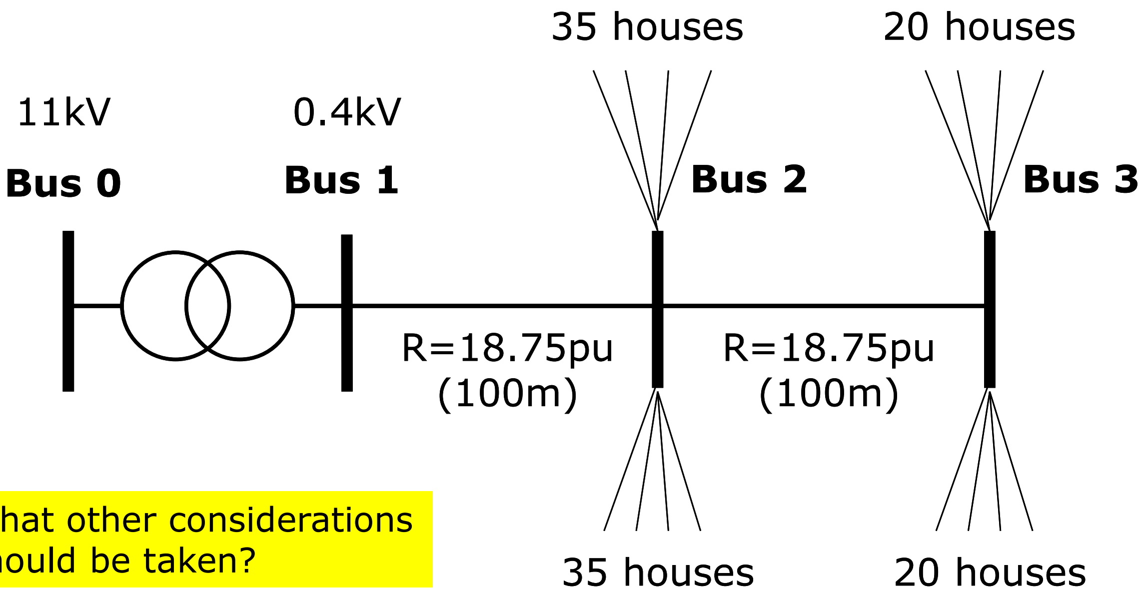
$$V_{drop} = \frac{R \cdot \left(P_2 + P_{losses}\right) + X \cdot \left(Q_2 + Q_{losses}\right)}{\left|\overline{V}_1\right|} \cong \frac{R \cdot P_2 + X \cdot Q_2}{\left|\overline{V}_1\right|}$$

$$V_{drop} = \frac{R \cdot P_2 + X \cdot Q_2}{\left|\overline{V}_1\right|}$$

Example 1.3

- ADMD of 1.5kW and load allowance of 8kW.
- Would a 180kVA transformer be OK?

A: Yes. Load = 173 kW



What other considerations should be taken?

End of Section 1

The University of Manchester

Section 2

Low Carbon Technologies

EEEN60352 *Smart Grids and SES*

Dr Haiyu Li

Senior Lecturer in Smart Distribution Networks & Smart Grids

The University of Manchester – April 2024

Outline

- Introduction to Low Carbon Technologies
- Photovoltaics (PVs)
- Electric Vehicles (EVs)
- Storages
- Heat Pumps (HPs)

Renewable

Electric Vehicle

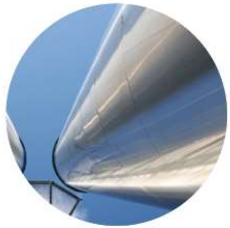
Energy efficiency in building

Wide range of low carbon technologies

Power Networks

Low Carbon Freight

Renewables



Carbon Capture and Storage

Energy Efficiency in Buildings

Cement

Low Carbon Transport Fuels

Climate Smart Agriculture

Forests

Chemicals

Source: http://lctpi.wbcsd.org/

Low Carbon Technologies in Power Networks

- Clean Fossil Fuels

  Oil and gas and clan coal
- Nuclear
- Renewables

  Wind, Wave and tidal, solar, Biomass, Geothermal and Hydroelectric
- Energy Stooge and Transmission

  Storage technologies, the grid, smart communications
- Energy Use and Efficiency

  Transport: Road - electric vehicles (EVs),

  Rail, shipping and aviation – electrification

  Industry: Energy efficiency in building, District heating Industrial combined heat and power (CHP)

  Domestic: Energy efficiency, Heat pumps, Microgeneration, Smart technologies

References

- Energy & Climate Change Committee, “Low carbon technologies in a green economy”, finial report of session 2009-2010 Vol 1, HC193-1, 17th March 2019. <https://publications.parliament.uk/pa/cm200910/cmselect/cmenergy/193/193i.pdf>
- Lopes, J.A.P.; Soares, F.J.; Almeida, P.M.R.; “Integration of Electric Vehicles in the Electric Power System”, Proceedings of the IEEE, Jan. 2011
- Z. Darabi, M. Ferdowesi, “Aggregated Impact of Plug-In Hybrid Electric Vehicles on Electricity Demand Profile”, IEEE Trans. on Sustainable Energy, vol 2, no 4, p 501-508, 2011
- M.H.J. Bollen, “The Smart Grid – Adapting the Power System to New Challenges”, Morgan & Claypool Publishers, 2011
- J. Momoh, “Smart Grid – Fundamentals of Design and Analysis”, Wiley and IEEE Press, 2012

Photovoltaics

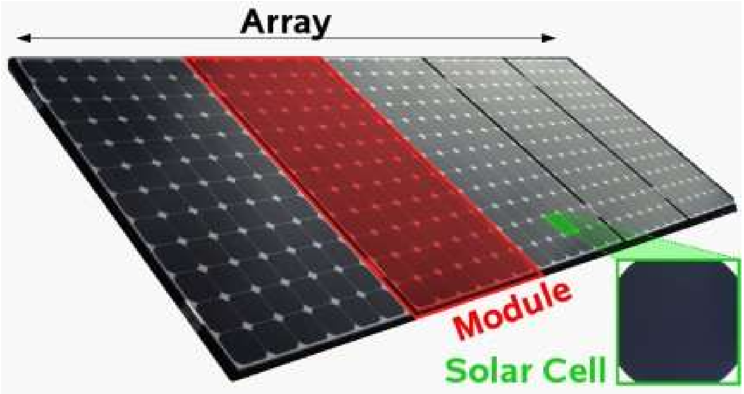
System Components,

Grid and Off Grid Systems

System Components

- PV Arrays made of multiple PV Modules
- Framework and Structure for Modules, or Trackers
- Storage: batteries, tank, flywheel, hydrogen production…
- Electronics: Power Conditioner, Inverter (DC-AC), Charge Controller, Rectifier, DC-DC converter
- Other generators: diesel/gasoline, wind turbine
- Monitoring System: Sensors and Data Storage Devices

Cells → Modules → Arrays → System

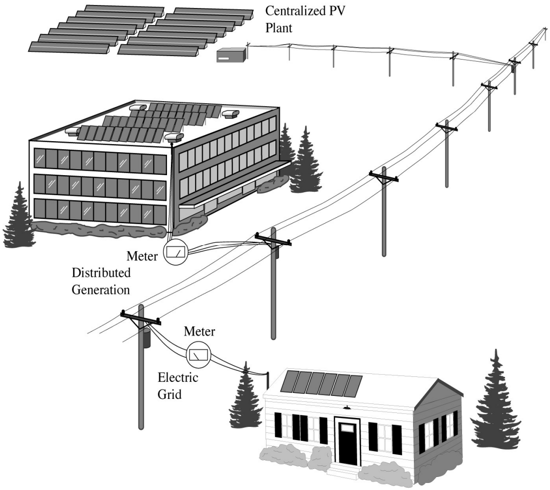


Source: www.solar-designs.com.au

- Solar cells embrace the active Photovoltaic material
- PV modules can hold a number of Solar Cells connected in series and parallel to build up Peak Power
- Arrays are PV Modules mounted together measuring up to several meters
- PV System is made of a number of Arrays

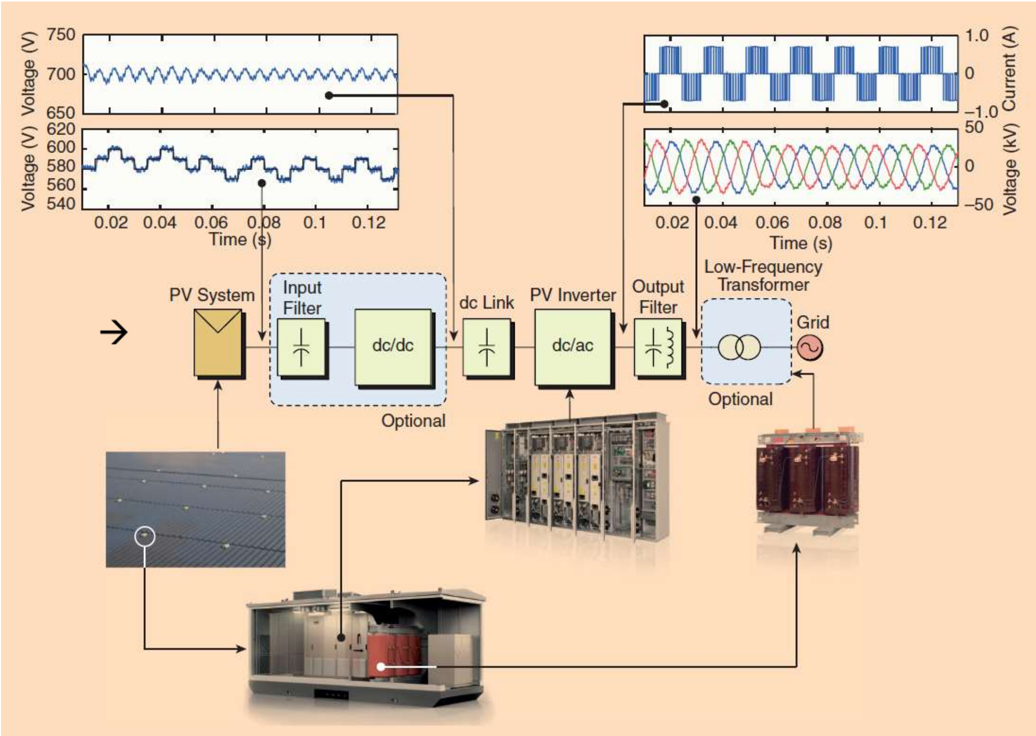
Grid-Connected Systems

- PV Integration
  - Distributed / Decentralised / Micro-Generators
  - Centralised
- Not usually cost-effective without subsidies, requires long-term commitments by manufacturers, governments. This is changing.
- Justified by:
  - Image
  - Environmental benefits
  - Market stimulus



Source: Photovoltaics in Cold Climates, Ross & Royer, eds.

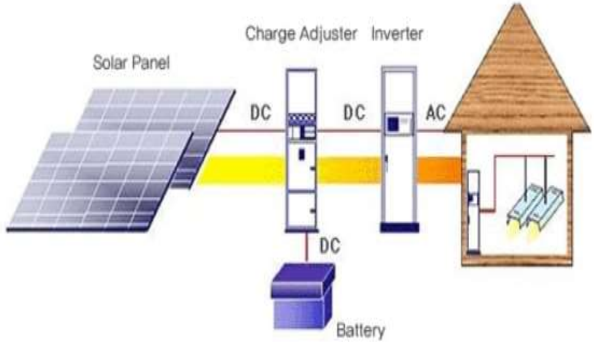
Grid-Connected Systems



IEEE industrial electronics magazine ■ March 2015

Off-Grid Systems

- Configuration
  - Stand-Alone or Hybrid
- For very remote sites due to…
  - Cost of grid expansion or upgrade
  - Seasonal load correlation
  - More reliable than grid
- Often very cost-effective
  - Small loads best (< 10kWp)
  - Lower capital costs than grid extension
  - Lower O&M costs than gensets and primary batteries
- Hybrid Village Power Systems, Remote Cottages, Telecom & Monitoring systems industrial system



PV Generation Profiles

Distribution Networks

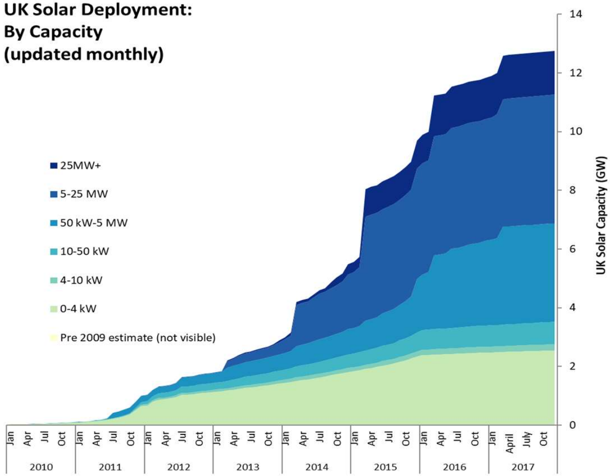
- In the UK there is a FIT ('feed in tariff') to incentivise the adoption of PV panels
  - Energy produced is metered and paid for
  - Energy produced can be consumed locally but not stored
  - Energy exported to the grid is also metered and paid for

- The PV installed capacity in the UK exceed 11.5 **GW** in end 2016, with 3.4% of total electricity consumption

Year end	2008	2009	2010	2011	2012	2013	2014	2015	2016
Capacity[3] (MW)	22	27	95	965	1,736	2,822	5,378	9,118	11,562
Generation (GW·h)	17	20	33	259	1,328	2,015	4,050	7,561	10,292
% of total electricity consumption	<0.01	<0.01	0.01	0.07	0.37	0.64	1.33	2.49	3.4
References	[38]	[38]	[38][39]	[39][40]	[37][41]	[41]	[42]	[43]	[43]

GB - Photovoltaic Systems

- Overall capacity: **12.748 GW**
- One of the largest markets in Europe
- **720,000+ installations** from 1kW to 5MW+
- Typical domestic installations
  - 1.5-3.5kWp per house
- Eng Recommendation G83
  - 16A per phase
  - 1p → 3.68 kW; 3p → 11.04 kW
  - Power factor 0.95 ind/cap

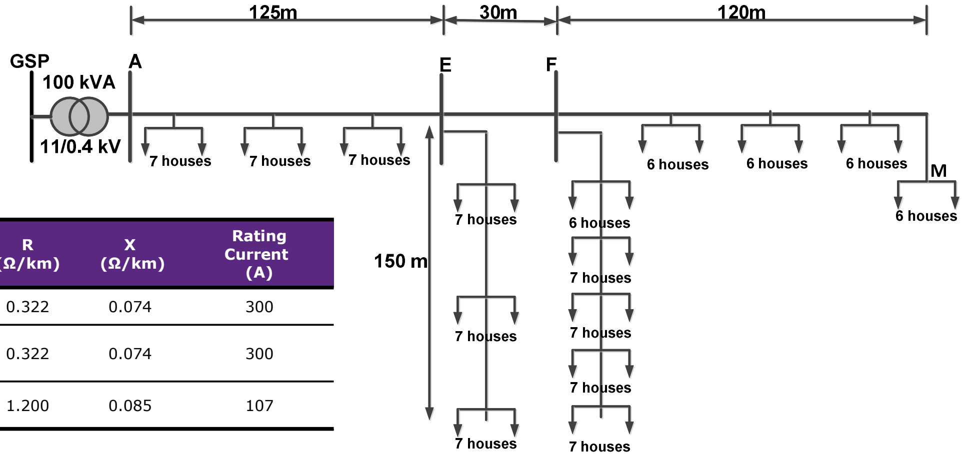


Monthly deployment of all solar PV capacity in the UK

- https://www.gov.uk/government/statistics/solar-photovoltaics-deployment

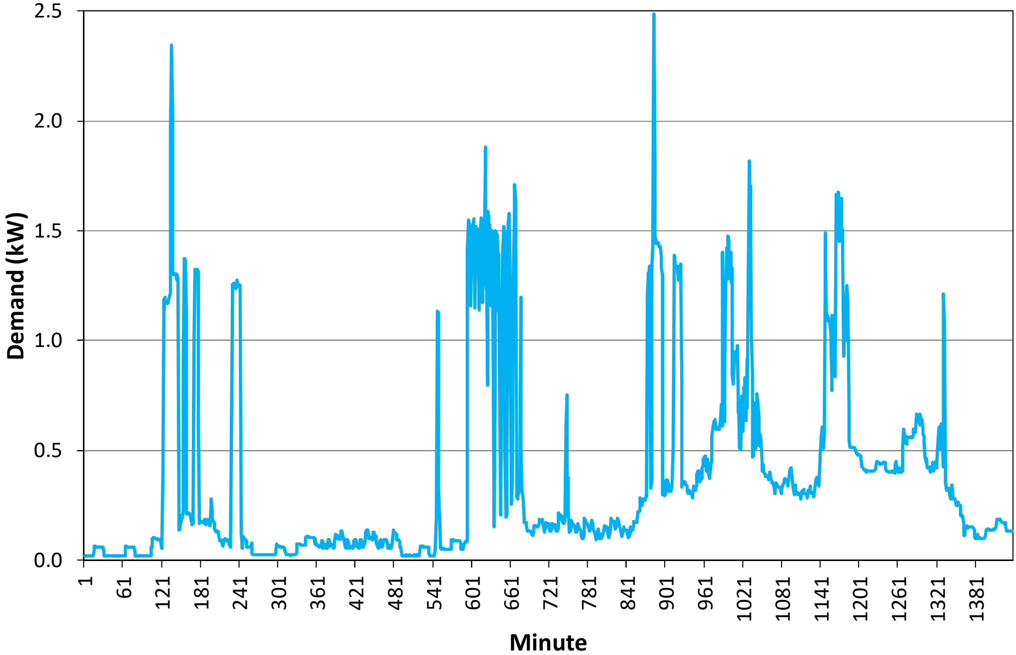
LV Networks and Photovoltaics

- Unbalanced network: <u>three-phase</u> plus neutral analysis
- 100 households, different load behaviours
- Peak demand of 86 kW (households use gas for heating)
- PV Panels: 2.5 and 3.5 kW during a 'summer day' in the midlands

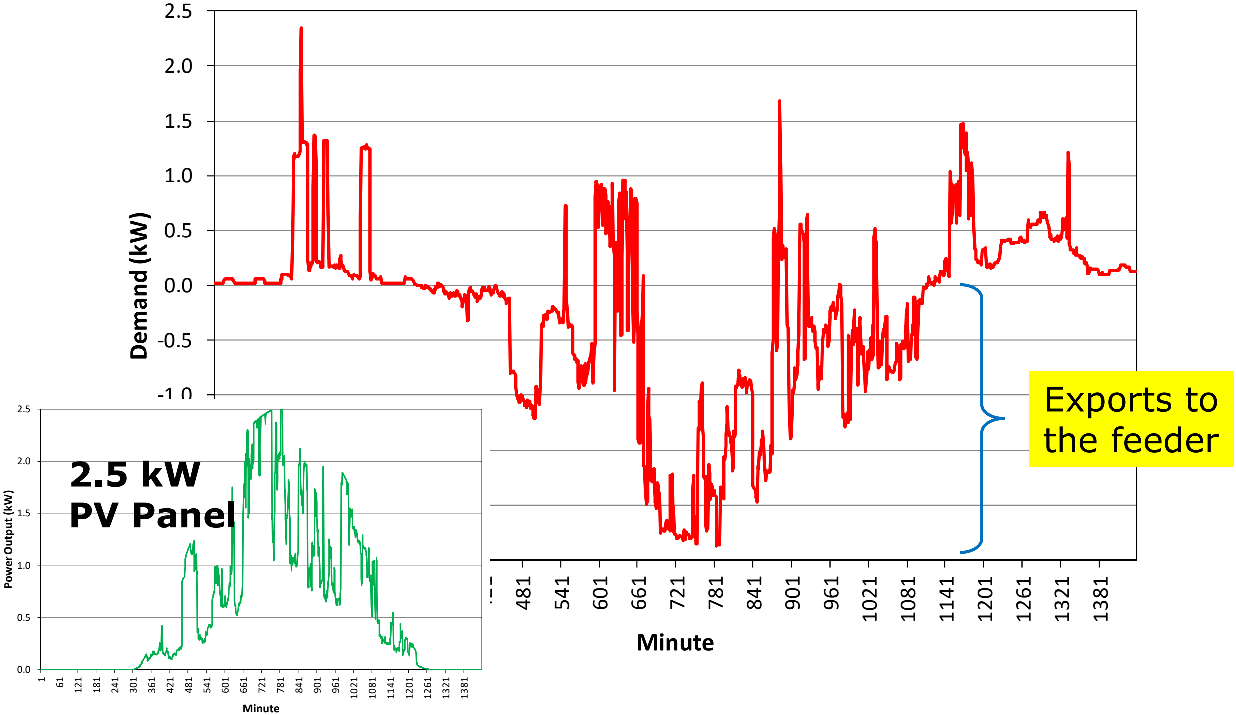


Section	Conductor CSA(mm²)	R (Ω/km)	X (Ω/km)	Rating Current (A)
Main Line (A-F)	4*95	0.322	0.074	300
Segments Line (Other sections)	4*95	0.322	0.074	300
Service Cable	1*25	1.200	0.085	107

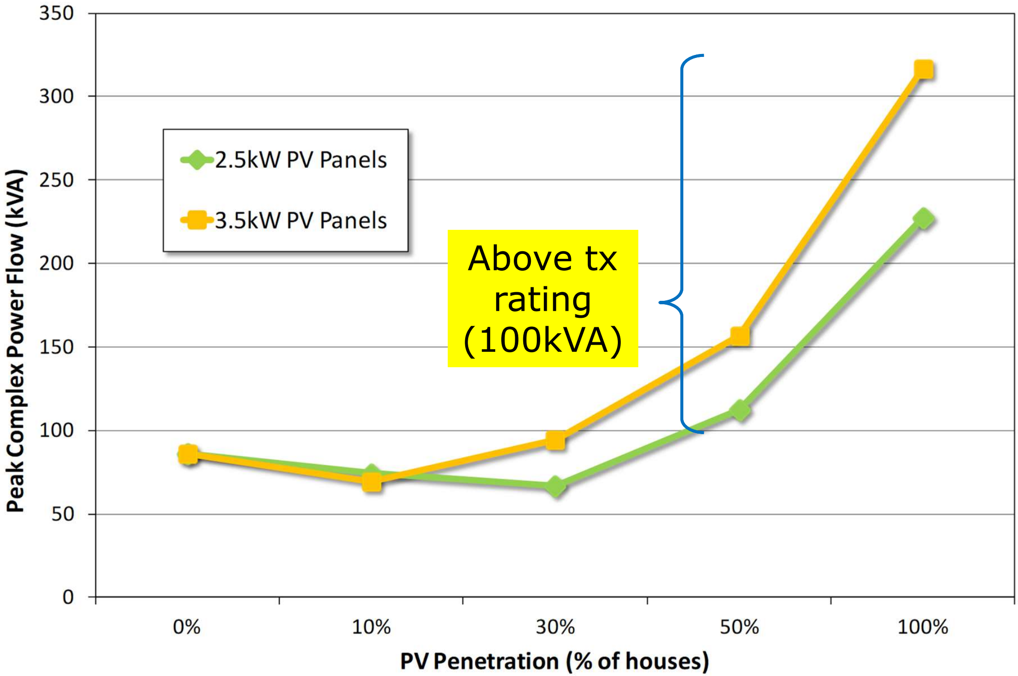
Daily Demand from a Single Household



Daily **Net** Demand from a Single Household with a 2.5 kW PV Panel

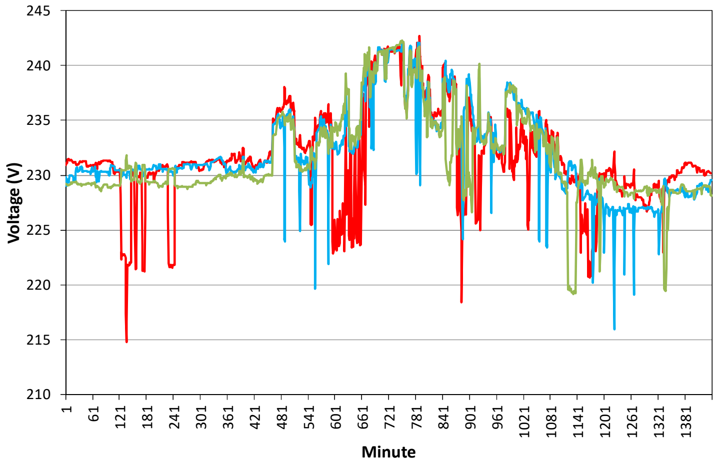


Total Peak Loading at the Distribution Transformer



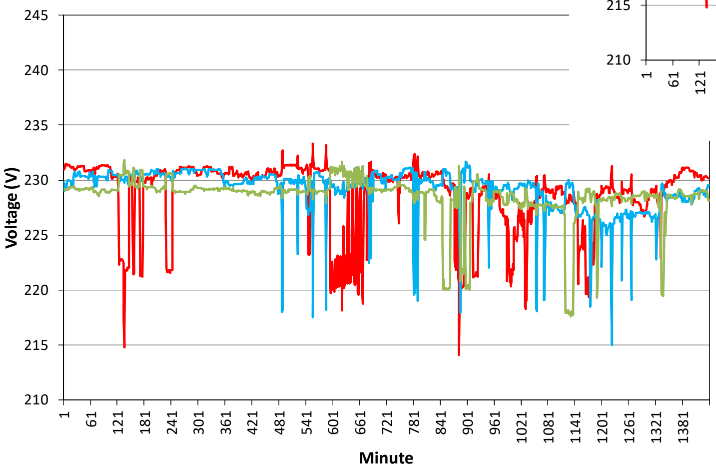
Voltage Rise: End of the Feeder

Significant increase



2.5kW PV, 30%

No PV

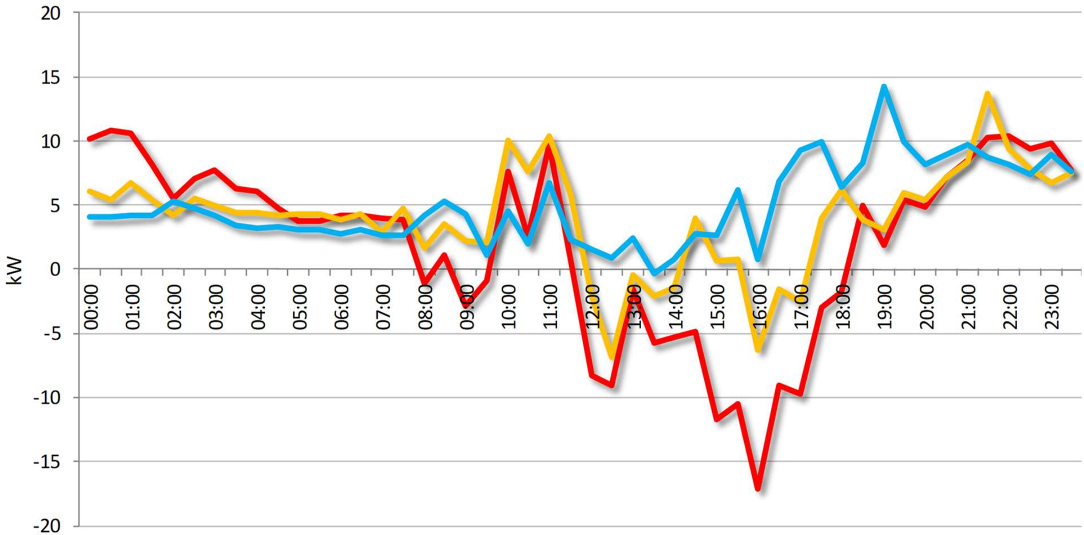


This is actually happening

- Example: Dunton Green, Stockport (Greater Manchester)

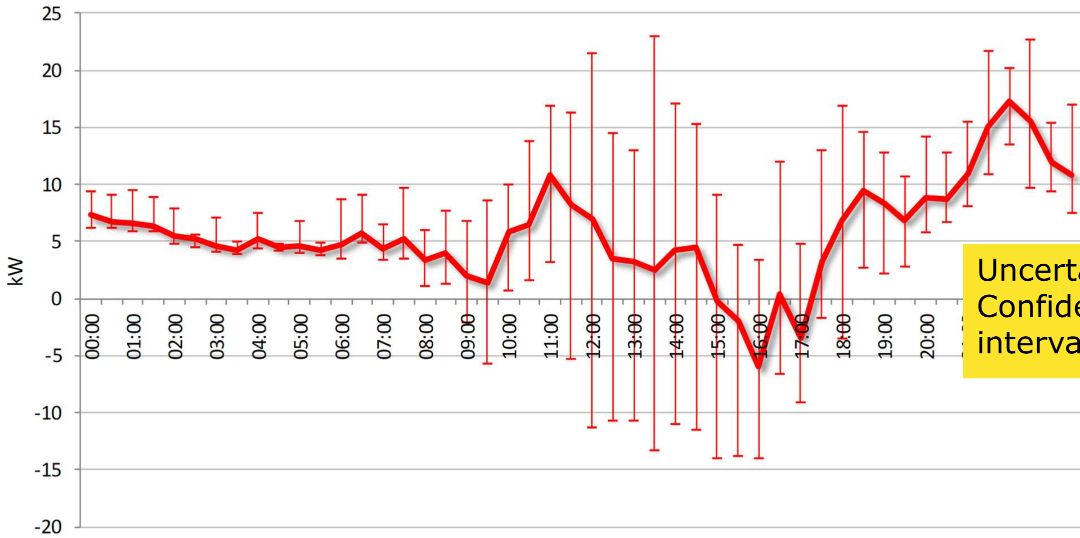
Measurements at LV busbar

- Actual measurements, LV busbar, Dunton Green, Stockport
  - 1 of 4 ways, Pabc, 30 min average, July 29th 2012



Measurements at LV busbar

- Actual measurements, LV busbar, Dunton Green, Stockport
  - 1 of 4 ways, Pa, 30 min average/min/max, July 29th 2012



Uncertainty & Confidence interval ?

Impact of small PV systems

Impact Analyses of Low Carbon Technologies

- LV transformers are already experiencing reverse power flows

- Voltage and capacity issues are yet unknown
  - upon complaint or fault

- Realistic models and sophisticated approaches are required to assess the extent to which LV networks can cope with high penetrations
  - What is the max penetration?
  - When do DNOs need to start 'worrying'
  - What is the likelihood of given penetration to create problems?

ENWL LV Networks

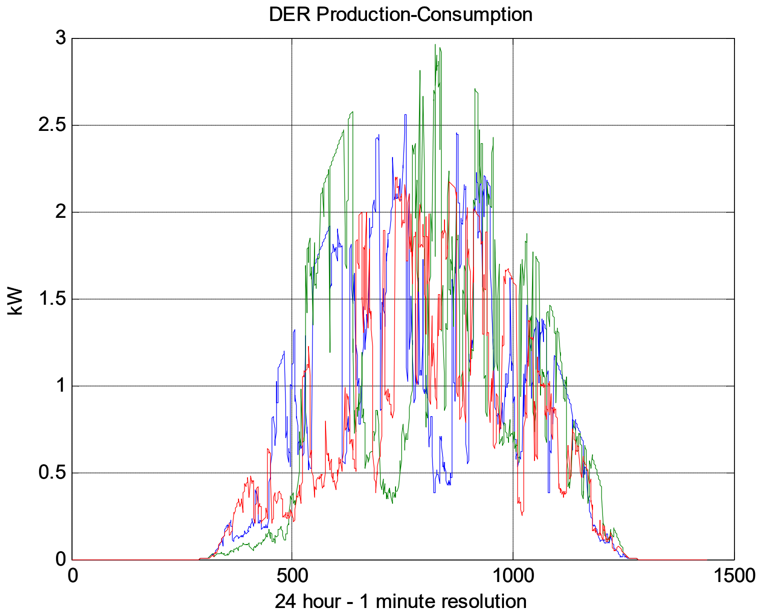
- Typical topology of urban networks shown in Graphic Information System (GIS)

Real-life LV Networks: Challenges

- Connectivity issues
  - To run power flow studies all nodes in the Graphic Information System (GIS) database should be connected. This does not necessarily always happen
- Lack of data
  - Conductor information (underground cable or overhead line) is sometimes limited or erroneous
  - Type of connections are not known (i.e., grounded, etc.)
  - Phase connection of MPANs is not known
  - Demand data is limited to aggregated profiles according to type of customer
  - Etc. etc.

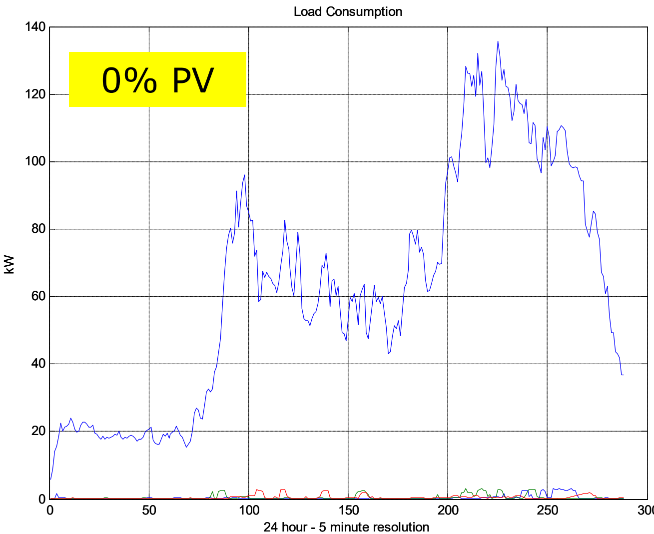
Impact of Small-Scale PV Systems

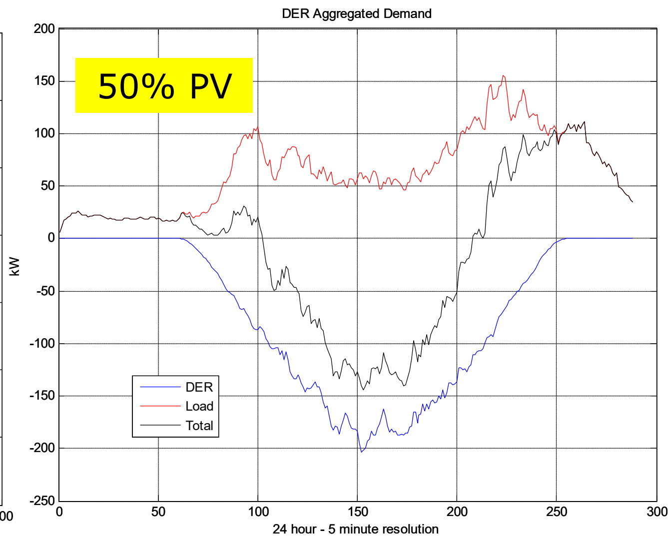
- Using 5-min resolution profiles created with models that consider ‘cloud transients’ and the solar irradiation in the UK



Impact of Small-Scale PV Systems

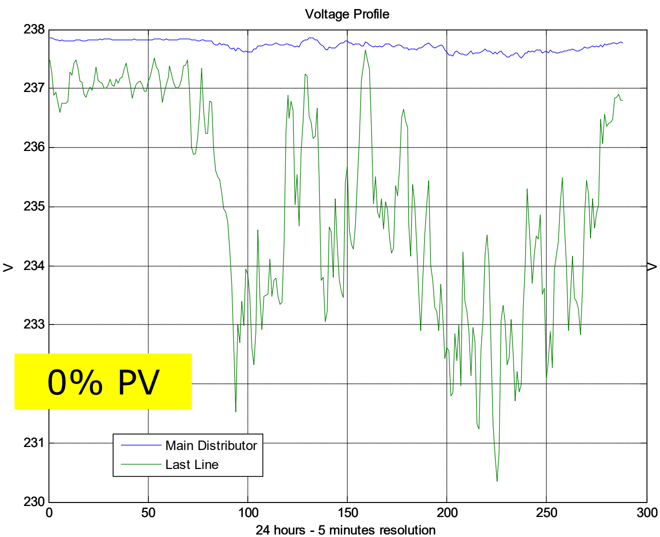
- Generic UK LV feeder with 100 houses
- PV systems (as DER) randomly allocated (2 and 3kW)
- Active power flow at the beginning of the feeder (one day):

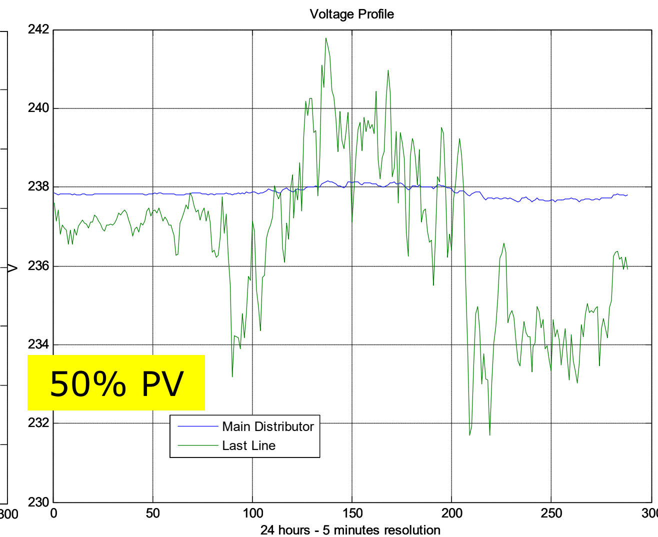




Impact of Small-Scale PV Systems

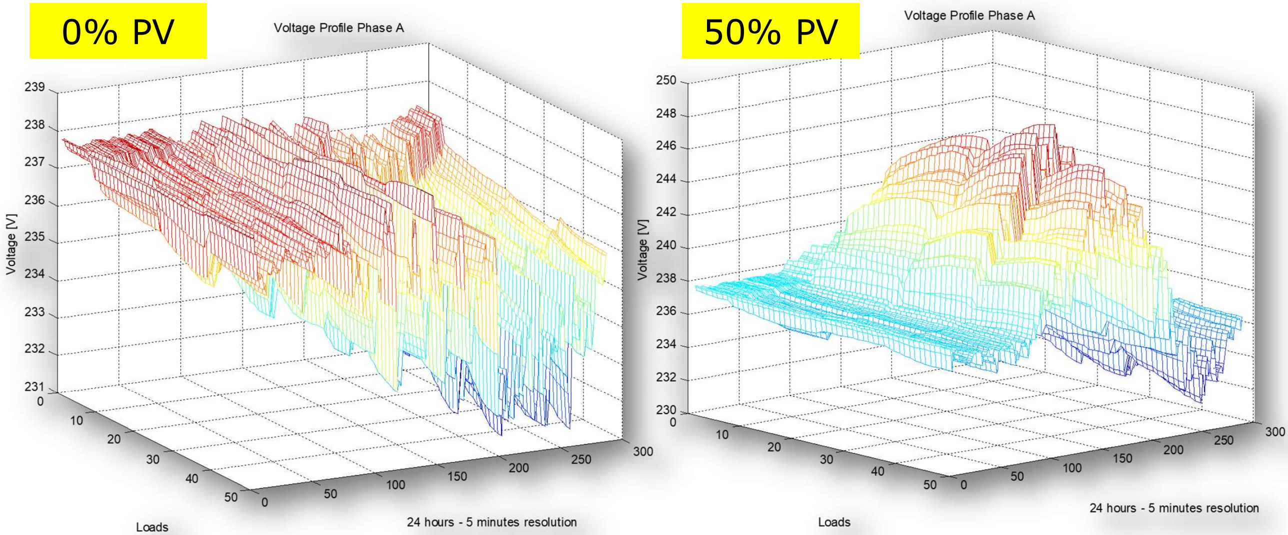
- Generic UK LV feeder with 100 houses
- PV systems randomly allocated (2 and 3kW)
- Voltages (LV busbar with fixed 412V L-L):





Impact of Small-Scale PV Systems

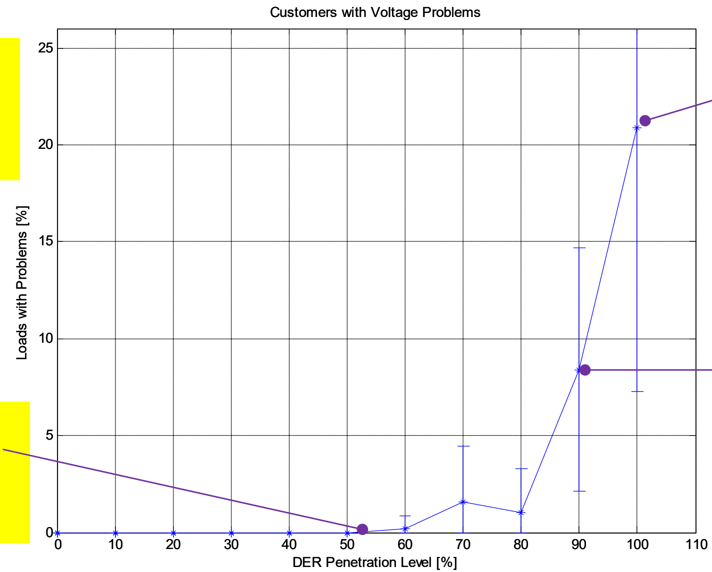
- Single-Phase Voltages in Time Series (Voltage-Load–Time)



Impact of Small-Scale PV Systems

- Quantifying voltage rise issues (EN 50160) per customer
  - 95% of each 10 min means rms values of voltage: Un +/- 10%
  - All 10 min means rms values of voltage: Un +10% / -15%

10 random load and generation simulations per penetration level



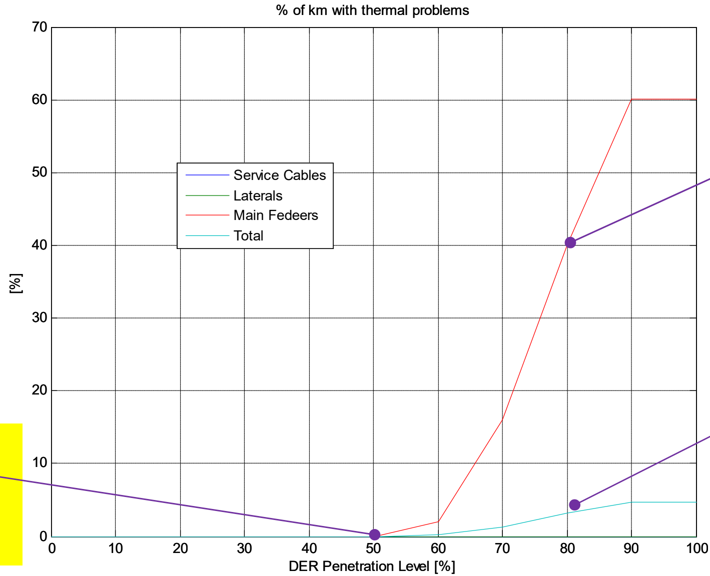
2% customers with voltage problems when100% PV penetrations

8% customer with voltage problems when90% PV penetrations

0% customers with voltage problems when 53% PV penetrations

Impact of Small-Scale PV Systems

- Quantifying thermal issues over the length of the circuit
  - Cable overloaded for more than one hour



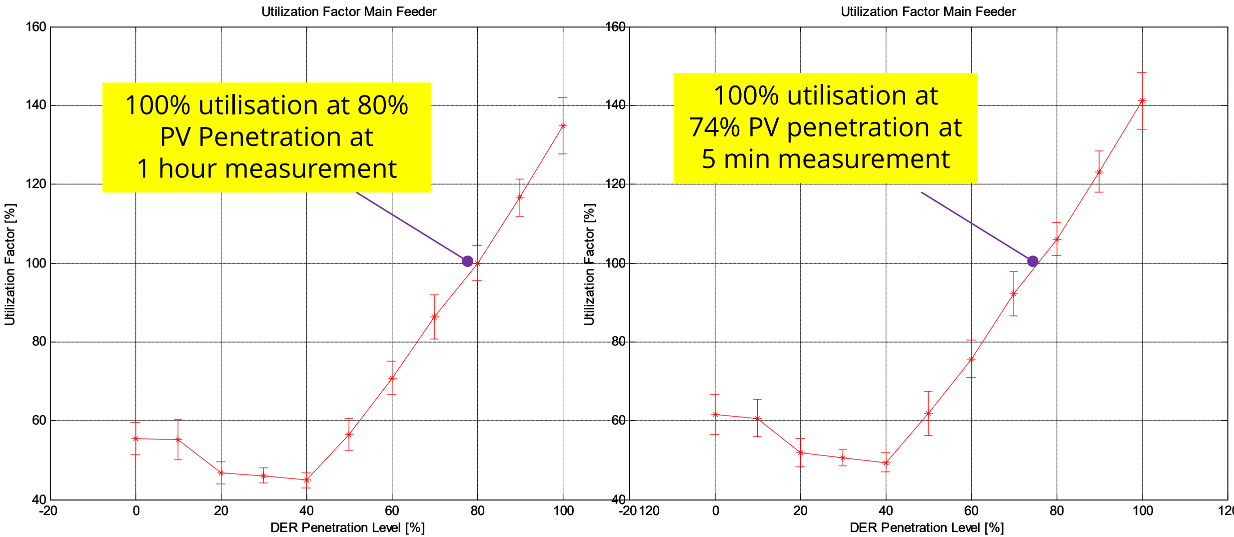
40% of km main feeder cable with thermal problems when 80% DER penetration

<4 % of km service or laerals cable with thermal problems when 80% DER penetration

0% of km cable with thermal problems when 50% DER penetration

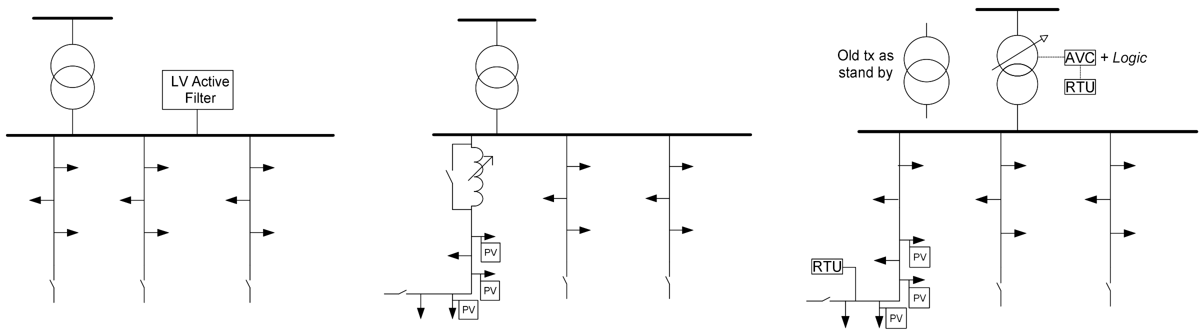
Impact of Small-Scale PV Systems

- Utilization Factor in the main feeder
  - Max power during period relative to nominal capacity



Potential Solutions for LV Networks

- From the DNO
  - On load tap changers (perhaps with remote measurements)
  - In line voltage regulators
  - Reduction of unbalance and harmonics
  - ‘Intelligent’ disconnection of PV
- From the PV systems
  - Reactive power (power factor 0.95 inductive)



OLTC-Fitted LV Transformer (ENWL)

- LV distribution transformer (11/0.4kV) equipped with OLTC
  - 9 Taps, +/- 8%, 2% per step

Transformer Tap position	HV	LV	
	L-L (V)	L-L (V)	L-N (V)
+9 (+8%)	11000	400.9	231
+8 (+6%)	11000	408.5	236
+7 (+4%)	11000	416.3	240
+6 (+2%)	11000	424.5	245
+5 (0%)	11000	433.0	250
+4 (-2%)	11000	441.8	255
+3 (-4%)	11000	451.0	260
+2 (-6%)	11000	460.6	265
+1 (-8%)	11000	470.7	271

MR OLTC in Leicester Ave

PV Summary

- Photovoltaic technology plays a significant role in the generation mix at a distribution level particularly in countries where this is incentivised or where it is needed to give people access to electricity
- PV like other renewable generation, similar to wind, intermittency is the main issue to limit high adoption of PV technology
- However FIT schemes have resulted in a high adoption rates of the technology
- The corresponding impacts should be carefully assessed and understood to produce sensible (smart) solutions

EVs, Specifications and Demand, Charging Requirements and Methods

EVs, Specifications and Demand

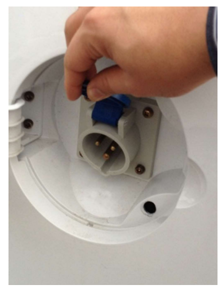
KEPCO Smart Grid Pilot Jeju Island, South Korea, 2011



MANCHESTER 1824
The University of Manchester

Electric Vehicles (EVs)

KEPCO Smart Grid Pilot
Jeju Island, South Korea, 2011



Electric Vehicles (EVs)

Paris, 2012

London, 2012

Warsaw, 2012

MANCHESTER
1824
The University of Manchester

Electric Vehicle Infrastructure

Nanjing (SGCC), 2011

Jeju Island, 2011

London, 2012

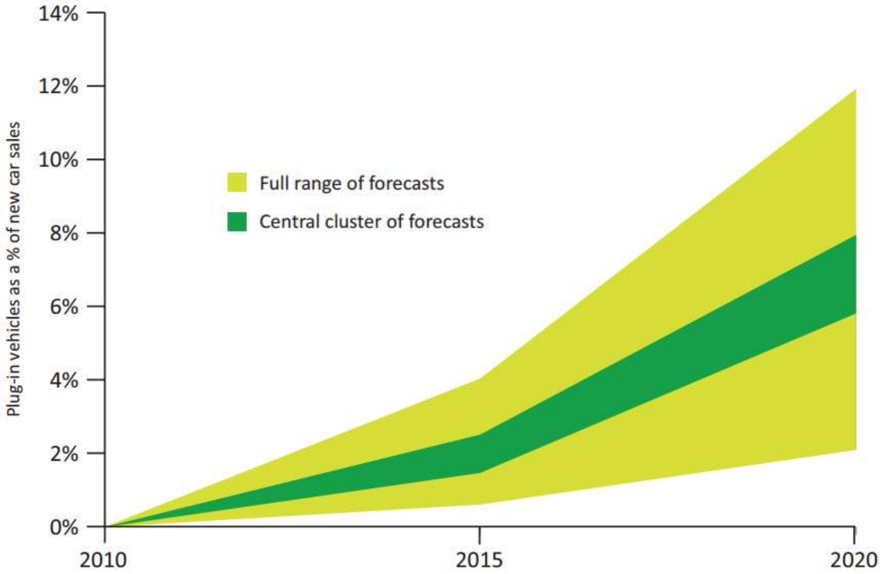
Amsterdam, 2012

Electric Vehicles in the UK

- Electrification of transport → less CO_2 emissions
- UK registrations in 2020 will be ~2.4 million (?) vehicles
  - 11 per cent (274,000 units) electric vehicles (EVs)
  - 10 per cent (235,000 units) hybrids
- Forecasts in growth of electric vehicles mainly depend on cost to consumers
  - £5,000 electric car grant scheme launched in 2011
- Average age of car in the UK is 7.1 years (DFT 2010)
  - Rapid changes in the number of electric vehicles could take place

Plug-in Vehicle Uptake Forecasts (UK)

- For 2015 and 2020
  - Source: UK Office fro Low Emissions Vehicles, 'Making the Connection' 2011



Electric Vehicles – Some Specs

	Tesla Motors Roadster	Toyota RAV4 EV	EDrive Systems Plug-in Toyota Prius
Range	200+ miles	80 - 125 miles	50-60 miles (all electric)
Top Speed	130 mph (governed)	80 mph (governed)	34 mph (governed)
Weight	2500 lbs	3480 lbs	2989 lbs
Motor	185 kW AC (248 peak hp)	50 kW perm. magnet	50 kW perm. magnet AC (67 HP)
Batteries	Lithium-ion	24 12-volt NiMH	Lithium-ion
Charger Type	110V / 220V; conductive	220V/ 30A; 5 kW inductive	110V/ 15A, 1 kW; conductive
Battery Capacity	53 kWh	25.9 kWh	9 kWh

Electric Vehicle Demand

- Energy usage of an electric vehicle:
  - Nissan Leaf ~ 34 kWh per 100 miles or 0.21 kWh/km

- How far do people drive?
  - Average annual distance a private car drives in the UK is 13,301km (correct as of 2009 – DFT data)

- What would be the energy required to recharge the car at the end of the day? Assume 100% charging efficiency

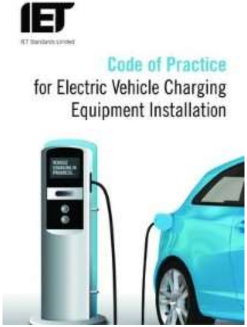
Electric Vehicle Charging Requirements

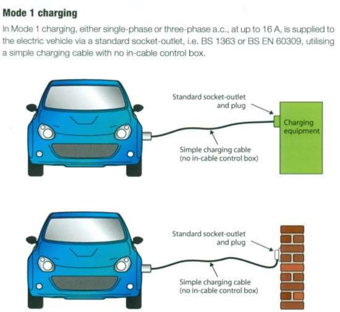
- A number of options have been defined for EV charging
- Fast vehicle charging is possible but this comes at a cost of high current consumption
- Take a car with a 30 kWh battery as an example:

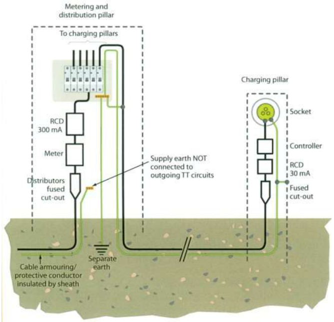
Charging Speed	kVA	Time Required	Charging Supply
Slow	1-5	6-30h	230V, 16/32A 1ϕ
Medium	10-25	1.2-3h	230V, 32/63A 3ϕ
Fast	180-400	5 – 10min	DC Rectifier

IET Code of Practice for EV Charging Equipment Installation

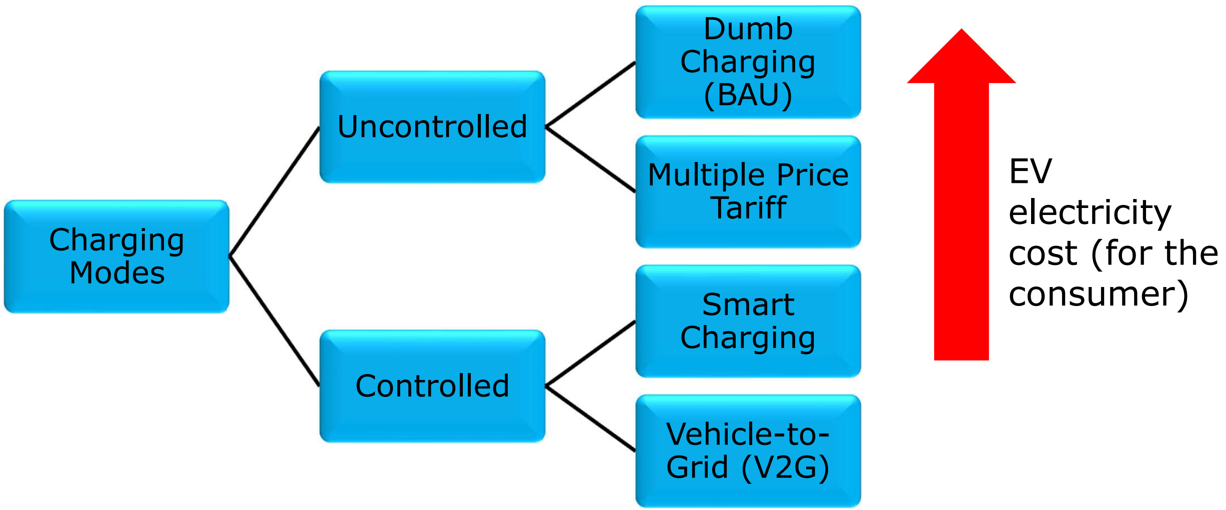
- Published in 2012 to provide guidance to installers
  - Applies to the installation of dedicated conductive charging equipment for pure and hybrid EVs
  - Domestic, on-street and commercial installations





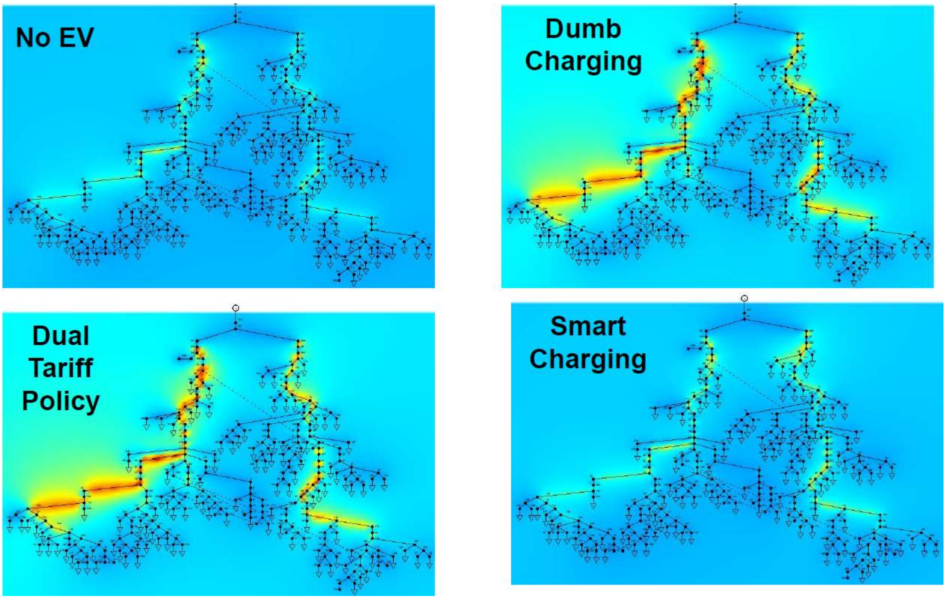


Electric Vehicles: Charging Approaches



MV Networks and Electric Vehicles

- Typical Portuguese MV network (30% penetration)
  - peak 7.3 MW, annual consumption 32 GWh, power factor 0.96

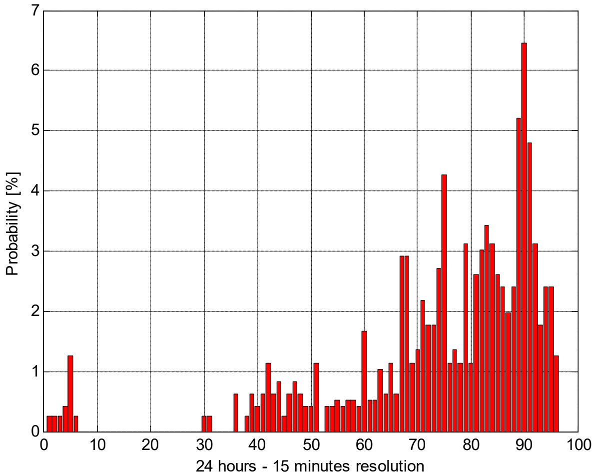


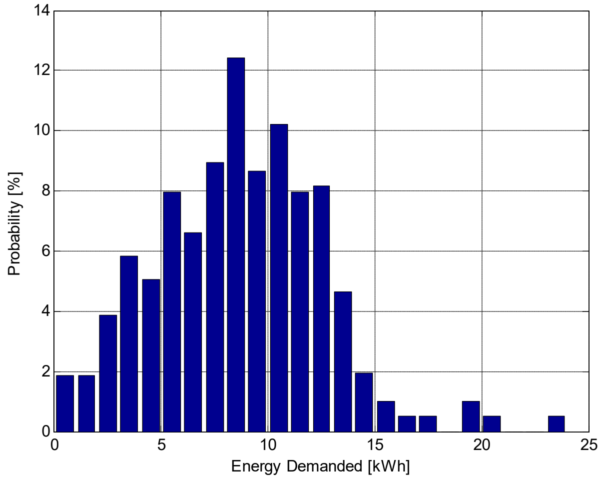
Source: João A. Peças Lopes, INESC Porto, 2011

Impact of EV on LV Networks

How People are going to charge EVs?

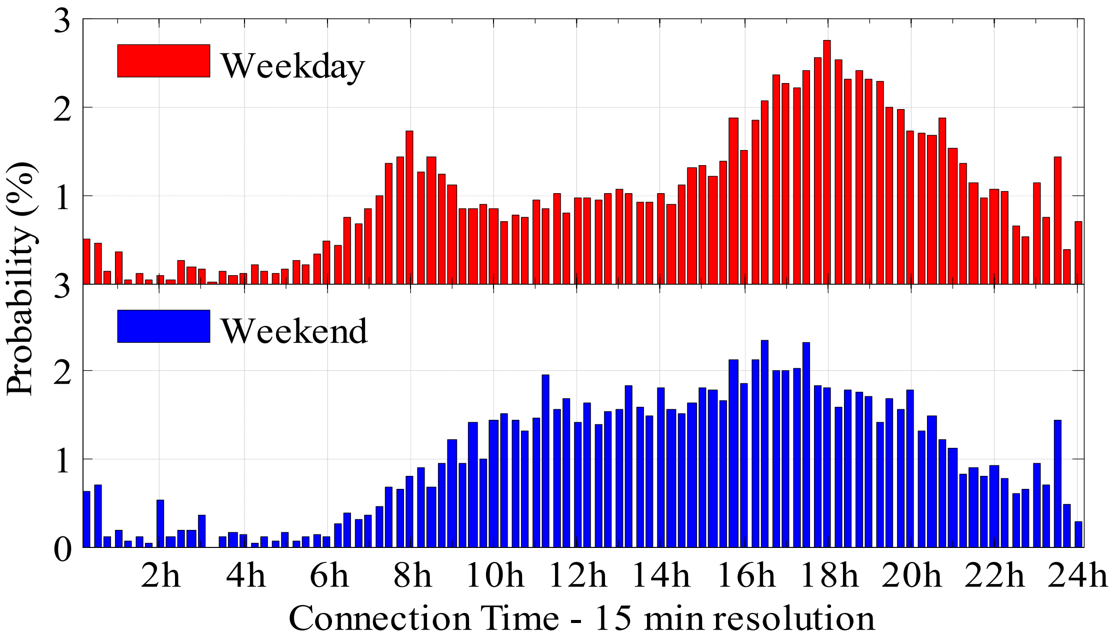
- Information Source: "Impact of Electric Vehicle Charging on Residential Distribution Networks : An Irish Demonstration Initiative" (CIRED, 2013).
- From this project (2 EVs rotated among houses):
  - Probability distribution function of EV connection times.
  - Probability distribution function for the daily EV energy requirement.





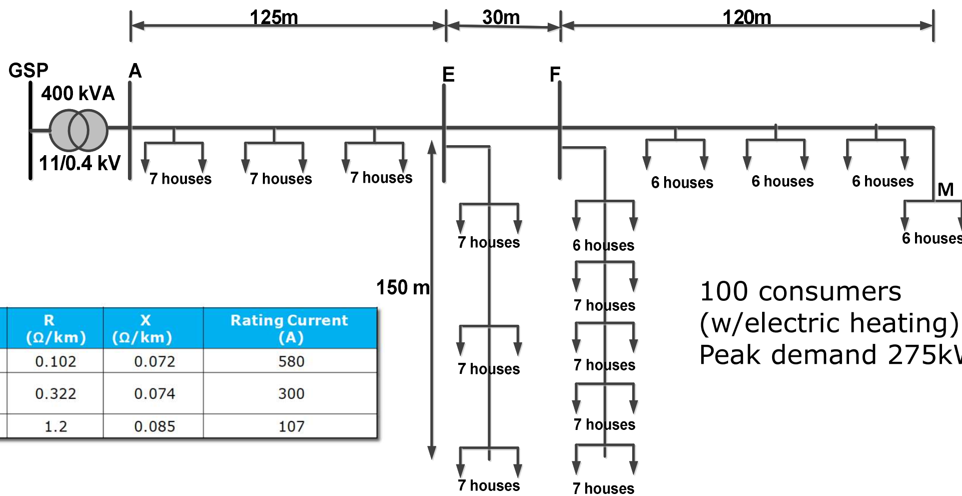
How People are going to charge EVs?

- Project “My Electric Avenue” (myelectricavenue.info)



LV Networks and Electric Vehicles

- Impact Analysis (Deterministic approach)
  - Considering driving patterns, different types of EVs, penetration, charge start time, battery state
  - OpenDSS-based analysis (three-phase plus neutral)

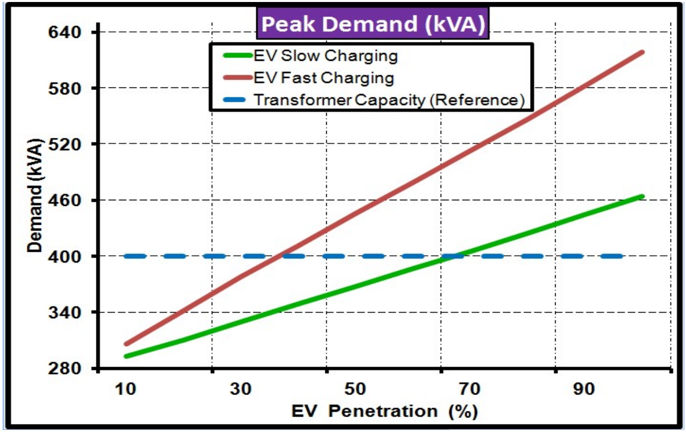


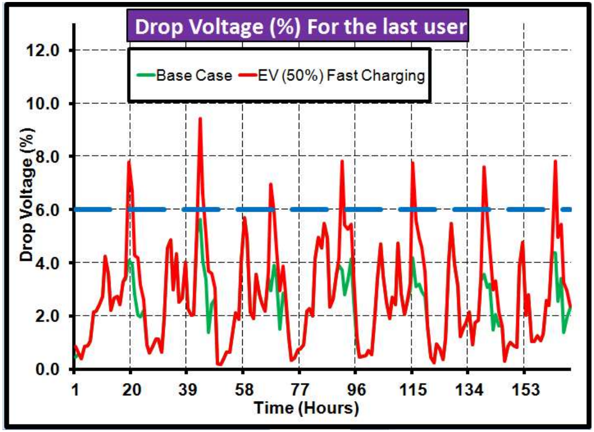
Section	Conductor CSA (mm²)	R (Ω/km)	X (Ω/km)	Rating Current (A)
Main Line (A-F)	4*300	0.102	0.072	580
Segments Line (Other sections)	4*95	0.322	0.074	300
Service Cable	1*25	1.2	0.085	107

100 consumers
(w/electric heating)
Peak demand 275kW

LV Networks and Electric Vehicles

- Slow and fast charging analysis
  - 16kWh, 230V: ~4.5 and 2h → 16 and 32A





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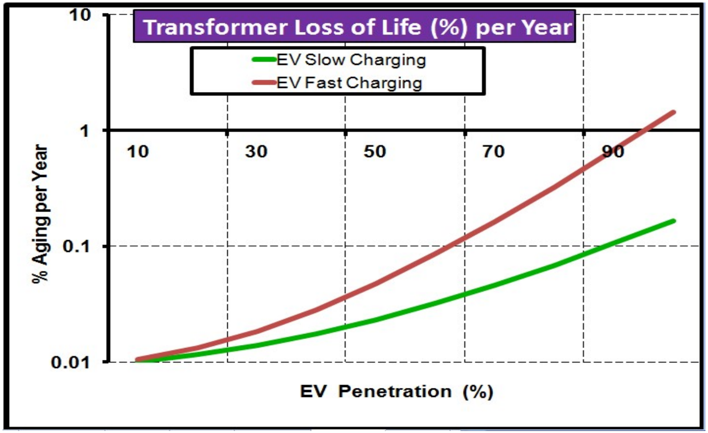
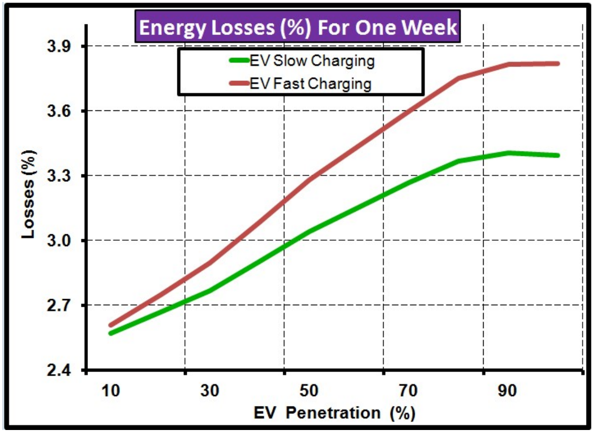
LV Networks and Electric Vehicles

- Slow and fast charging analysis
  - 16kWh, 230V: ~4.5 and 2h → 16 and 32A





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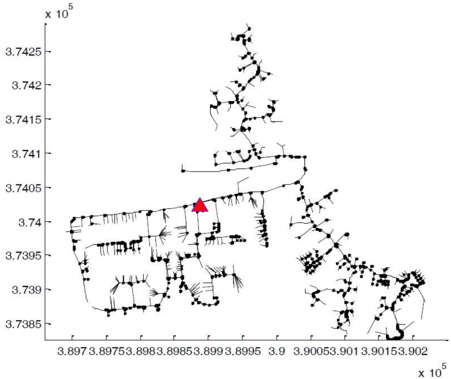
LV Networks and Electric Vehicles

- Impact Analysis (Monte Carlo approach)
  - Real residential LV network (5 feeders, 326 customers). Loads considering CREST model and the UK ONS data
  - Slow charging mode (Nissan Leaf, 24kWh, 8 hours)
  - One weekday and one weekend per month
  - OpenDSS-based analysis (three-phase plus neutral)



Household size	Percentages	Number of Profiles
One person	29.4	590
Two people	35.0	700
Three people	16.1	320
Four or more people	19.6	390
Total	100	2000

Li Han
MSc Student 2011-2012

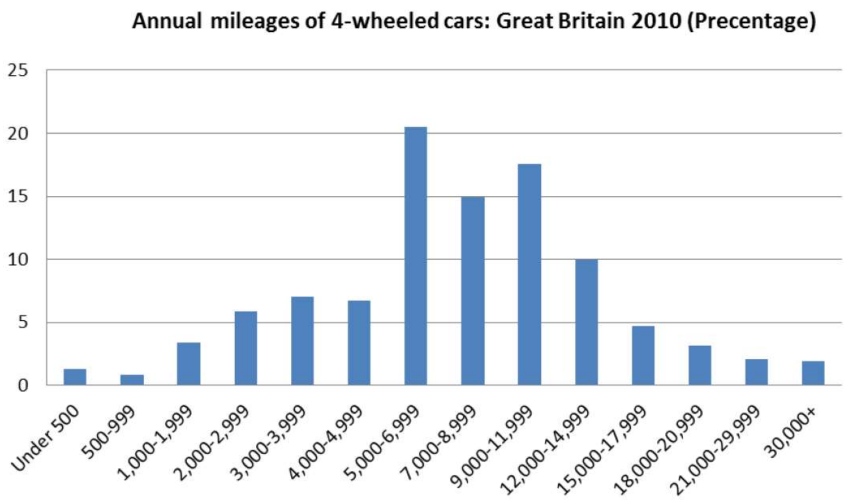
LV Networks and Electric Vehicles

- Further considerations
  - Probability of travel end time
    - USA National Household Travel Survey 2001
    - Z. Darabi, M. Ferdowesi, "Aggregated Impact of Plug-In Hybrid Electric Vehicles on Electricity Demand Profile", IEEE Trans. on Sustainable Energy, vol 2, no 4, p 501-508, 2011

Travel end time	Number of profiles	Probability	Travel end time	Number of profiles	Probability
13:00	50	5%	19:00	130	13%
14:00	50	5%	20:00	120	12%
15:00	60	6%	21:00	100	10%
16:00	90	9%	22:00	70	7%
17:00	130	13%	23:00	30	3%
18:00	170	17%	Total	1000	100%

LV Networks and Electric Vehicles

- Further considerations
  - Travel distance
    - UK National Travel Survey → Can be translated into average daily mileage



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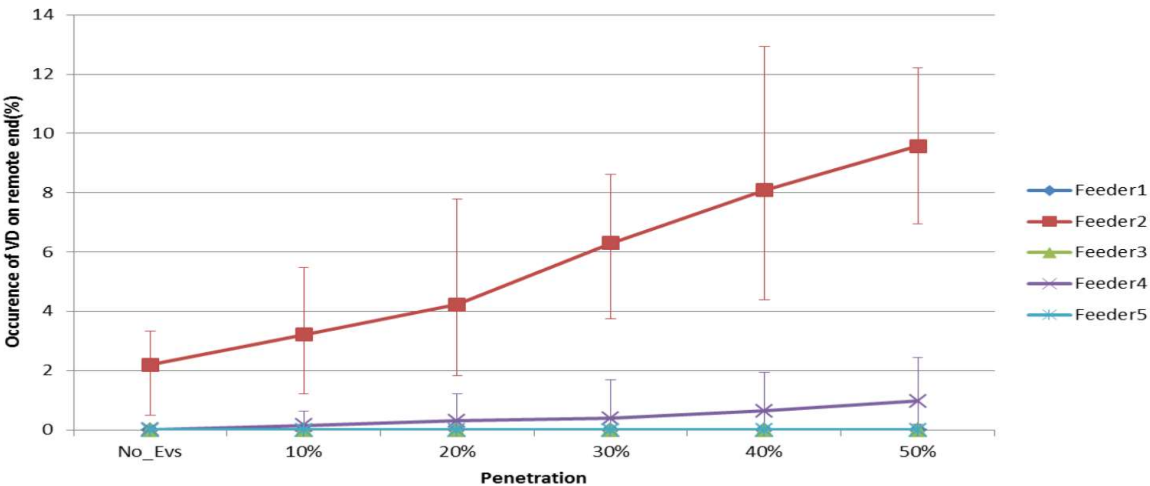
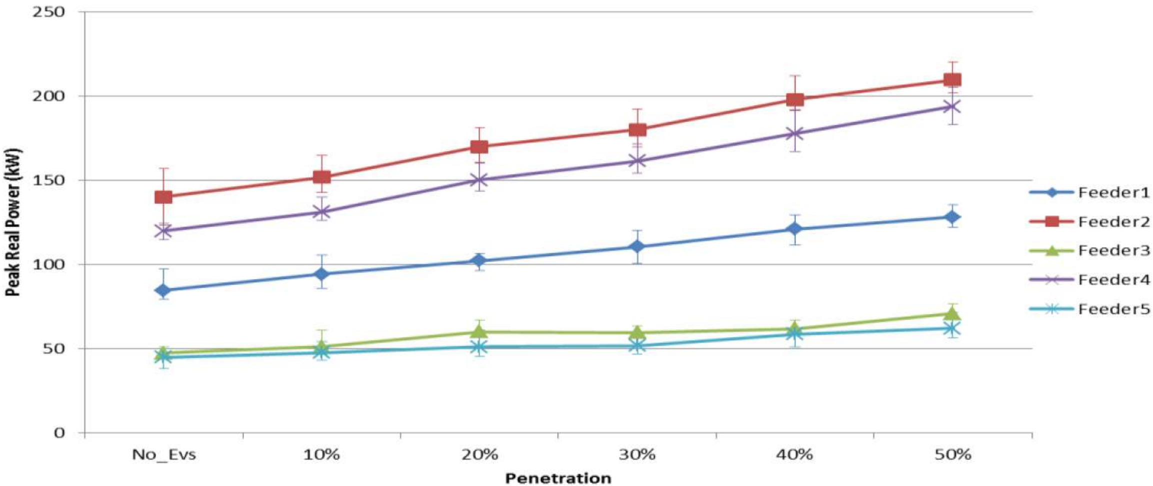
LV Networks and Electric Vehicles

- Voltage Drops
  - As expected, more likely to happen with higher penetrations



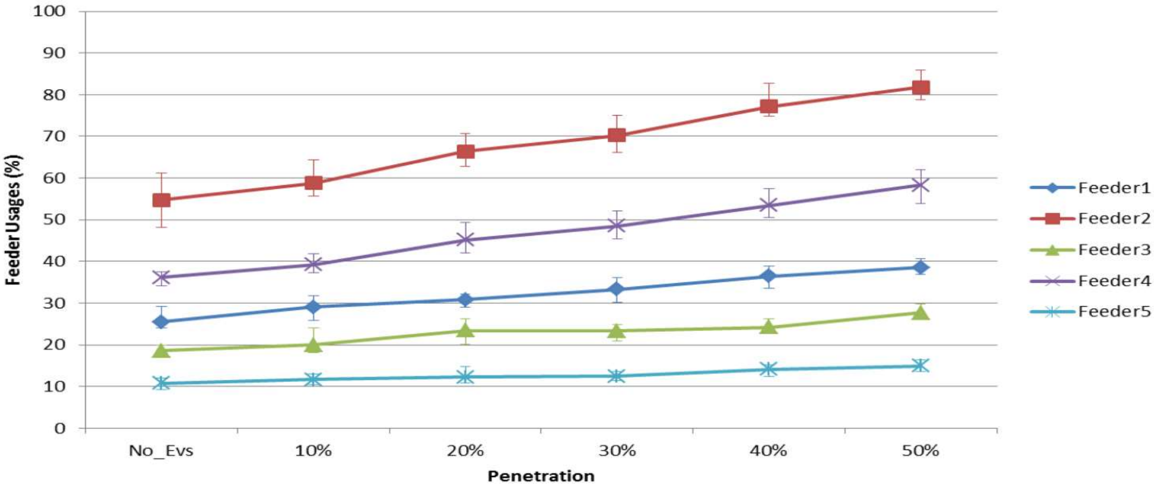
LV Networks and Electric Vehicles

- Peak Demand
  - As expected, increases with higher penetrations
  - How much does it increase for the transformer?



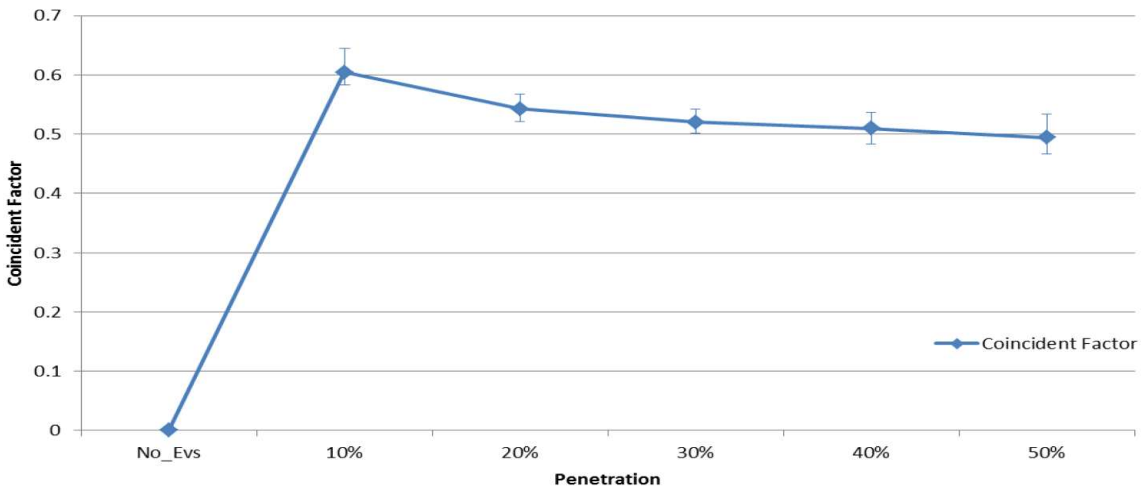
LV Networks and Electric Vehicles

- Usage of assets
  - With 50% of penetration one feeder is approaching its limit.



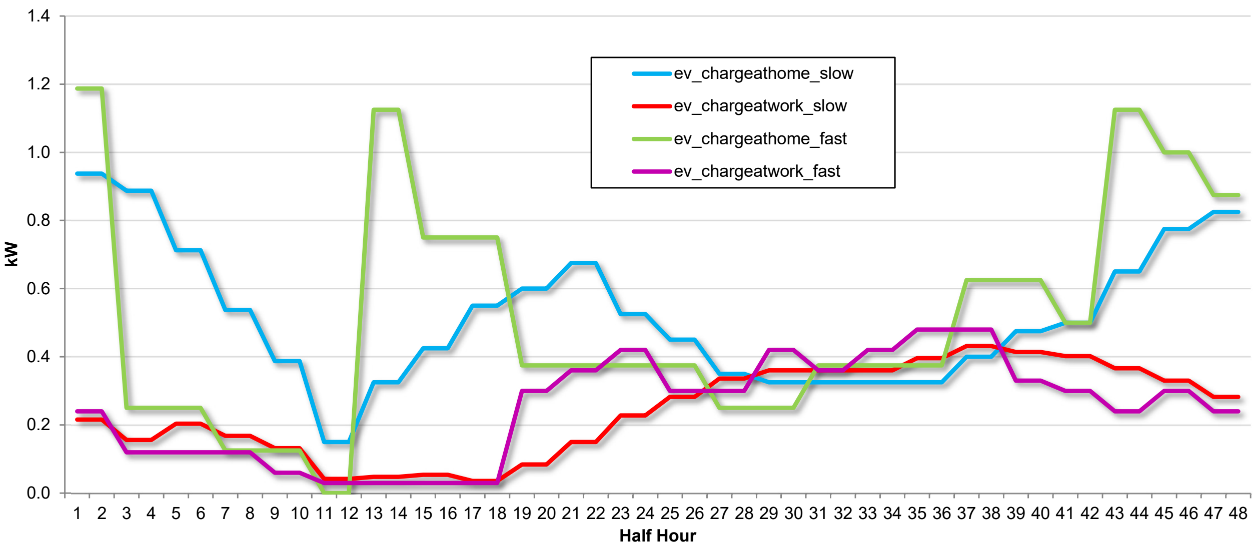
LV Networks and Electric Vehicles

- Coincident factor
  - Coincidence of EVs during the peak
  - Why is this important?



UK Smart Grids Forum – Work Stream 3

- 2012 Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks
  - Diversified charging profiles of EVs



Examples of Impact of EV Use

Example 2.1 - Impact of Electric Vehicle Use

- One third of 150 houses in an LV feeder have purchased an electric vehicle (18 kWh)
  - ADMD is of each house is 1.5 kW
  - All will use a low charge regime (5 hours from empty)
  - The average distance travelled by one person in a day is 20 miles
  - The distribution transformer has a capacity of 400 kVA

(i) What is the extra energy requirement?

(ii) Can the network deliver this extra energy?

(iii) How could the network accommodate this?

- "Integration of Electric Vehicles in the Electric Power System" Lopes, J.A.P.; Soares, F.J.; Almeida, P.M.R.; Proceedings of the IEEE, Jan. 2011

Example 2.2 - Impact of Electric Vehicle Use

- The University multi-storey car park has 200 parking spaces

  Having travelled an average of 10 miles, staff park in the car park and wish to charge the electric vehicles inside

(i) What is the total energy requirement?

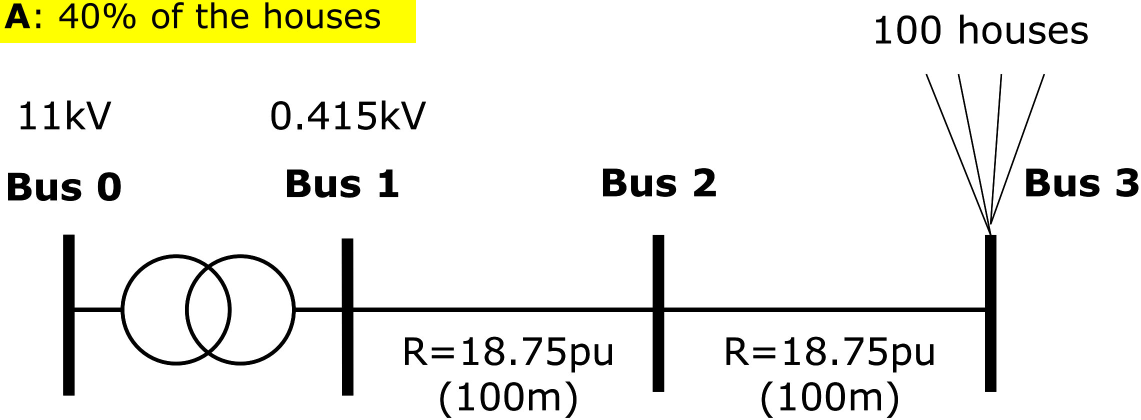
(ii) What is the peak power requirement?

(iii) How could the peak load be managed?

Example 2.3

- ADMD of 1.5kW and load allowance of 8kW.
- What is the max penetration of EVs for the network below?
  - Consider EVs with a 24kWh battery that fully charges in 8 hours
  - Transformer capacity 500kVA

A: 40% of the houses



Storage and Other Technologies

Outline

- Storages Specifications and Technologies
- Example of Storage Application
- Heat Pumps (HPs) Technologies

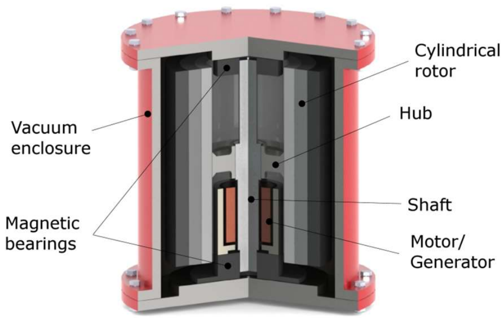
- M.H.J. Bollen, "The Smart Grid – Adapting the Power System to New Challenges", Morgan & Claypool Publishers, 2011
- J. Momoh, "Smart Grid – Fundamentals of Design and Analysis", Wiley and IEEE Press, 2012

Storage: Changes Everything

- The ‘holy grail’ of power systems
- Technologies: batteries, flywheels, compressed air, etc.
- Applications:
  - Frequency control
  - Peak shaving
  - Constraint management (voltage, thermal)
    - active and reactive support
  - Intentional islanding?
  - Other ancillary services?

Storage Technologies

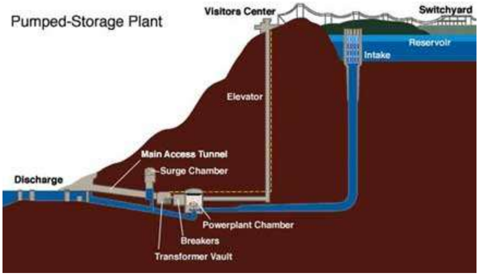
- Flywheels
  - Cylinder that spins at a very high speed, storing kinetic energy
  - Pros: fast charge and discharge, compact, long life span
  - Cons: power loss faster than batteries
  - Business case: ancillary services (USA)



Source: IEEE Spectrum / Beacon Power Corp.

Storage Technologies

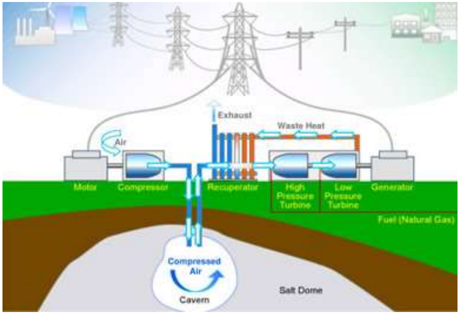
- Pumped hydro
  - The process of water being pumped from a lower reservoir uphill (off-peak) then allowing it to flow downhill through turbines to produce electricity (during peak)
  - Pros: Readily available and widely used in high power applications. Lower cost of power, can be used for **frequency regulation and reserves**.
  - Cons: Planning due to environmental aspects. Can only be implemented in areas with hills.



Source: bravenewclimate.com

Storage Technologies

- Compressed air
  - The process of air being compressed and stored in airtight underground caverns (off-peak) then allowing it to expand through a combustion engine to produce electricity (during peak)
  - <u>Pros</u>: Conserves natural gas by using low-cost, heated compressed air to power turbines.
  - <u>Cons</u>: Low efficiency due to extra reheating to turn on turbines (e.g., for every 1 kWh in only 0.5 kWh out). Areas with suitable underground caverns.



Source: www.renewable-energy-info.com

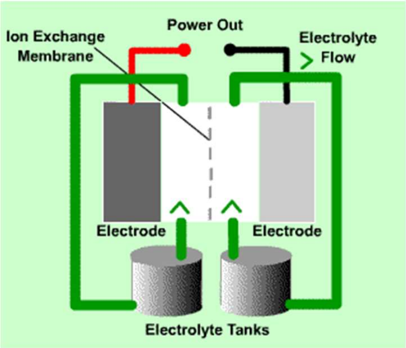
Storage Technologies

- Advanced batteries
  - Include lithium-ion (Li-Ion), polymerion, nickel metal hybrid (Ni-MH), sodium sulphur (NaS)
  - Pros: Less space than lead-acid batteries
  - Cons: Too expensive for large-scale applications

SSE: Shetland NaS Battery 1MW, 6h

Storage Technologies

- Flow batteries
  - Similar to lead-acid batteries but the electrolyte is stored in an external container and it circulates through the battery cell stack
  - Pros: Unlimited electrical storage capacity (limitation is the size of the electrolyte storage reservoir)
  - Cons: Number of cycles of usage can be limited



Source: www.mpoweruk.com

Use of EV as Energy Storage

- Total of around 24 million cars on UK roads
- Average battery capacity of 30 kWh if electric
  - Total energy storage of 720 GWh
- Total UK energy consumption in single day is 1037 GWh
- Clearly, electric vehicles could play a significant role as an energy source
- Should a power outage occur – an EV could play a role in keeping supplies on (?)
  - Vehicle to Grid (V2G) Technology: how feasible?

Storage: Technical Characteristics

- Comparison of some tech properties for some technologies

Technology	Efficiency	Life Cycles	Density kWh/m^3	Rating
NaS	87%	2000	200	10 MW, 10h
Flow Battery	80%	2000	25	1 MW, 6h
Li-Ion	95%	4000	300	1 MW, 15min
Ni-Cd	60-70%	1500	50	5 MW, 10min
Flywheel	93%	20000	15	1 MW, 15min
Compressed Air	75%	10000	-	100 MW, 10h
Pumped Hydro	70-85%	20000	-	1000 MW, 24h

Note: These are figures from ~2010.

Storage: Capital Cost

- Comparison of the capital cost for some technologies

Technology	Capital Cost US$/kW	Capital Cost US$/kWh
NaS	1000-2000	200-1000
Flow Battery	700-2500	150-600
Li-Ion	700-1500	800-3000
Ni-Cd	500-1500	800-1500
Flywheel	4000-10000	1000-3000
Compressed Air	500-1000	30-100
Pumped Hydro	600-1500	50-150

Note: These are figures from ~2010.

Storage: Regulatory Aspects

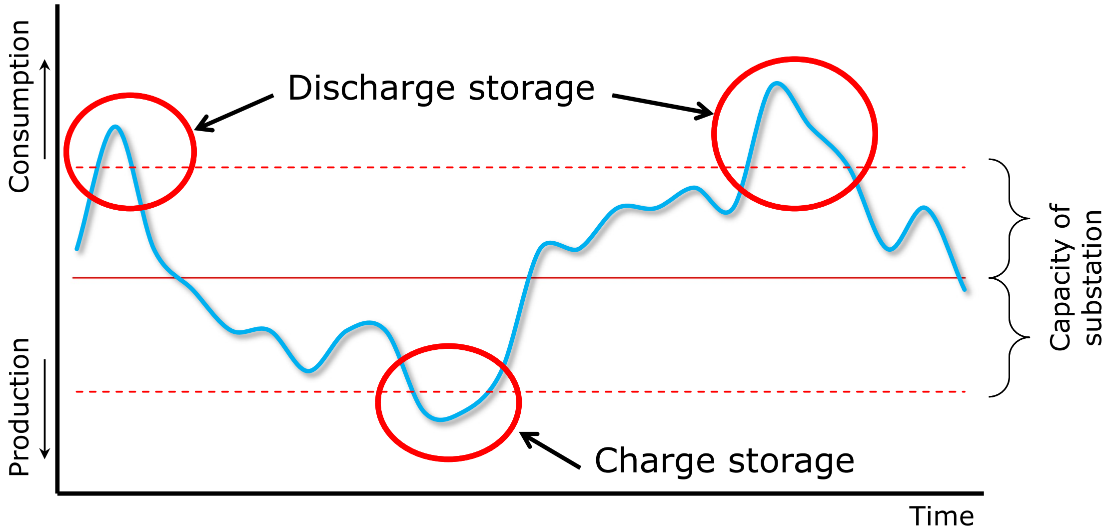
- Vertically integrated market
  - The multiple potential benefits of storage can be 'added up'
    - network management, reduced cost of electricity, etc.

- Competitive market (unbundling rules)
  - Are transmission and distribution network operators allowed to own and operate a storage installation?
    - TNOs and DNOs are not allowed to own production units
      - Storage can be considered a production unit
    - Overall network efficiency is the best justification
      - How to deal with energy production?

Examples of Storage Usage

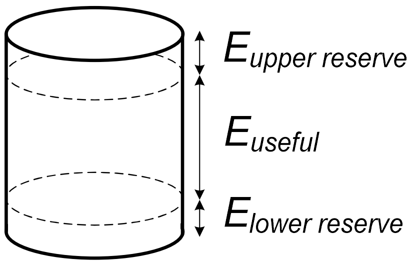
Storage: Active Power Management

- Variation in power flow through a substation with DG
  - Storage facility is downstream the substation



Storage: Active Power Management

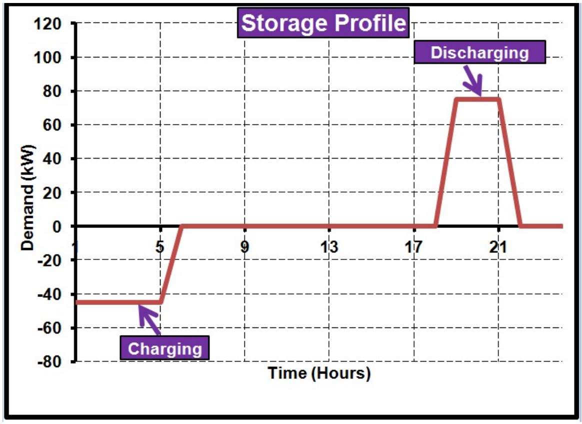
- (Some) important parameters for dimensioning and scheduling storage
  - Amount of useful energy that can be stored (kWh)
    - Maximum energy level minus minimum
  - Maximum charging rate (kW)
  - Maximum discharging rate (kW)
  - Efficiency (%), ratio of the energy output to the energy input

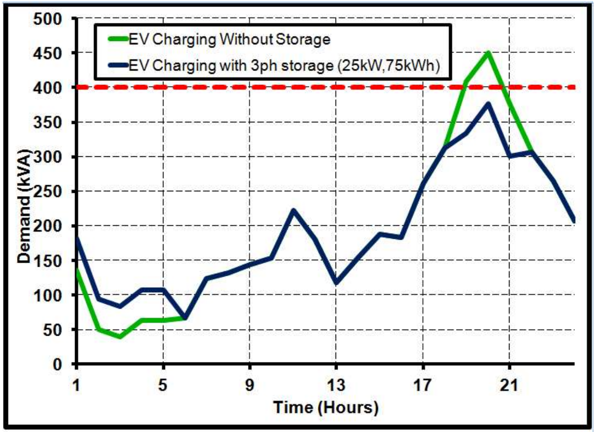


Technology dependent

Storage: Increase Electric Vehicles

- Consider three - one phase 25kVAx3h in the network in previous video. Assume charge between 1-5am, and discharge between 7-9pm, it can help to increase the connection of EV from 65% to 70%:





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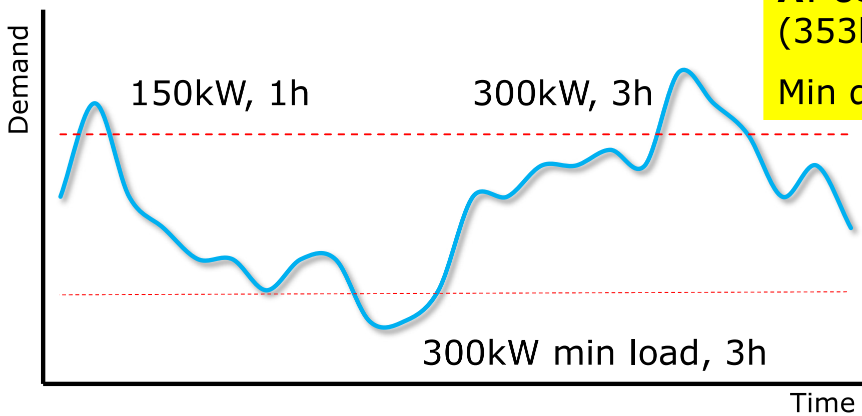
Exercise 2.1

- The values in the load profile show the max power exceeding the nominal capacity (1.2 MW) of the substation and the length of the corresponding critical period.
  - Determine the max cost of a NaS battery (installed downstream the sub for peak shaving) with roundtrip efficiency of 85%.
  - When would it be more suitable to charge the battery?

A: US$ 1,058,000 (353kW, 1.5h).

Min demand.



Storage: Aggregation

- What are aggregators?
  - Third-party companies that 'aggregate' the available storage (charge, discharge, etc.) from hundreds to millions of customers. The aggregated resource can then be provided as services to DNOs or the system operator.

PROS (from the lecture)

- Customers make the most of their storage
- More options and flexibility for system/network operators
- Deferral of investments
- Aggregators benefit from diversity

CONS (from the lecture)

- Dispersion of resources might not be good for local services
- Concentration of resources might require coordination with DNOs
- Market and tariffs structure
- ICT becomes challenging

Note: The roles of 'aggregators' have to be clearly defined by the regulatory authority

Storage: Final Remarks

- Offers many potential benefits but they depend on the corresponding regulatory framework
- Solutions depend on who owns and operates storage
  - DNO
    - Peak shaving / congestion management / investment deferral
    - Integration of renewables
    - Ancillary services
  - DG owner/operator
    - Integration of renewables / increased dispatchability
  - Third party (e.g., aggregator)
    - Peak shaving / congestion management
    - Ancillary services
    - Reduced cost of electricity during peak

Heating Pumps Technologies

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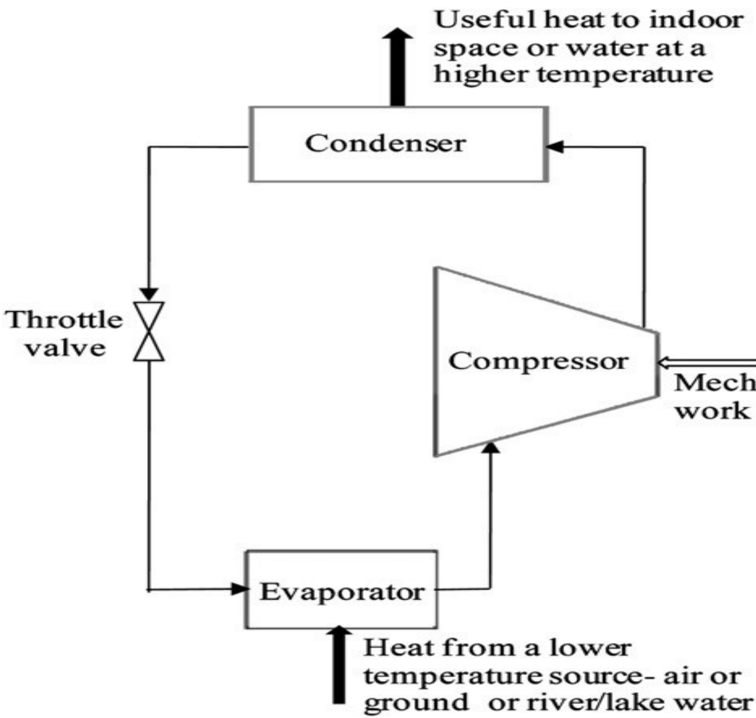
Heat Pumps Technologies

References

- A. Schafer, et all, “Modelling heat pumps as combined heat and power plants in energy generation planning,” IEEE Energytech, May. 2012.
- H. Singh, et all, ”Factors influencing the uptake of heat pump technology by the UK domestic sector,” Renewable Energy, vol. 35, no. 4, pp. 873-878, Apr. 2010.
- ”Managing the future network impact of electrification of heat,” Delta Energy& Environment, Jun. 2016.
- Zikai Lu, “Probability Assessments of Heat Pump Usages and Their Impacts on Distribution Systems”, 2016 MSc dissertation, University of Manchester 2016

Operation Principle of A Heat pump



- H. Singh, et all, ”Factors influencing the uptake of heat pump technology by the UK domestic sector,” Renewable Energy, vol. 35, no. 4, pp. 873-878, Apr. 2010.

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Heat Pump Characteristics

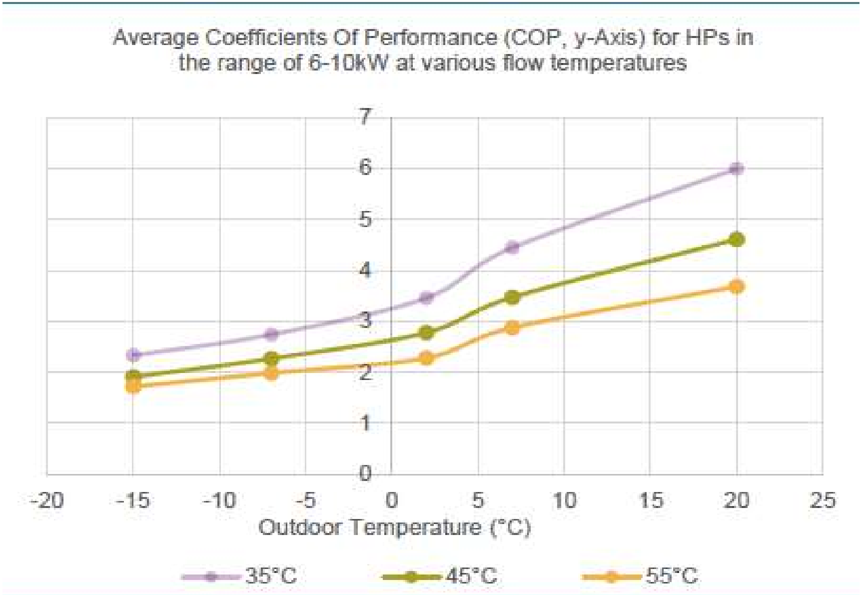
- Electric heat pumps (EHP) - One of high efficient devices, capable of transferring thermal energy from a place with a lower temperature level to a place with a higher temperature level
- For domestic heating, the place with a lower temperature level is heat source that Electric heat pump extract heat energy from ambient air, ground soil and water.
- The heat sink is the place with the higher temperature level such as space heating or domestic hot water.
- performance of heat pump is usually described in terms of coefficient of performance (COP).

$$COP = Q/W,$$

Q is useful heat output of heat pump; W is the compressor, fan and power consumed. The coefficient of performance (COP) of heat pump is usually in the range of 3-5.

Heat Pump Characteristics

- Relationship between the COP of HP and the outdoor temperature



- FINAL report for ENWL, " Managing the future network impact of electrification of heat," Delta Energy& Environment, Jun, 2016.

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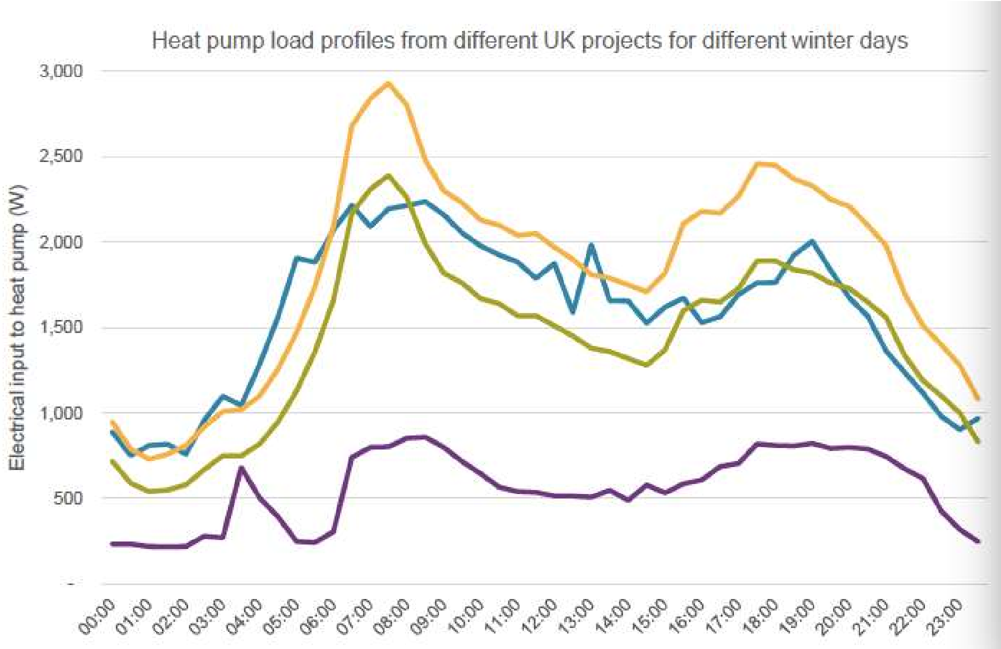
Load profiles of Heat Pumps

- Heat pump load profiles from four different UK projects



- FINAL report for ENWL, " Managing the future network impact of electrification of heat," Delta Energy& Environment, Jun. 2016.

Types of Heat Pump

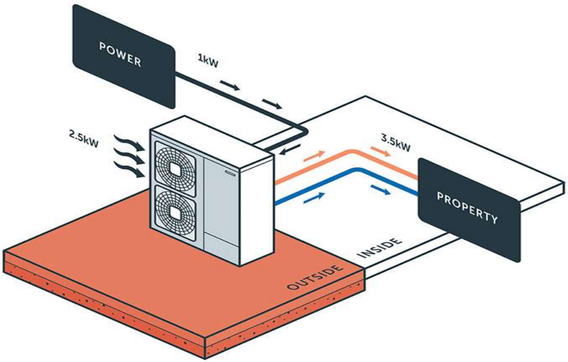
- (a) Air Source Heat Pump (ASHP), (b) Water Source Heat Pump (WSHP) and (c) Ground Source Heat Pump (GSHP)

a) Ground Loops GSHP   b) Borehole Loops GSHP   c) ASHP

- Zikai Lu, "Probability Assessments of Heat Pump Usages and Their Impacts on Distribution Systems", 2016 MSc dissertation, University of Manchester 2016

Air Source

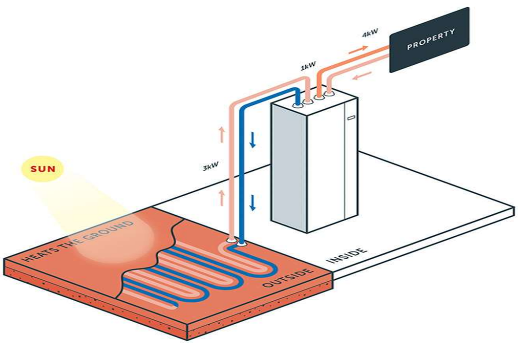
- COP of a Typical Heat Pump =3 – 3.5 (i.e. output of 3.5kW = 2.5 kW air source + 1 kW electricity) for an air source

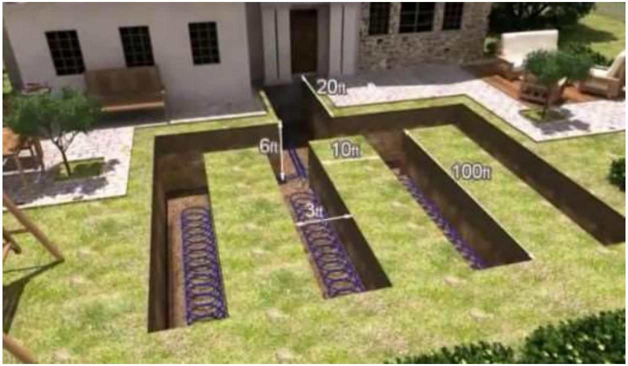


- Picture from webs

Ground Source

- COP of a Typical Heat Pump for ground sources = 4 - 5 (i.e. output of 4kW = 3 kW ground + 1 kW Electricity





- Picture from webs

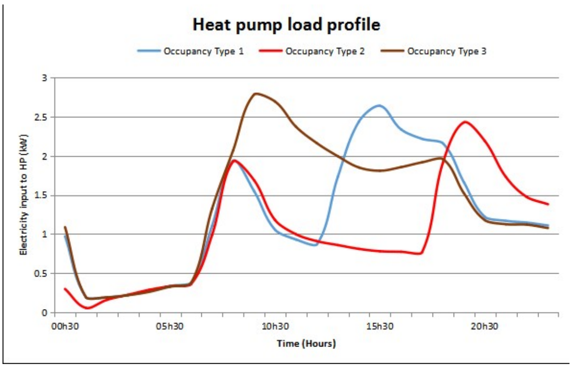
Modelling of HP for Different Occupancy

Assumption:

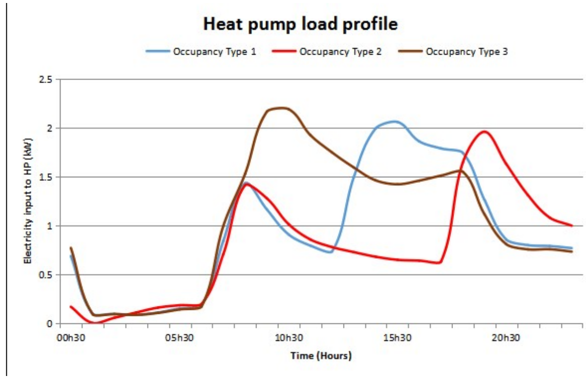
- Occupancy type 1: At least one of the occupants in this type of family have part-time job in the morning session. The Unoccupied time is from 09:00-13:00.
- Occupancy type 2: The occupants in this type of family all have full-time job. The Unoccupied time is from 09:00-18:00.
- Occupancy type 3: The occupants in this type of family may have one or more pensioner, disabled person and unemployed. Thence the dwelling is occupied through the day.

Modelling of HP for Different Occupancy

- Three typical heat pump load profiles



(a) Base case

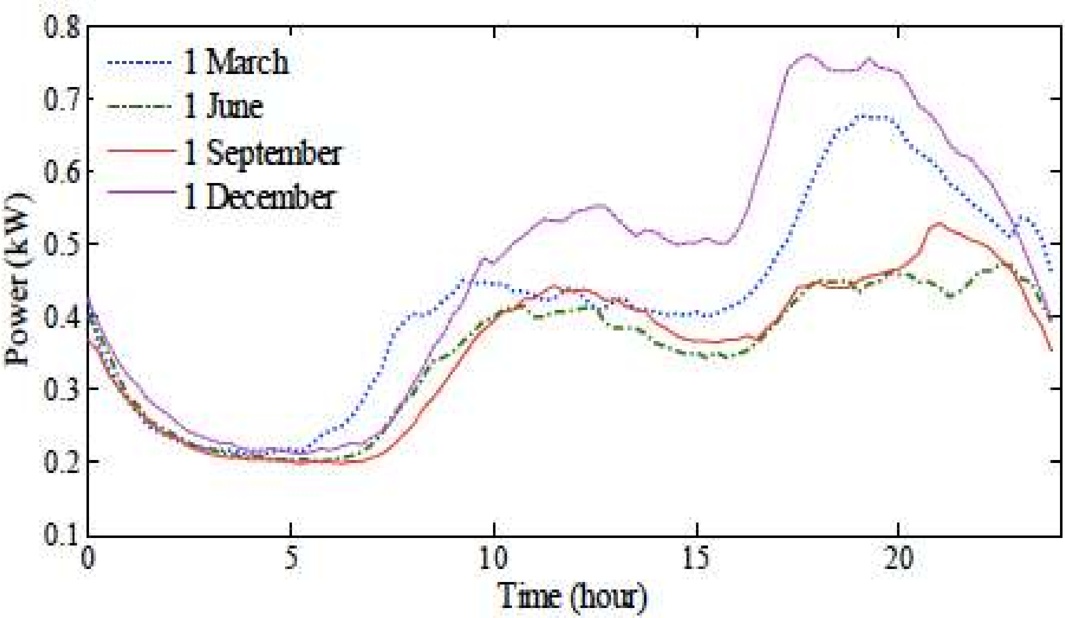


(b) Well insulated dwellings

- Zikai Lu, "Probability Assessments of Heat Pump Usages and Their Impacts on Distribution Systems", 2016 MSc dissertation, University of Manchester 2016

Load profiles of Heat Pumps

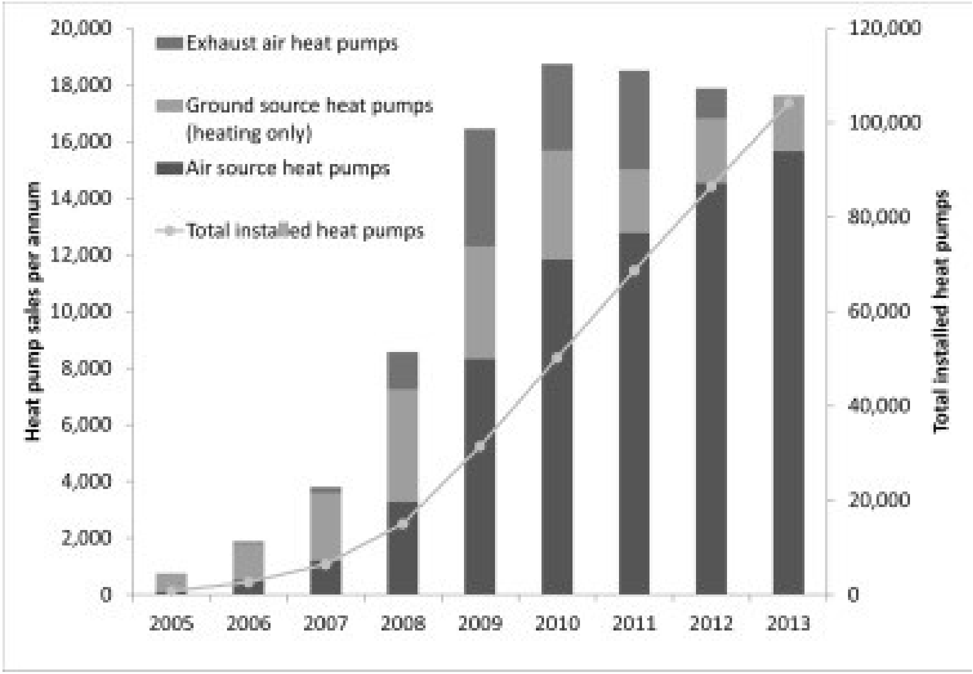
- Daily Load Profiles of A Household



- Veldman. E, et al, "Modelling future residential load profiles," Proceedings of the Innovation for Sustainable Production 2010, 22-25 April 2010, Bruges, Belgium. - Bruges : I-SUP, 2010. - p. 64-68

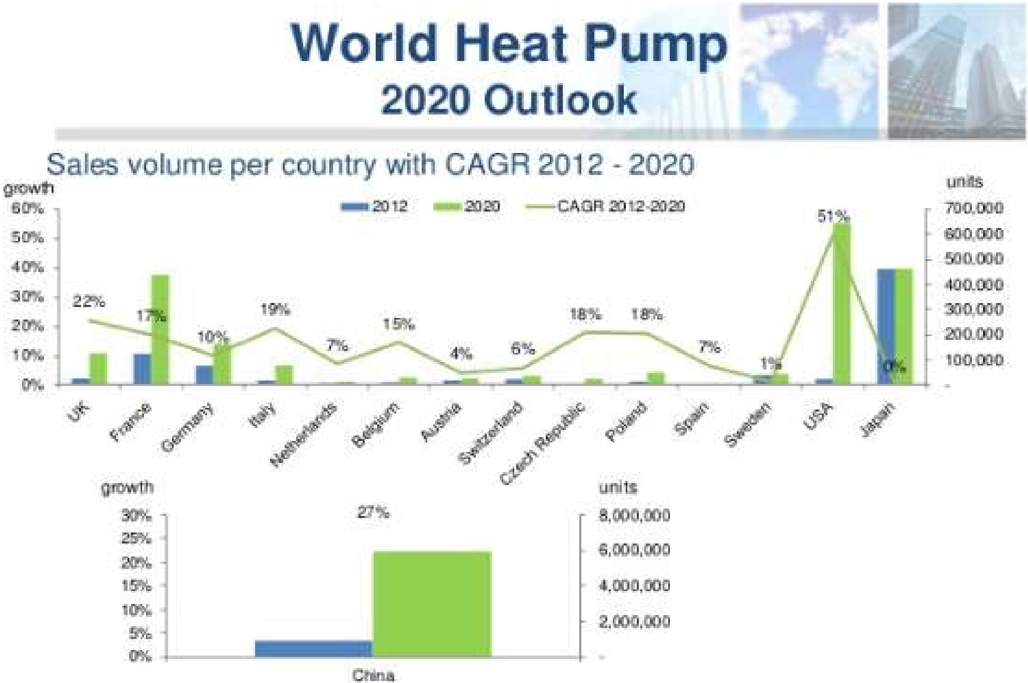
UK heat pumps growth

UK heat pumps sales per annum and total operational devices



https://www.imperial.ac.uk/a-z-research/rcuk-energy-strategy-fellowship/discussion/raising-the-temperature-of-the-uk-heat-pump-market/

Heat pumps growth worldwide



https://airideal.wordpress.com/category/geothermal-hvac/

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End of Section 2

Section 3

Integration of LCT and Methods

EEEN60352 *Smart Grids and SES*

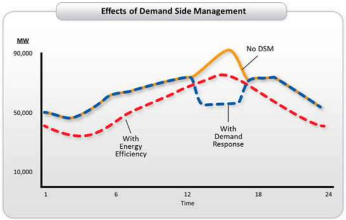
Dr Haiyu Li

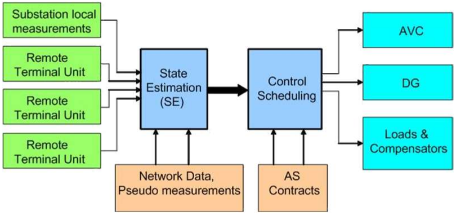
Senior Lecturer in Power Systems Automations & Smart Grids

The University of Manchester – April 2024

Outline of Section 3

- DG Integration and Challenges
- Smart Metering
- Demand Side Management
- Active Network Management





DG Impacts and Challenges

Distributed Generation

- Embedded Generation
- Dispersed Generation
- Distributed Resources

"electric power generation within distribution networks or on the customer side of the network"

EPSR, Ackermann *et al*., 2001

CIGRE, Invernizzi *et al*., 2004

Drivers for Distributed Generation

- Environmental
  - Use of renewable energy and low-carbon technologies (e.g., CHP) to limit GHG emissions
  - Avoid construction of new transmission circuits and large generating plants
- Commercial
  - General uncertainty in electricity markets favours small generation schemes
  - Cost effective route to improved Power Quality and Reliability
- National/Regulatory
  - Diversification of energy sources and competition policy

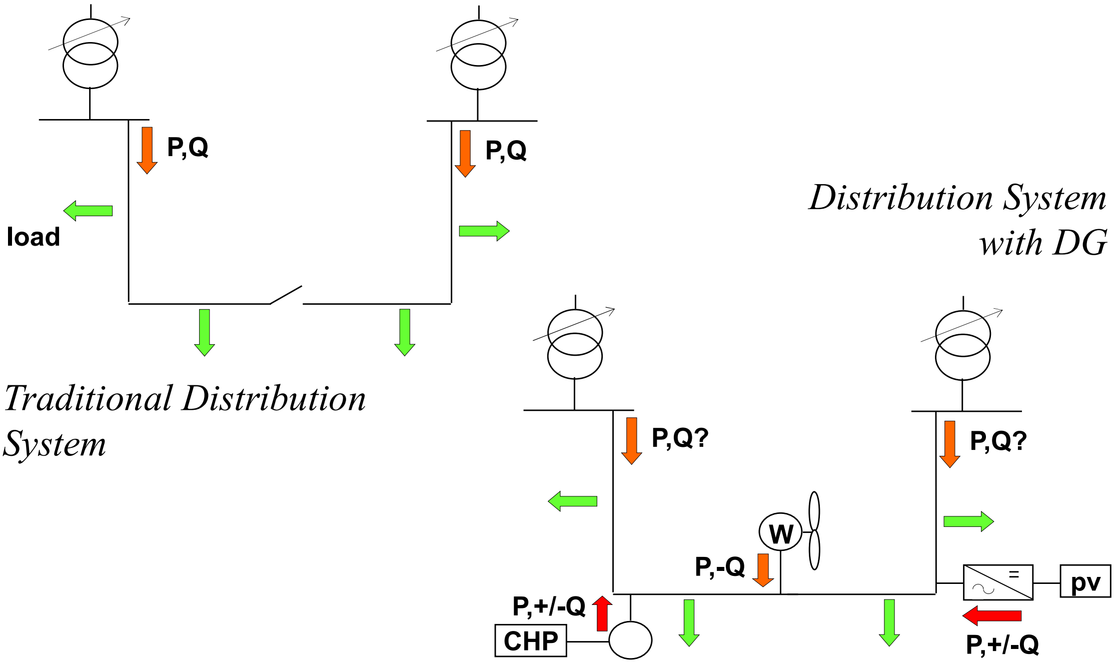
DG Technologies

- Wind power
- Combined heat and power (CHP)
- Fossil fuel-based
- Micro CHP
- Biomass (landfill gas, energy crops, forest residues, etc.)
- Small hydro
- Photovoltaic
- Concentrated solar power
- Geothermal
- Wave and tidal power

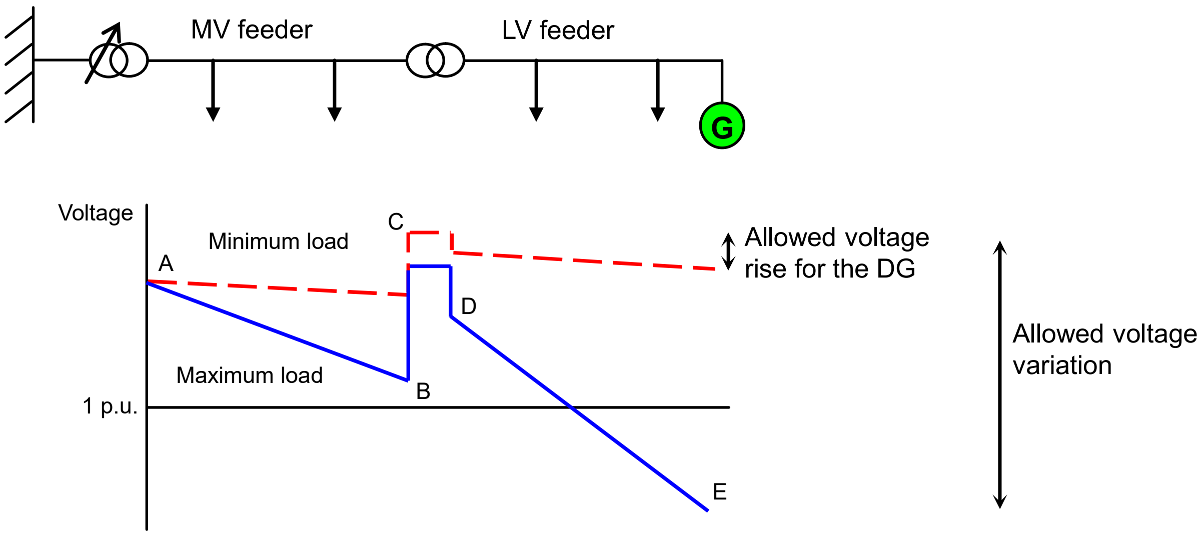
Main Technical Issues for DNs with DG

- MV Distribution Networks (11kV and 33 kV)
  - Voltage rise (rural overhead networks)
  - Increase in short circuit level (urban underground)
  - Power quality
  - “Islanding” and Protection
  - Increased energy losses?
  - Variability?
- HV Distribution Networks (132 kV)
  - Thermal limits
  - Stability and reserve requirements
  - Variability?

DG Impacts: Active and Reactive Power



DG Impacts: Voltage



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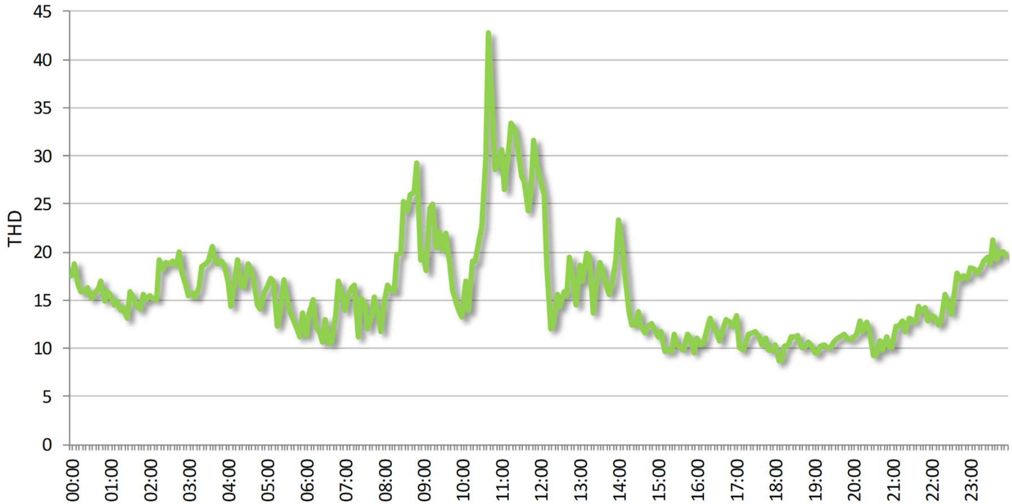
DG Impacts: Power Quality

- General term describing impacts on the voltage wave shape
  - Flicker - repetitive short term RMS voltage variations
  - Dips/sags - single event reductions in RMS voltage
  - Harmonics - repetitive distortion of voltage wave

- Impact of DG may be to increase or lower Power Quality
  - Particular issues associated with wind turbines (Flicker)
  - Power electronics-based technologies might lead to more harmonics

DG Impacts: Power Quality

- 5min average 24-hour Total Harmonic Distortion (THD) profile for residential customers
  - Current THD. 10th October 2012 (ENWL)
  - One of 4 feeders. 70 consumers of which 28 have PV systems.



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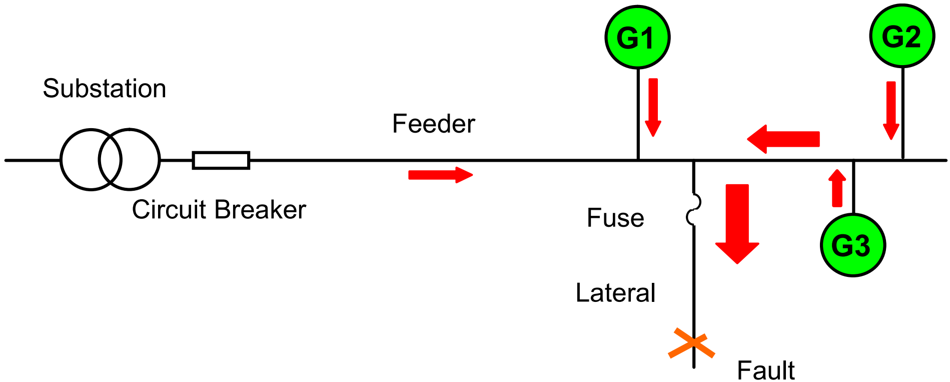
DG Impacts: Fault Levels

- All directly connected spinning electrical machines contribute to fault (short-circuit) level
- Synchronous machines contribute to sustained fault currents
- Induction machines contribute only to transient 3-phase fault currents
- Fault level contribution from converters (power electronics) is, in general, much smaller or negligible

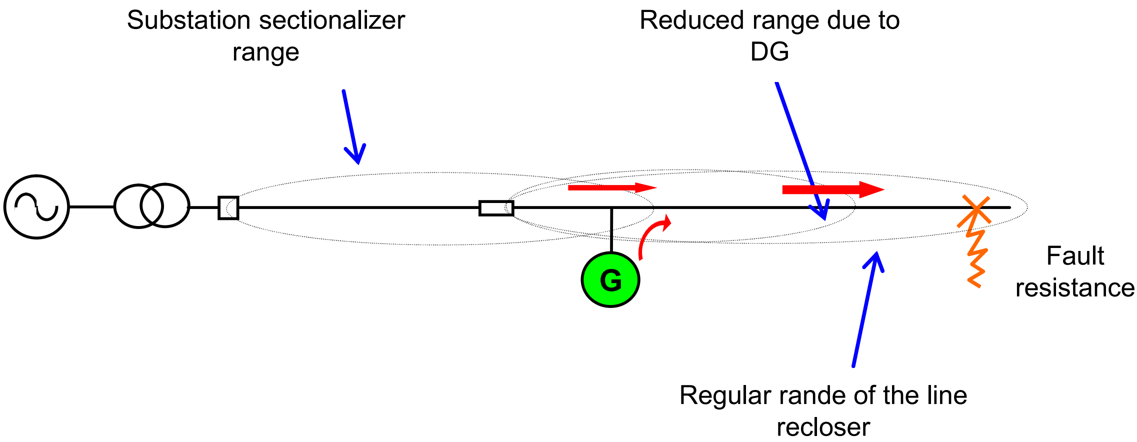
DG Types and Their Fault Contributions

Type of equipment	Network (kV)	Network Coupling		
		Direct	Transformer	Power Electronics
Induction generator	0.4 - 33	5 - 8	3 - 7	NA
Synchronous generator				
small	0.4 - 33	5 - 8	3 - 7	NA
medium	11 - 132	5 - 6	3 - 5	NA
large	132	NA	2.5 - 4.5	NA
Battery Energy Storage System	0.4 - 132	NA	NA	1 - 1.2
Biomass system	0.4 - 33	Dependent on generator type		
CHP system	0.4 - 132	Dependent on generator type		
Fuel Cell system	0.4 - 33	NA	NA	1 - 1.2
Landfill gas system	0.4 - 11	Dependent on generator type		
Mini CHP turbine	0.4 - 11	5 - 8	3 - 7	NA
Tidal stream system	11	5 - 8	3 - 7	NA
Waste incineration	0.4 - 132	Dependent on generator type		
Wave power system	0.4 - 33	5 - 8	3 - 7	NA
Wind turbine				
squirrel cage induction	0.4 - 11	5 - 8	3.5 - 6.5	NA
DFIG, type I	11 - 132	1 - 2	1 - 1.5	NA
DFIG, type II	11 - 132	4 - 6	3 - 5	NA
direct-drive synchronous	11 - 132	NA	NA	1 - 2

DG Impacts: Protection



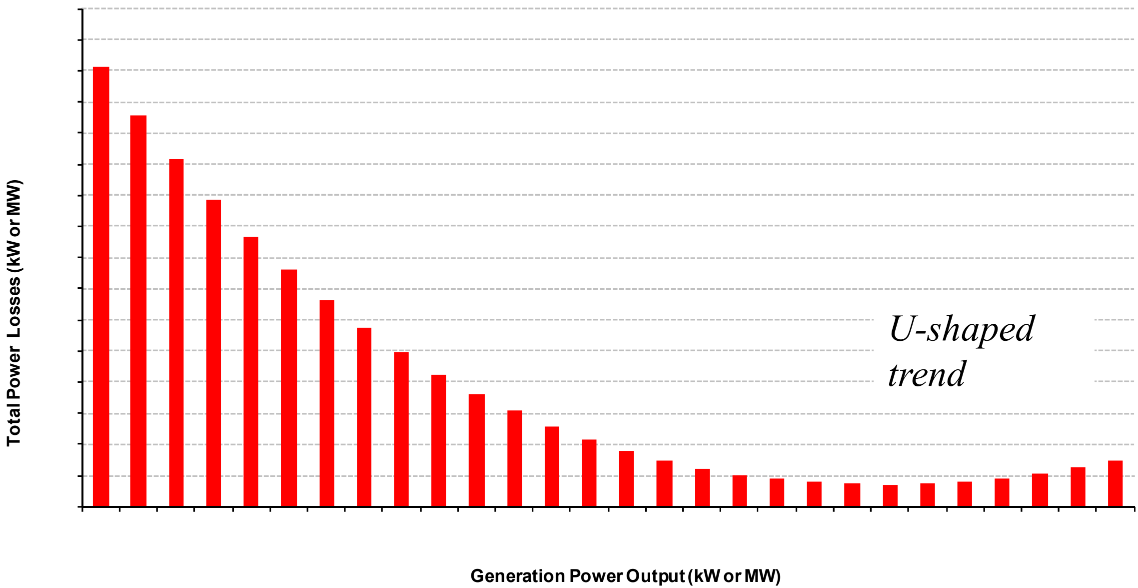
DG Impacts: Protection



DG Impacts: Stability

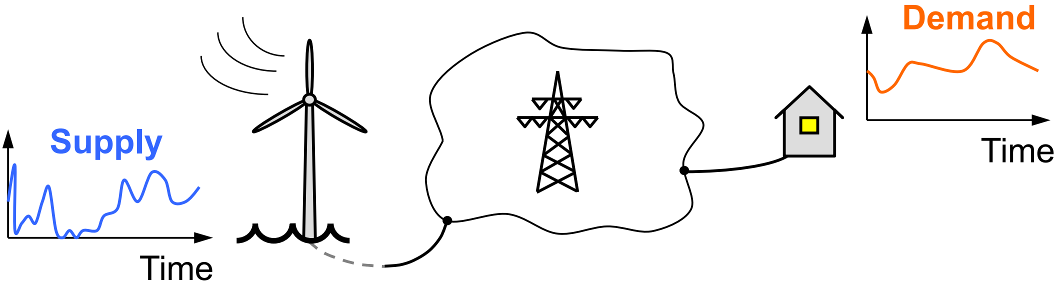
- For induction generators voltage stability is important while for synchronous machines angular stability is the main issue
- If embedded plant becomes a significant part of generation then transient stability becomes important. Mal-operation of loss-of-mains (LOM) relays not acceptable
- Need to find ways to maintain stability for remote faults - either increasing speed of protection, reactive power injection and/or fast generator control

DG Impacts: Losses



DG Impacts: Variability

- The wind doesn't blow when we want to turn the lights on.



- To what extent can renewables supply the demand?

Matching Renewable Electricity Generation with Demand (2006)

- Diversification of the resources and the corresponding geographical dispersion improves matching the hour-by-hour demand
- There will be many hours in a year where wind, wave and tidal power are not enough to meet the demand target. Thus, balancing with conventional generation is needed.
- A strong interconnected transmission system will reduce the need of local balancing generation and will increase reliability.
- Storage, demand side management, and active distribution networks will make it possible for renewables to supply higher volumes of demand.

DG Integration Challenges

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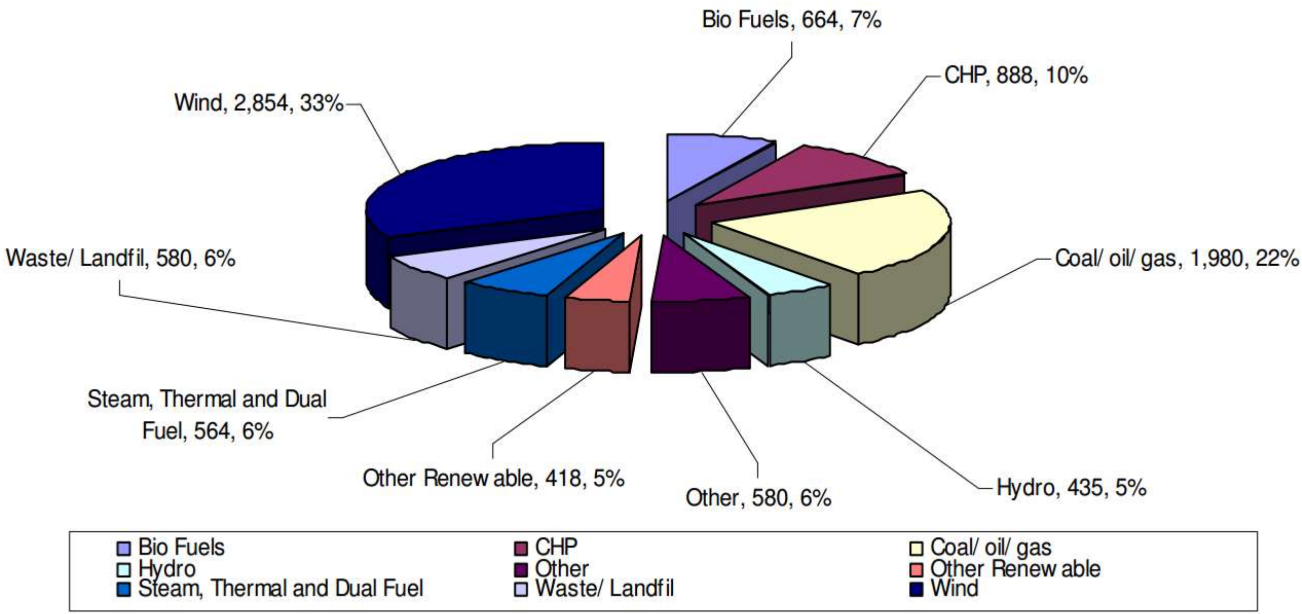
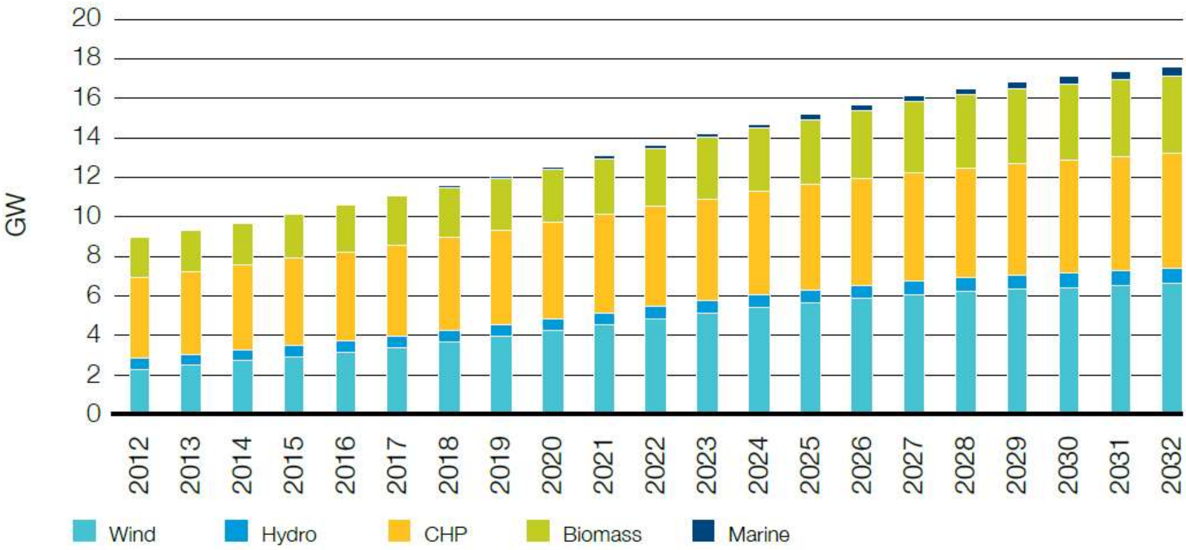
Distributed Generation in the UK (2011)

- Main Types of Distributed Generation (MW) according to the 2011 Seven Year Statement from National Grid



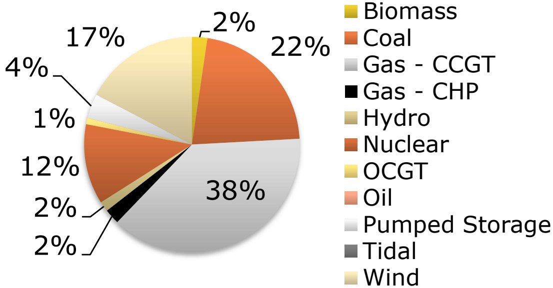
Distributed Generation in the UK (2012)

- 2012 National Grid Ten Year Statement
  - 'Gone Green' Scenario

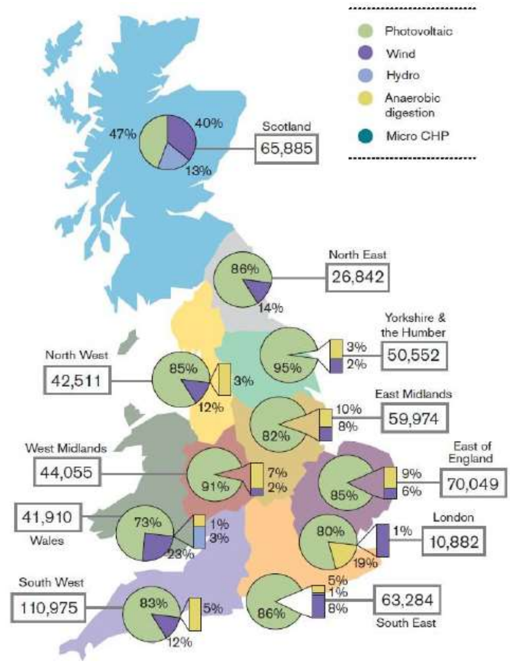


Great Britain – General Statistics

- Installed Capacity (2014): ~85GW
  - Production (2014): ~336TWh



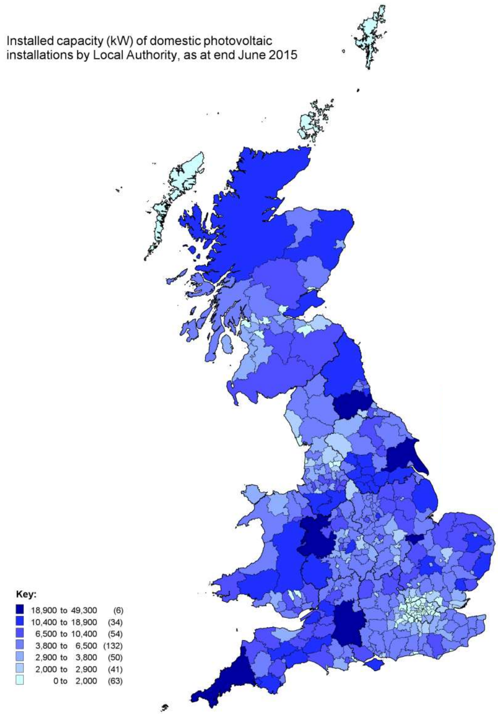
- Peak Demand: ~60GW
  - Consumption (2014): ~360TWh
- PV Generation: ~8GW
- Wind Generation: ~13GW
- Number of EVs: ~43k



- DECC, Digest of UK Energy Statistics 2015
- National Grid, Electricity Ten Year Statement 2014

Great Britain - Photovoltaic Systems

- Overall capacity: **7.75 GW**
- One of the largest markets in Europe
- **720,000+ installations** from 1kW to 5MW+
- Typical domestic installations
  - 1.5-3.5kWp per house
- Eng Recommendation G83
  - 16A per phase
  - 1ϕ → 3.68 kW; 3ϕ → 11.04 kW
  - Power factor 0.95 ind/cap



- Gov.UK, Subregional Feed-in Tariffs statistics, June 2015

- DECC, Solar photovoltaics deployment, June 2015

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Connection or Integration?

- Main focus so far:
  - Development of DG technology and cost reduction
  - Deployment of DG
- DG to displace energy produced by conventional plant but not capacity, flexibility and controllability (?)
- DG not capable of providing system support (?)
- Increased deployment of DG under “fit and forget” policy begins to create operational problems!
  - DG does not provide network and system support
  - Inefficient network connection and network operation

Fit-and-forget approach to integration could reduce DG deployment rate, undermine security and increase cost.

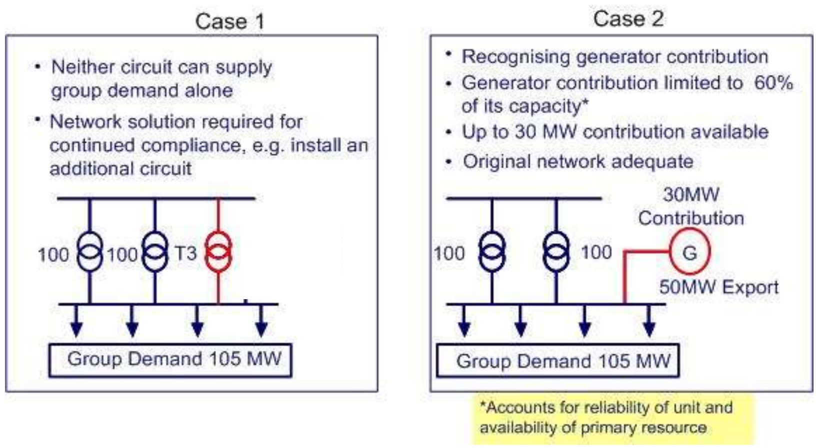
Benefits and Challenges of DG Integration

- Benefits:
  - Increased network asset utilisation
  - Asset displacement and T&D investment deferral
  - Enhanced reliability and security
  - Early DG deployment helps meeting renewable targets
- Challenges:
  - Information, communication, control infrastructure (increased complexity and cost)

… are the benefits greater than cost?

Benefits of DG: Investment Deferral

- Distribution network investment deferral depends on
  - location and DG technology
  - E.g. PV will not have any value at 7:00 in mid winter (sun is not shining!) whereas micro CHP has. If peak flows occur in summer PV has some value



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Benefits of DG: Losses

- Reduction in transmission and distribution losses – depends on penetration level
  - At high penetration levels losses could increase

- Impact of micro CHP on distribution losses could be very significant
  - average distribution losses in UK are approx 7%
  - losses could be as high as 20% at peak!
  - currently there is no appropriate framework for micro CHP to realise this benefit

Pricing and Competitiveness of DG

- Connection Charges
  - Shallow
  - Deep
- Use of system charges
  - Use of transmission system charges
  - Use of distribution system charges
- Losses
- Reactive power
- Reliability and service quality

Access to Networks

Central Generation

- Shallow connection charges
- Users that reduce transmission assets cost may be rewarded
- CG integrated in network operation and development
- Protected from network constraints

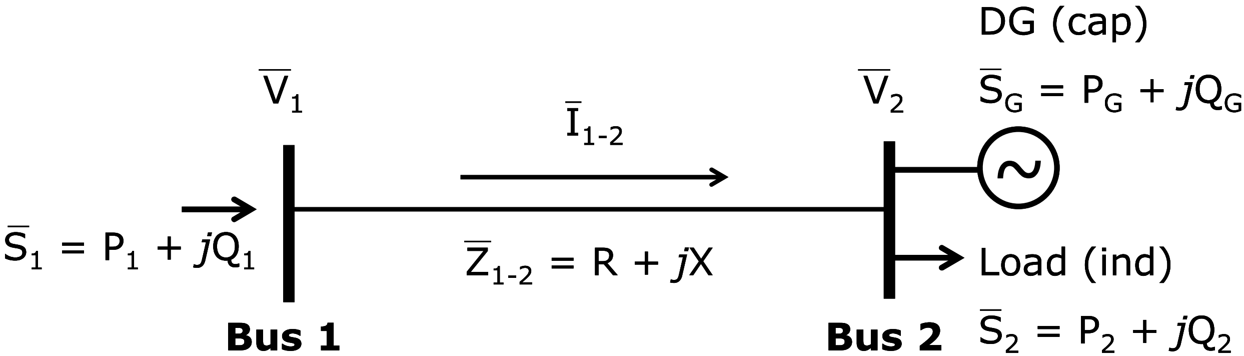
Distributed Generation

- Deep connection charges
- No concept of negative charges
- DG not integrated in network operation and development
- Exposed to network to constraints

(traditionally, no longer the case in the UK)

Voltage Drop/Rise Calculations with DG

- Simplified Calculation (neglecting losses)



$$V_{drop} = \frac{R \cdot (P_2 - P_G) + X \cdot (Q_2 - Q_G)}{\left|\overline{V}_1\right|}$$

Note: care should be taken with reactive power signs.

Exercise 3.1
Voltage Drop/Rise Calculations with DG

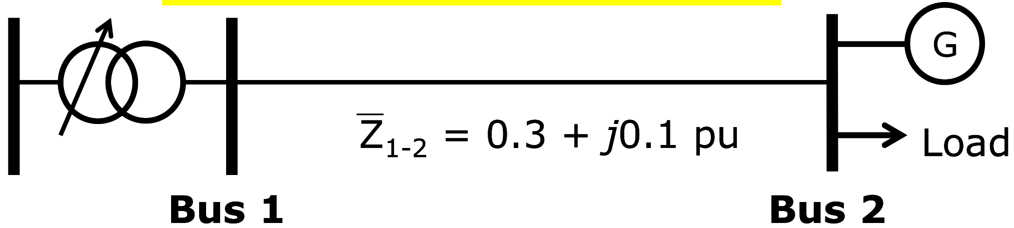
- The 11kV feeder below has the voltage target at the secondary of the substation set to 11.22kV.
  - Load is 8MW, 0.9 capacitive power factor.
  - A CHP plant injects 15MVA, unity power factor.

(i) Is the voltage at bus 2 within statutory limits? Neglect losses.

A: Yes (V2=1.0444pu)

(ii) Would the voltage still be OK during minimum demand (30% of peak)?

A: Just about OK (V2=1.0582pu)



What can be done if the voltage is too high? **Taps, DG P/Q mgmt**

Smart Metering

Electricity Meters: Now

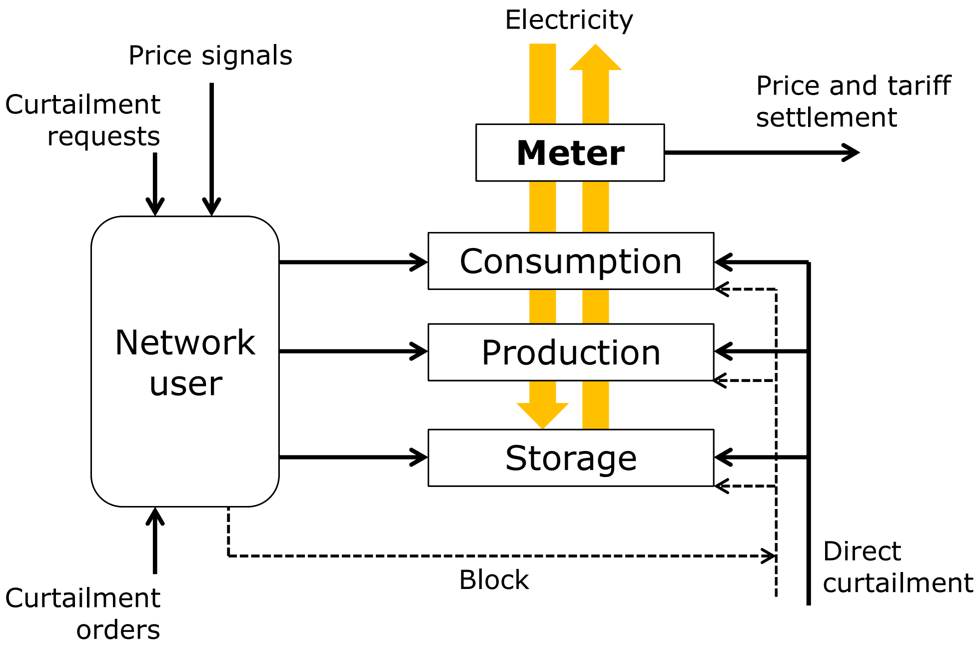
(Domestic customers)

- Read regularly or occasionally
  - Depending on the cost to the utility
  - Largely a manual procedure
- Customer billed for the electricity consumption
- Time-of-use (TOU) tariffs
  - Traditionally with two meters/counters active during different times of the day (e.g., Economy 7 in the UK).
  - With Smart Meters this is simpler, e.g., Hydro One, PG&E .

Most meters around the world are read manually

Smart Meters: (Future) Network User and the Grid

- Power flows and communication



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Smart Meters: Expectations

- Automatic readings
  - Consumption sent to the DNO (or a data concentrator) via a telecommunication link
    - Overall consumption: power-line communication
    - Hourly readings: radio links, telephone (GPRS, 3G), internet
- Provision of prices to customers
  - Hours ahead, near real time
    - Increased volumes of communication
- Enabler of demand side management
  - Gateway for customer and markets
  - Smart appliances (prices, TNO/DNO signals)
    - Interacting with markets → more reliability needed
    - Curtailment → reliability (comms) is critical

Smart Meters: Business Case

- Italy → (DNO) High OPEX, energy theft
  - Already looking at new generations of meters and clever ways of using the data
- Sweden → (DNO) High OPEX, metering expensive/infrequent
  - Already looking at new generations of meters and clever ways of using the data (expensive!)
- UK → (Gov) Energy cost, empowering customers, smart grids
  - Gov.uk (Mar 2014): “Over the period to 2030, the installation of smart meters will provide £6.2 billion net benefits to the UK: the programme will cost £10.9 billion and provide £17.1 billion in benefits.”

Smart Meters: UK Deployment

- (Mar 2011) £11.3 billion will be spent in replacing 53 million gas and electricity meters, which are expected to deliver **total benefits of £18.6 billion over the next 20 years**.
  - Savings in energy consumption and OPEX
- Most households will have smart meters installed by their energy company between 2015 and 2020.
- UK smart meters
  - Owned by Energy Suppliers not DNOs
  - Central Data 'Concentrator' (www.smartdcc.co.uk)
  - No (pseudo) real-time info to DNOs

Smart Meters: UK Deployment

- Common Requirements
  - Gas and electricity meters with smart functionality
  - An In-Home Display (IHD) for domestic customers
  - A wide area network (WAN) module to connect to the central communications provider
  - A home area network (HAN) to link different meters within customer premises, the WAN module and the IHD (and potentially other consumer devices, such as microgeneration and load control devices).

Smart Meters: UK Deployment

- (Some) Functional Requirements
  - All electricity meters and domestic gas meters should be required to have functionality to support **remote enablement and disablement of supply**.
  - The **HAN should use open standards and protocols** – so as to achieve interoperability and enable innovation by equipment manufacturers.
  - <u>Loss of supply alerts</u>. To alert suppliers and networks when a consumer's electricity supply is lost. This will help network operators to respond to outages effectively and quickly.
  - <u>Data stored at the meter</u>. Metering systems to store at least 12 months of half-hourly consumption data. To benefit consumers and promote competition in both retail supply and the energy services markets.

What is the challenge of implementing certain functionalities?

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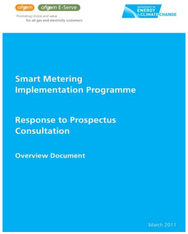
Smart Meters: UK Deployment

	High-level functionality	Electricity	Gas
A	Remote provision of accurate reads/information for defined time periods ▪ delivery of information to customers, suppliers and other designated market organisation	✓	✓
B	Two way communications to the meter system ▪ communications between the meter and energy supplier or other designated market organisation ▪ upload and download data through a link to the wide area network, transfer data at defined periods, remote configuration and diagnostics, software and firmware changes	✓	✓
C	Home area network based on open standards and protocols ▪ provide "real time" information to an in-home display ▪ enable other devices to link to the meter system	✓	✓
D	Support for a range of time of use tariffs ▪ multiple registers within the meter for billing purposes	✓	✓
E	Load management capability to deliver demand side management ▪ ability to remotely control electricity load for more sophisticated control of devices in the home	✓	
F	Remote disablement and enablement of supply ▪ support remote switching between credit and prepayment modes	✓	✓*
G	Exported electricity measurement ▪ measure net export	✓	
H	Capacity to communicate with a measurement device within a microgenerator ▪ receive, store, communicate total generation for billing	✓	


Smart Metering Implementation Programme

Response to Prospectus Consultation

Overview Document

March 2011

The University of Manchester

Smart Meters: Final Remarks

- Business case is fundamental to adopt the technology
  - DNOs/Suppliers: Typically to reduce OPEX, non-technical losses

- Smart Meters are enablers of ‘Smart Grids’ depending on
  - Granularity of data flows (minutes to hours)
    - Market interaction → hours, minutes
    - DNO/TSO real-time network management → minutes
      - large volumes of data, reliability of comms
  - Monitoring (energy, power?, loss of supply?, voltages?)
    - DNO improved/real-time network management
  - Management of data (data concentrators, DNOs, etc.)
    - DNO network planning → offline
    - Real-time network management → latency?

Exercise 3.2
Smart Meters: PROS & CONS

Exercise

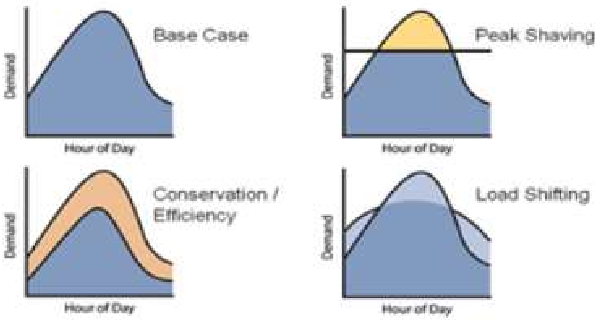
- Discuss in pairs
- List (potential) pros and cons for smart meters
- You have 10 minutes

Demand Side Management Techniques

DSM Techniques

Demand Side Management (DSM) techniques provide variety of measures to reduce energy consumption, hence to have more manageable demand.

- Direct load control.
- Load limiters.
- Commercial/industrial programs.
- Frequency regulation.
- Time of use (ToU) pricing.
- Demand bidding.
- Smart metering and appliances.

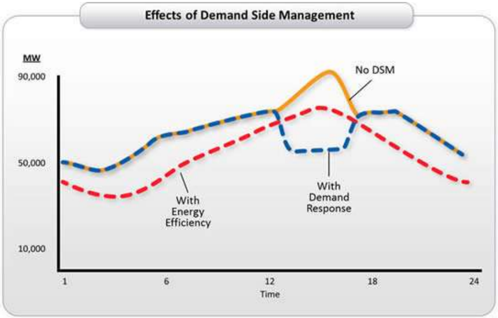


www.powerwise.gov.ae/en/research/programmes..
./demand-side-management.html

Demand Side Management

- DSM (also Demand Response) are options/strategies developed for effective means of modifying the consumer demand to cut cost. Most applications aim to reduce capital expenditure (CAPEX).

- (Some) DSM options:
  - Peak shifting
  - Valley filling
  - Peak clipping / shaving



- For DNOs, DSM could be classified into three categories
  - Direct control of load (DNO controls customer load/generation)
  - Local load control (self-adjustment to limit peak demand)
  - Distribution load control (DNO sends real-time prices/signals)

Demand Side Management

- Typically referred to a customer adapting its consumption to the electricity price.
  - Reducing consumption during peak prices
  - Shifting consumption from hours with high price to hours with low price
  - <u>Not considered here</u>: Overall reduction in electricity consumption due to high prices

- What does this entail?
  - Time-varying prices (dynamic prices)
  - Customer awareness
  - Customer ability to adapt consumption (manually or automatically)

Demand Side Management

- Time-of-Use Pricing
  - Commonly used in many countries (peak and off-peak prices)
    - Contract-based or near real time (comms)
  - Large consumers (commercial, industrial)

- TOU has been around for years and works. Is it enough?
  - Demand during peak-price periods can vary significantly
  - Worst case scenarios (e.g., extreme cold/hot weather and N-1 condition) could be managed better
  - Ratios of peak/off-peak prices are typically small (up to 2)
  - New types of production and consumption → new loading patterns

Demand Side Management (TOU)

- Report "Impact Evaluation of Ontario's Time-of-Use Rates: First Year Analysis", Nov 2013

- Main conclusions (domestic users):
  - There is load shifting but limited savings
  - Probably due to the relatively small differential between on-peak and off-peak prices

Impact Evaluation of Ontario's Time-of-Use Rates: First Year Analysis

PREPARED FOR

Ontario Power Authority

PREPARED BY

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Chris King
eMeter, a Siemens Company

November 26, 2013

THE Brattle GROUP

Demand Side Management

- Third-party Service Providers
  - Also known as aggregators (managing thousands or millions of customers)
  - DNOs/TSO do not require DSM implementation but the service
  - ‘Middle man’ between customers and DNOs/TSO
  - Contracts are between customers and aggregators
  - Face some challenges similar to those aggregating storage

- Examples
  - Enernoc (http://www.enernoc.com/)
  - Flexitricity (http://www.flexitricity.com/)

Demand Side Management

Existing Measures/Schemes

- Big consumers DSM (contracts for disconnection, TOU tariff)
- Economy 7 (dual metering)
- Critical peak pricing (small consumers too, eg CA, USA)

Potential Measures/Schemes

- Smart appliances reacting to prices from smart meters
- Granular TOU tariffs
- Energy Management Systems (Home, Building, etc.)

Demand Side Management

Existing Measures/Schemes

- Domestic Economy 7, Smart Meters TOU
- Commercial/industrial TOU
- Aggregators providing services to TSO (balancing, reserves)

Potential Measures/Schemes

- Smart appliances providing services (automatically)
- Intelligent management of specific technologies (e.g., EVs)
- Coordinated management of sub-management systems such as BEMS and HEMS

Demand Side Management in ENWL (C2C Project)

- Distribution network operators (DNOs) face in some parts of the circuits congestion problems (particularly during contingencies)
- Ofgem incentivises investment deferral

→ ENWL contracts DSM services from big consumers

→ ENWL uses aggregators ( ) for different services (e.g., demand shifting)

→ EnerNOC incentive: £2000/month/MW of availability → £2/kW

- <u>DNOs are becoming more and more like DSOs (not TNOs)</u>
- How does this affect DSOs? Energy suppliers?

CLASS:
Customer Load Active System Services

- Electricity North West Limited (ENWL)
  - Low-Carbon Network Fund 2012, Tier 2. Total awarded: £7.2m
- Scope
  - Investigating how reducing or increasing voltage on the distribution network can reduce peak demand or increase demand when needed → Services to National Grid
  - Tap Staggering. Use of reactive power capabilities through the use of circulating currents → Services to National Grid
  - Trial to consider only primary substations (33kV to 11kV or 6.6kV)

Improving LV Network Operation with DSM

Improving LV Network Operation with DSM

The understanding about the residential load behaviour makes it possible:

- To characterize the residential load (type of appliance and power consumption).
- To measure the effects of shifting passive load (potential of the washing group) in the peak demand reduction in a real LV network.
- To test the load shifting in a real LV network

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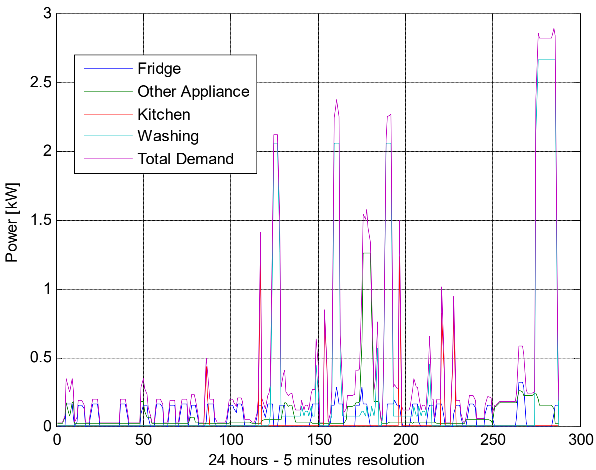
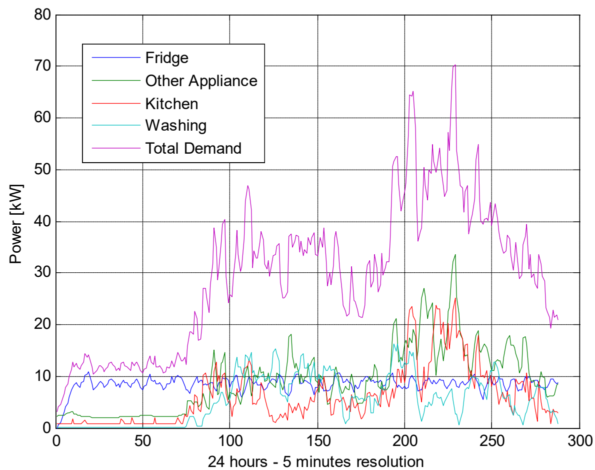
Improving LV Network Operation with DSM

- From residential load models it is possible to aggregate the appliances in families and observe the contribution of each family to the individual and aggregated profile.



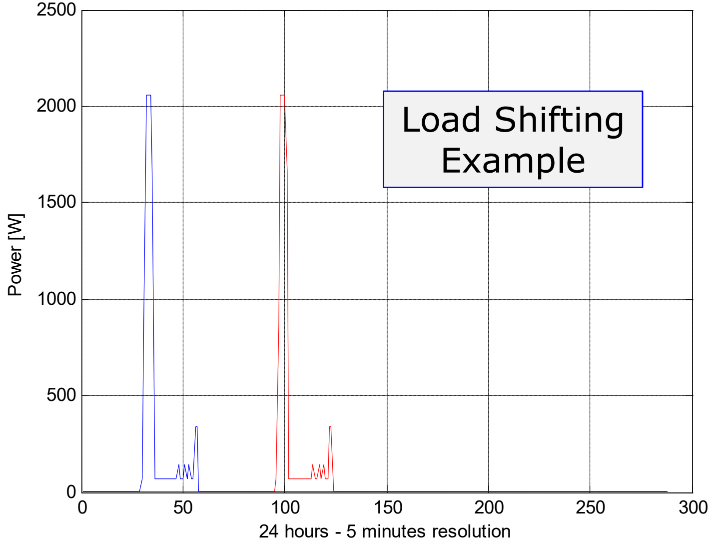


Aggregation of 100 Loads

Improving LV Network Operation with DSM

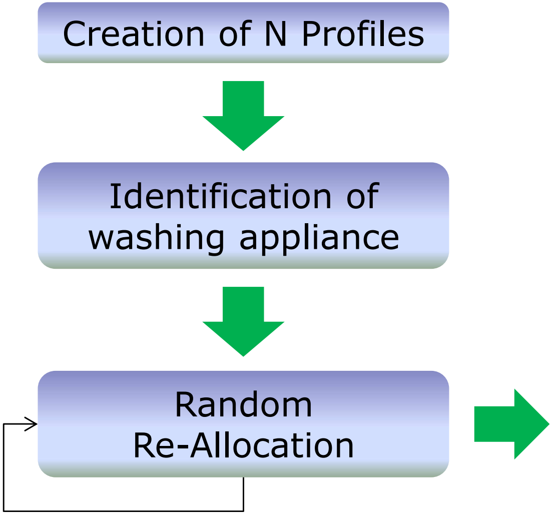
Potential of the 'washing group' of load

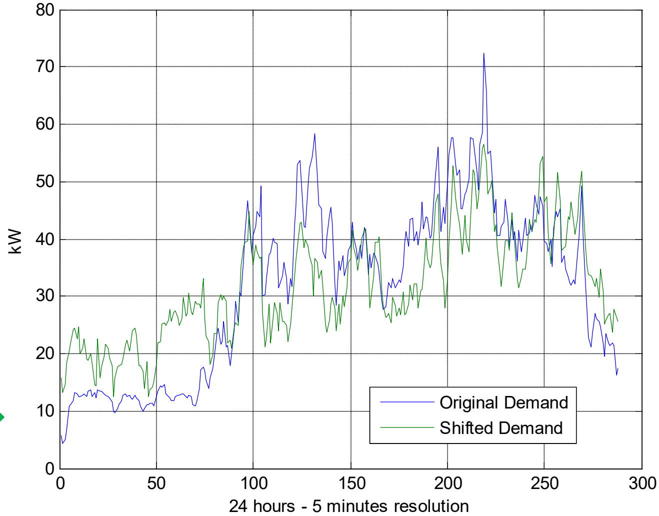
- These loads are passive. So, they can be shifted without disturbing the normal behaviour of the household occupants.
- This can be used to decrease the feeder peak demand



Improving LV Network Operation with DSM

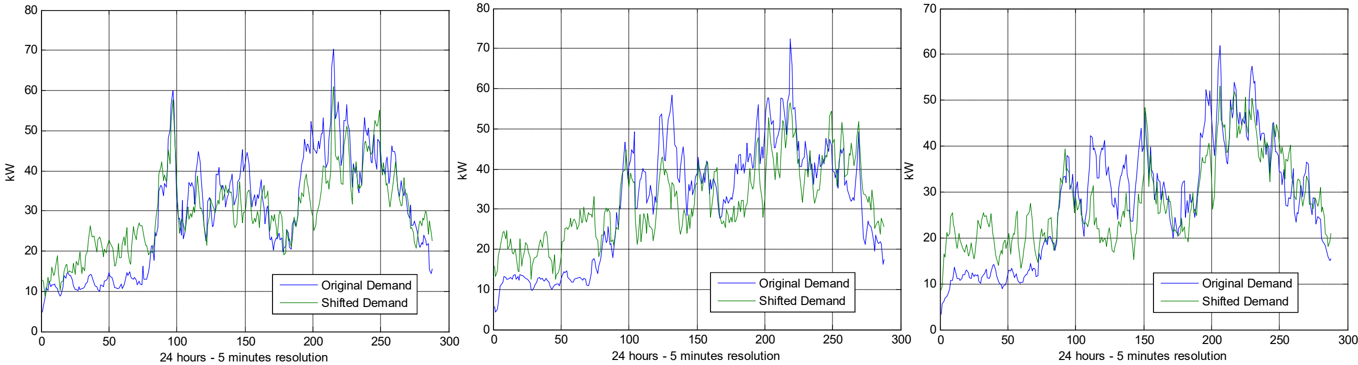
- To exemplify the load shifting impact, the following basic method was developed.





Improving LV Network Operation with DSM

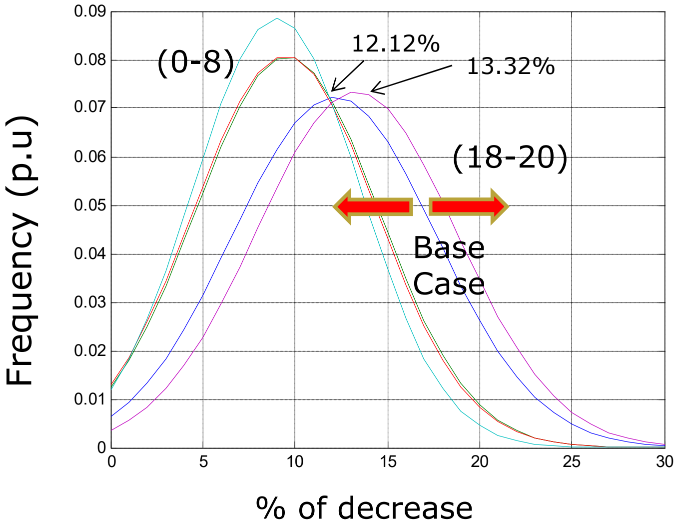
- The peak reduction will be different for different groups of N loads (each household uses the washing appliances differently).
  - Example: Methodology application for 3 groups of 100 loads.



- The peak reduction also will be different if some time periods are banned.

Improving LV Network Operation with DSM

- To understand the peak reduction distribution and the effect of time periods banned, 100 groups of N profiles for each case were analysed.



	% of Peak Reduction			
Temporal Restriccion	**Percentil 0.05**	**Percentil 0.5**	**Mean**	**Desvest**
Base Case	3.55	11.30	12.13	5.52
(1-6)	1.68	9.16	9.58	4.95
(0-6)	1.50	9.42	9.46	4.94
(0-8)	1.45	8.83	9.01	4.51
(18-20)	5.61	12.85	13.32	5.44

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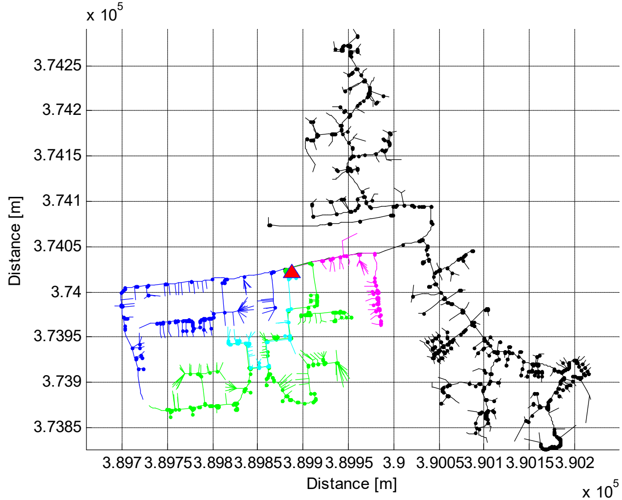
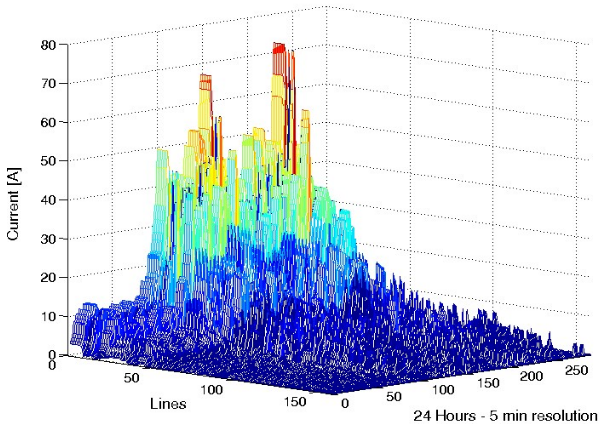
Improving LV Network Operation with DSM

- The load shifting algorithm is applied over a LV distribution network from the North West of England, owned and operated by Electricity North West Limited (ENWL).
- Network features:
  - 5 feeders.
  - 334 customers.
  - 8 km.

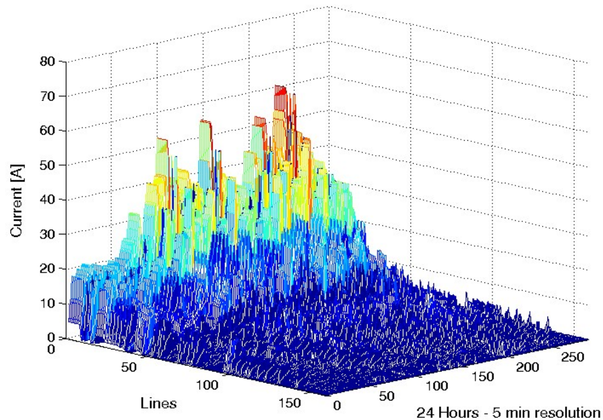


Improving LV Network Operation with DSM

- In particular, the load shifting algorithm with peak period banned is applied over each network feeder.
- A power flow before and after the load shifting is carried out.



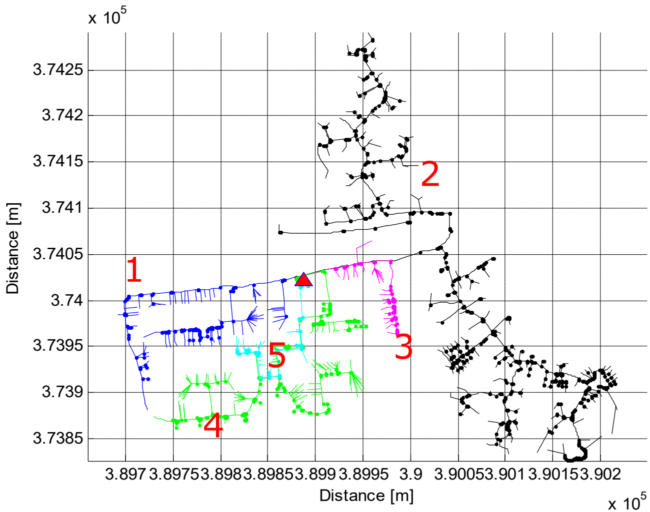
Example for one feeder



14% of peak reduction

Improving LV Network Operation with DSM

- To analyse the distribution of the peak reduction for each feeder, the network is simulated with 1000 different groups of loads.



Simulations Summary

	Customers	Percentil 0.05	Percentil 0.5
Feeder 1	63	2.43	12.05
Feeder 2	113	5.21	12.49
Feeder 3	28	0.64	12.54
Feeder 4	98	4.57	12.38
Feeder 5	24	0.41	12.98

The washing group can indeed be used to decrease the peak feeder demand.

Demand Side Management: Final Remarks

- Dynamic pricing is a key element in (many) DSM schemes
  - Contracts based on power availability and frequency of interruptions/curtailment also exist

- Viability of DSM schemes depend on the targeted load
  - Small-scale consumers
    - More in number, limited elasticity (?), extensive infrastructure, value has to be clear (and significant)
  - Medium-to-large scale commercial/industrial consumers
    - Less in number, efficiency oriented, less infrastructure
  - No direct customer involvement
    - Voltage-based DSM schemes could be an alternative to DNOs (but this has limitations)

Active Network Management (ANM)

Changing Networks

Now	*Mid-term*	*Long term*
Passive (Semi-active) Networks	Distribution Automation	**Smart Grids**
⌖ 'Fit and forget' connection of distributed generation (DG)	**Why?** ⌖ **Increase reliability** … but DG is treated the same way	**Why?** ⌖ **Increase and improve DG and DER integration** … high usage of assets

Motivations

How to cost-effectively manage a distribution network with high (renewable) DG penetration?

How to create a future-proof network?

Active Network Management (ANM)

- **Advanced Distribution Automation – USA**

The application of real-time control and communication systems to ensure the normal operation of (non-passive) distribution networks

- **Wikipedia**

ANM describes automated control systems that manage generation and load for specific purposes. This is usually done to keep system parameters (voltage, power, phase balance, reactive power and frequency) within predetermined limits.

... no ANM definition has been widely adopted.

What would ANM entail?

- Active power control of DG units
- Reactive power control of DG units
- Coordinated voltage control
- Dynamic line ratings
- Islanding and automatic synchronisation
- Fault level control (network topology mgmt)

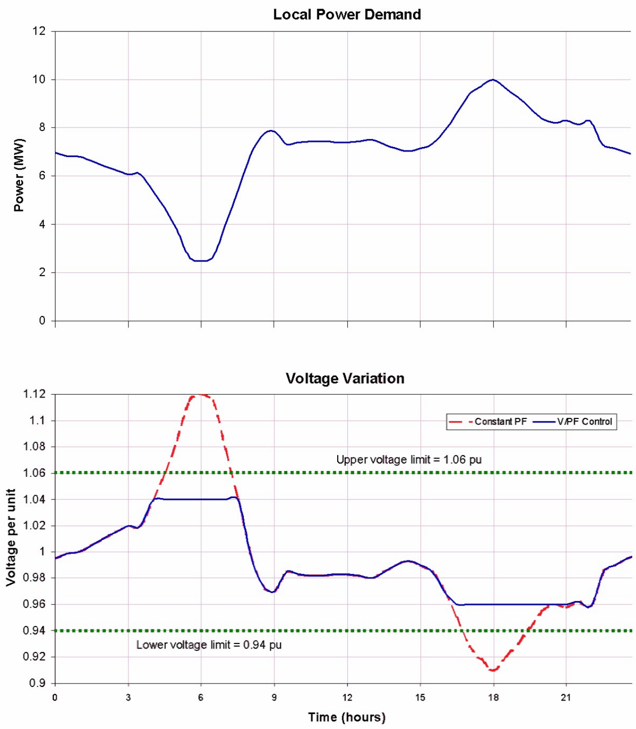
  - … distribution automation?
  - … demand side management?
  - … storage?

ANM Spectrum

Decentralised		*Centralised*
Voltage control made by DG	Coordinated OLTC/DG	Distribution Management System
Local measurements No coordination Limited optimisation Local control		Extensive measurements Full coordination Optimisation Extensive control

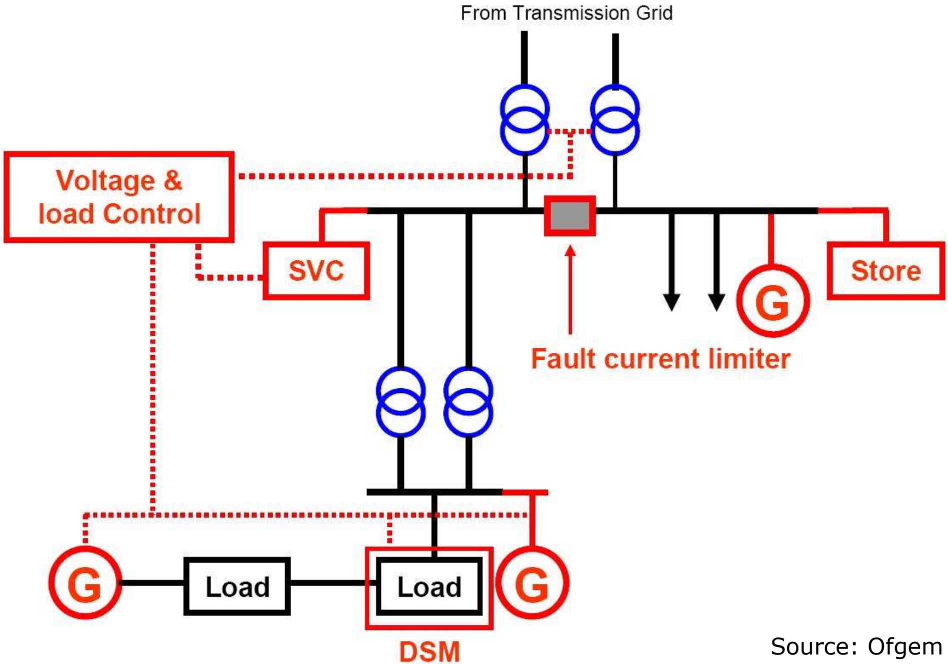
Decentralised: DG Voltage Control

- Generator control to avoid voltages outside limits
- Hybrid system: power factor/voltage control
- Power factor control when voltage is outside limits
- Voltage control to keep it values within limits
- Requires only local measurements



Centralised: Advanced Distribution Management System

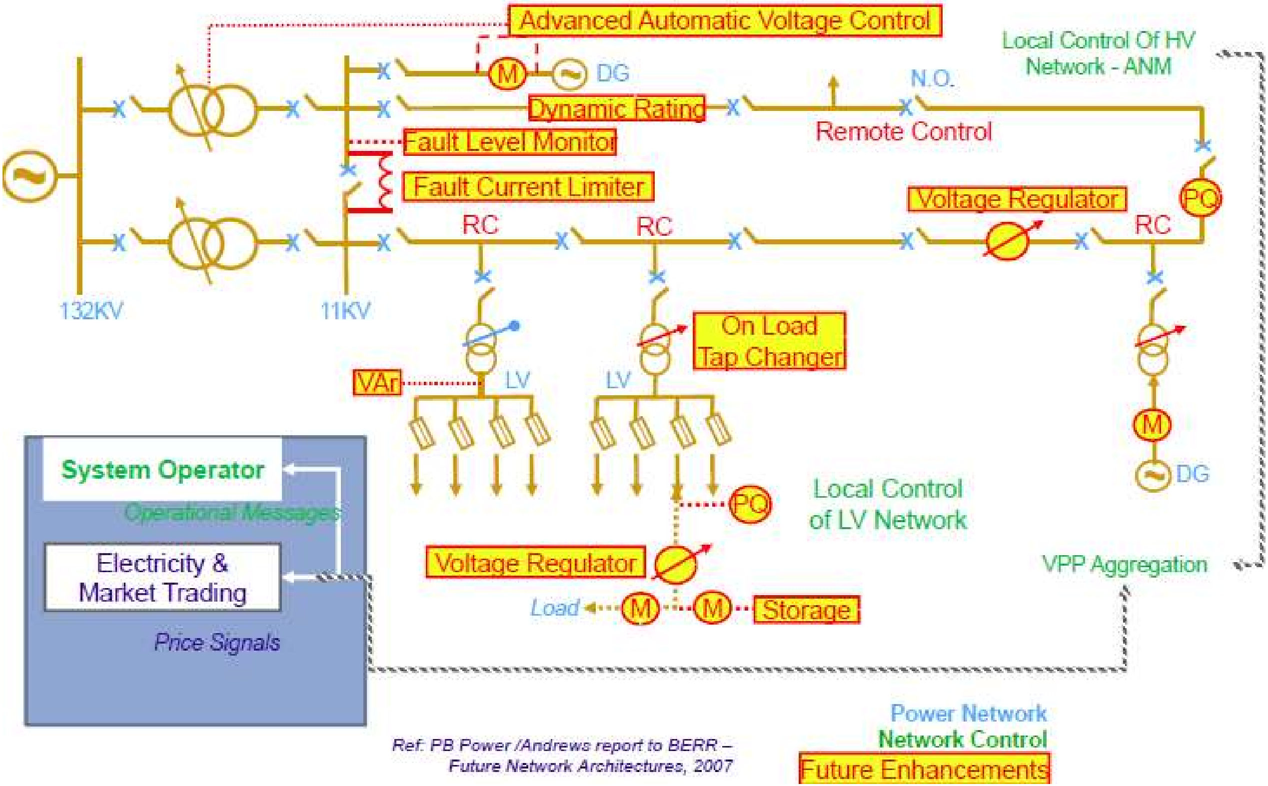
- Centralised control of devices and network participants



Source: Ofgem

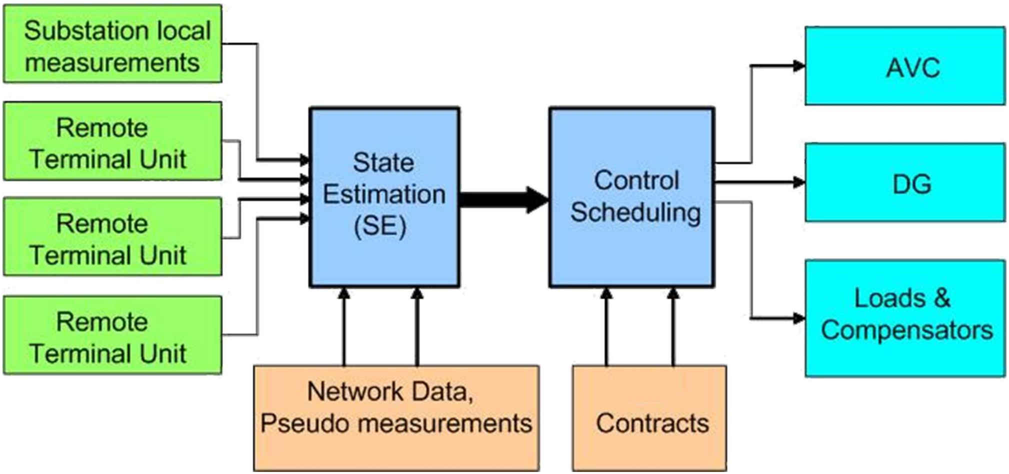
The University of Manchester

Functional Requirements in D-Networks



Ref: PB Power /Andrews report to BERR – Future Network Architectures, 2007

Architecture of an *advanced* DMS Controller



Active Network Management Modelling and Case Studies

DG Planning, Operation, Monitoring and Control

DG Planning & Operation

- To what extent can innovative schemes (a more ‘intelligent’ network) increase the penetration of (renewable) DG?
- Can DG be used to provide support to the system?
- To what extent rule-based control will handle evolving (in complexity) systems?

Control of Network Devices/Participants

- Centralised or Decentralised? Distributed?

Monitoring

- How to manage large volumes of data in order to provide meaningful results?

AC Optimal Power Flow

Max/Min Objective Function

Subject to:

Basic AC OPF

- real and reactive nodal power balance
- voltage level constraints
- voltage angle set to zero for the reference bus
- thermal limits (lines and transformers)
- constant power factor operation of DG units

- Snapshot approach → does not cater for the variability of demand and (renewable) generation
- No Smart Grid-like schemes → how to evaluate the envisaged benefits?

AC Optimal Power Flow: Embedding Operation into Planning

Max/Min Objective Function

Subject to:

Multi-Period AC OPF + Smart Grid Control Schemes

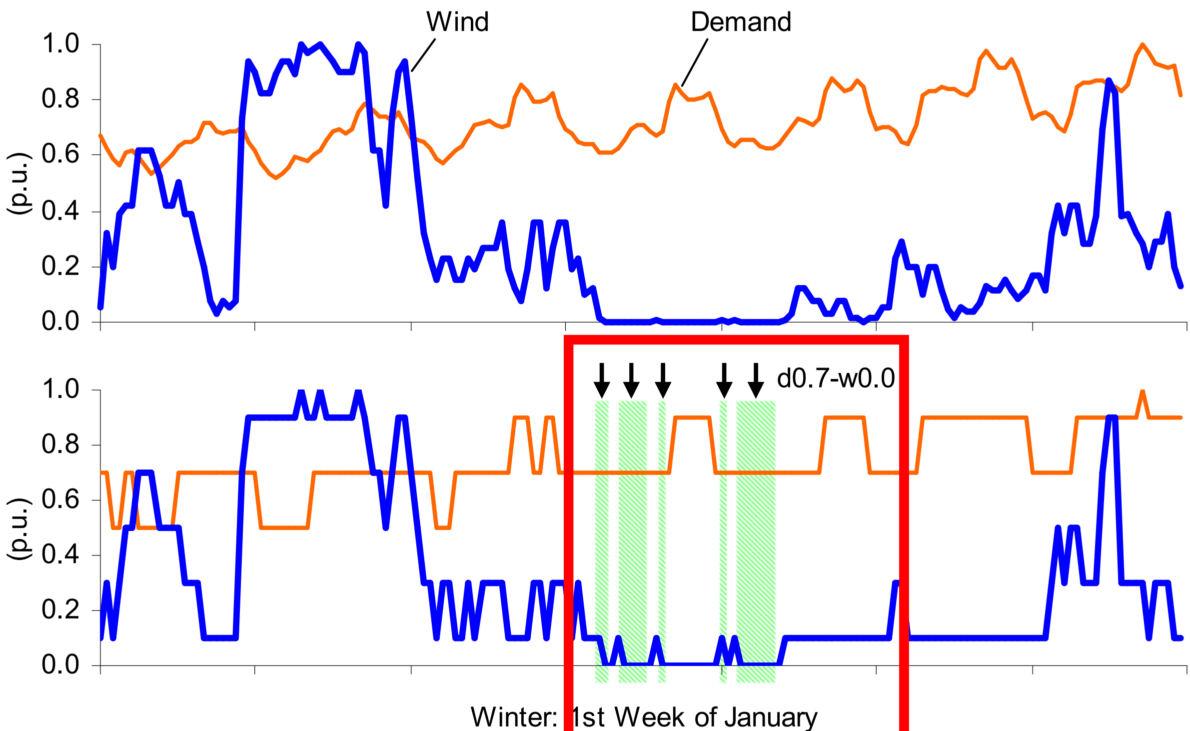
Basic AC OPF
- real and reactive nodal power balance
- voltage level constraints
- voltage angle set to zero for the reference bus
- thermal limits (lines and transformers)
- constant power factor operation of DG units

New Constraints
- voltage step change
- N-1 security constraints
- reverse power flow constraints
- fault level constraints
- etc., etc.

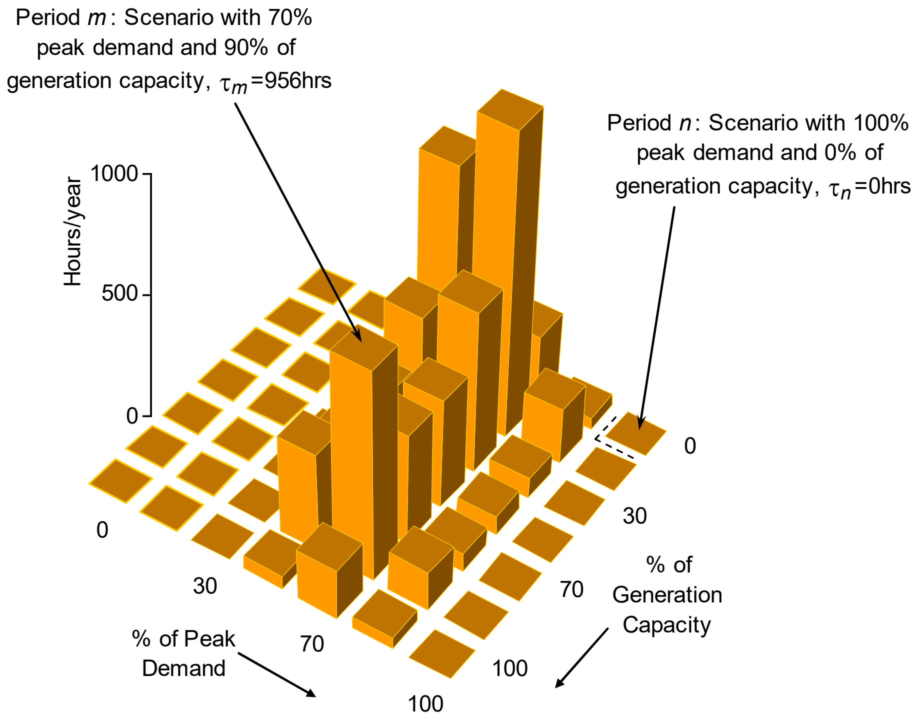
New Control Schemes
- coordinated voltage control
- adaptive power factor control
- generation curtailment
- dynamic ratings
- etc., etc.

Multi-Periods

Handling the Variability of Demand and Generation

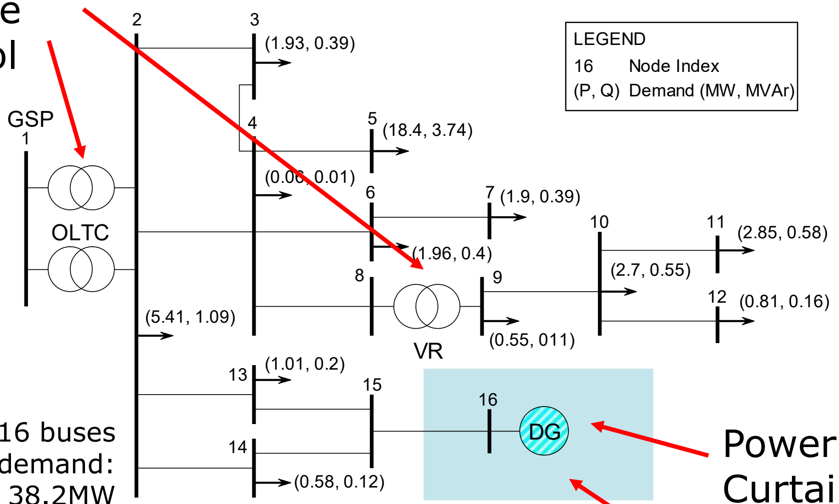


Multi-Periods
Handling the Variability of Demand and Generation



Case Study: UK GDS Simplified EHV1

Coordinated Voltage Control (CVC)



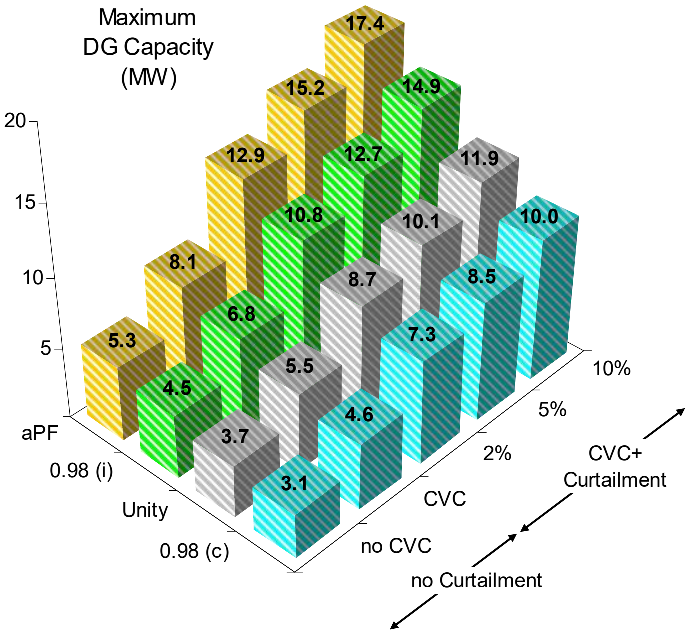
33/11 kV, 16 buses
Peak demand: 38.2MW
Energy Losses: 3.6%

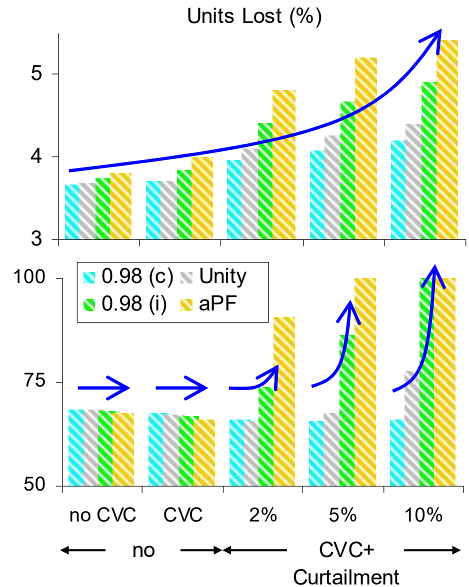
Power Curtailment

Adaptive Power Factor Control

Connectable (renewable) DG capacity

Planning: Maximising DG Capacity

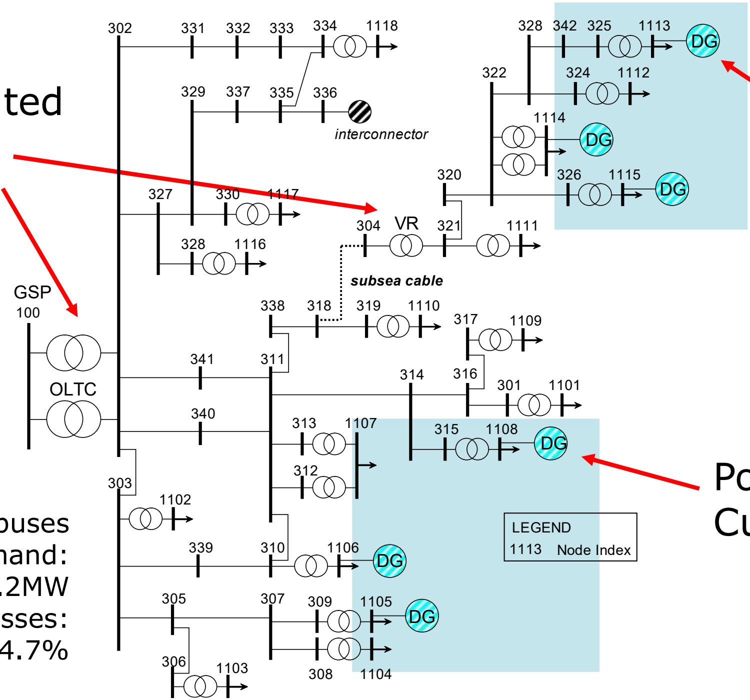




➔ CVC + adaptive PF control + 2% curtailment =12.9MW DG penetration of 34% (relative to peak demand)

Case Study: UK GDS EHV1

Coordinated Voltage Control



Adaptive Power Flow Control

Power Curtailment

33/11 kV, 61 buses
Peak demand: 38.2MW
Energy Losses: 4.7%

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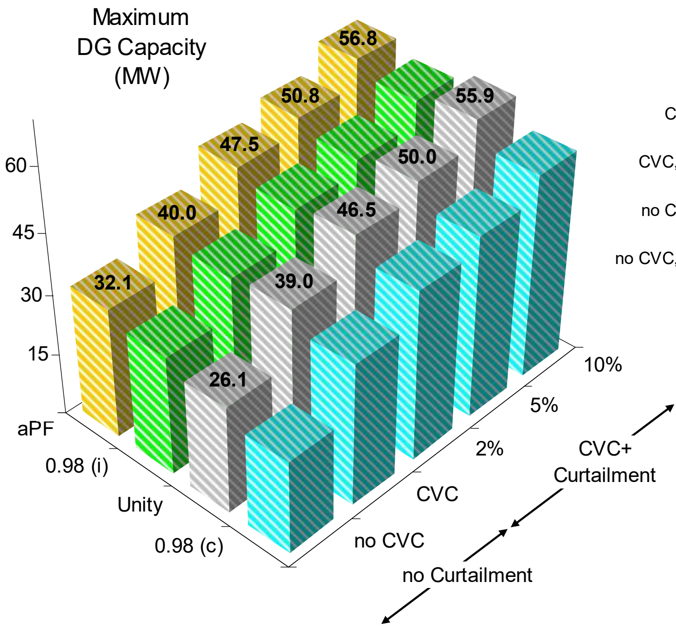
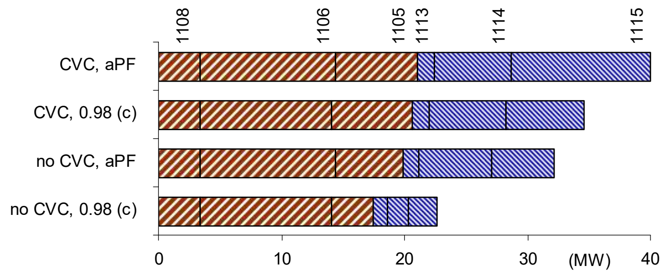
Connectable (renewable) DG capacity

Planning: Maximising DG Capacity



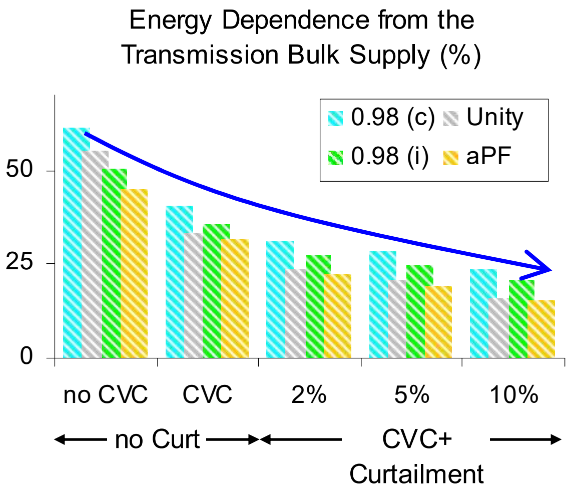


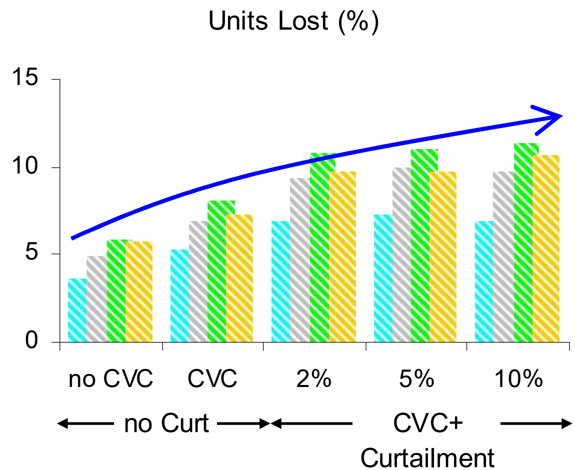
Locational Breakdown
Mainland / Island
(no curtailment)

➔ CVC + adaptive PF control + 2% curtailment = 47.5MW
DG penetration of 124% (relative to peak demand)

Connectable (renewable) DG capacity

Planning: Maximising DG Capacity

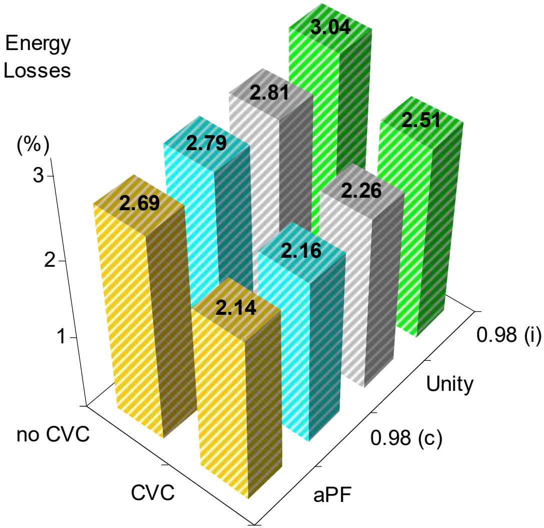


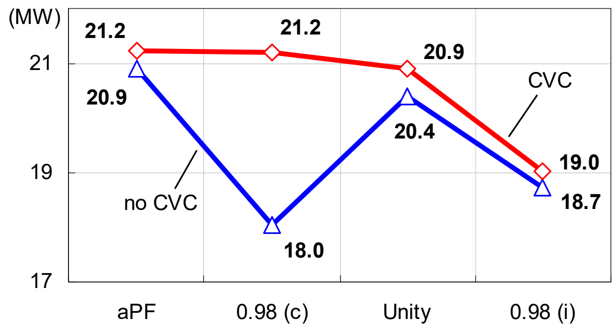


➔ CVC + adaptive PF control + 2% curtailment: 9.7% of losses and only 22% dependence

Connectable (renewable) DG capacity

Planning: Minimising Energy Losses



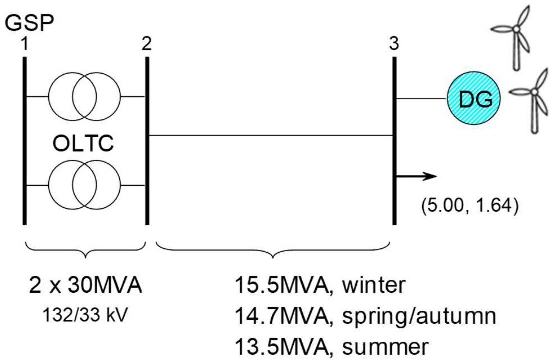


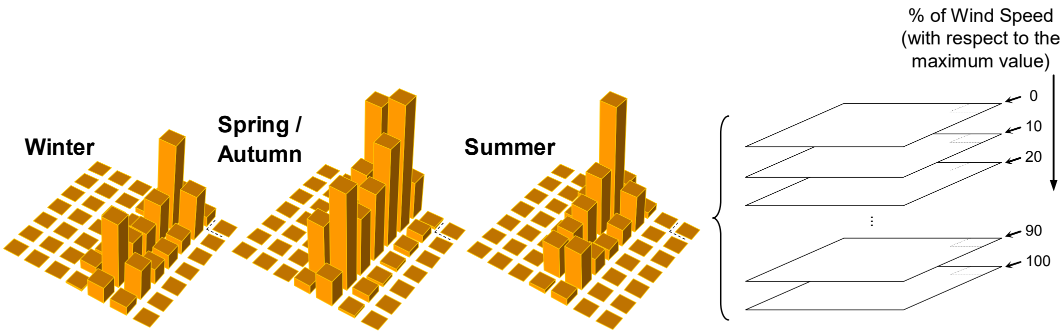
➔ CVC + adaptive PF control:
From 4.7% of energy losses to 2.1%
DG penetration of 55% (21.2MW relative to peak demand 38.2MW)

Case Study: Dynamic Ratings

The 5km-long feeder is composed by ACSR 2/0 conductors.

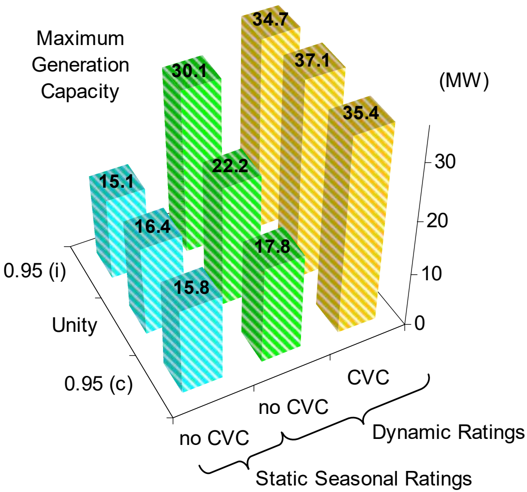
Peak demand 5MW.





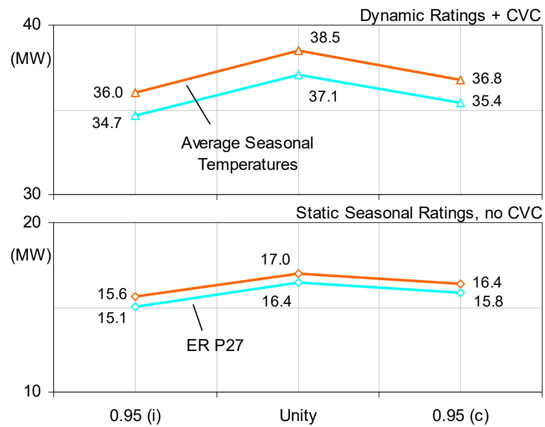
Connectable (renewable) DG capacity

Planning: Maximising DG Capacity



ER P27 temperatures are adopted.

Average seasonal temperatures are also adopted.



➔ Dynamic Ratings + CVC + unity PF:
DG penetration doubles that without ANM

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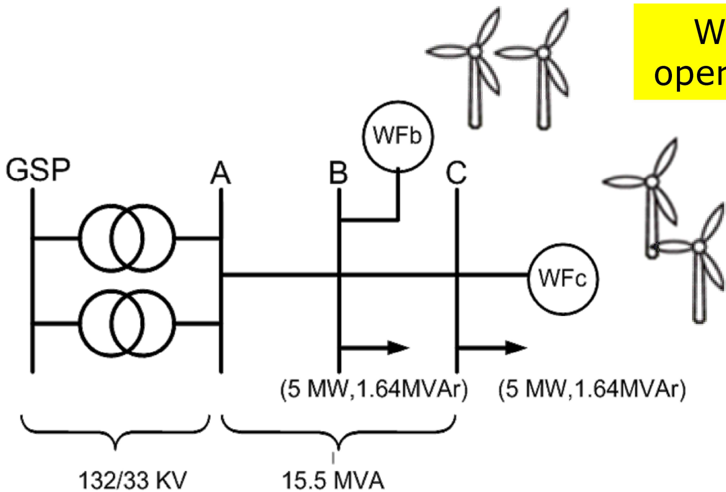
Connecting More DG in HV-EHV Networks

- Firm connections of renewables ‘sterilise’ the hosting capacity
- Non-firm connections (tripping of DG) are OK but not enough
- Is it possible to connect more?

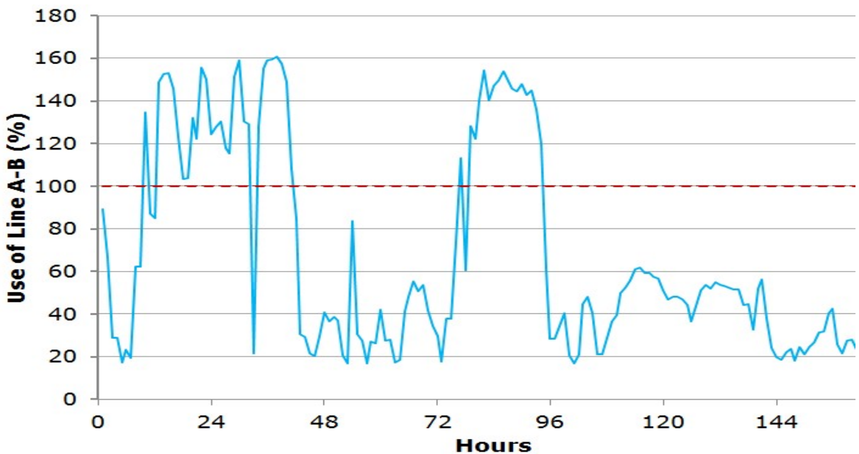


WFb free to operate its 8MW

WFc wanting to connect 20MW+

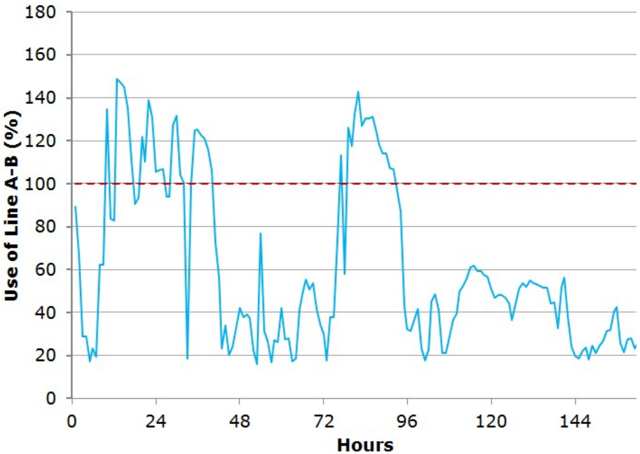
Connection of a 24 MW Wind Farm: No Control

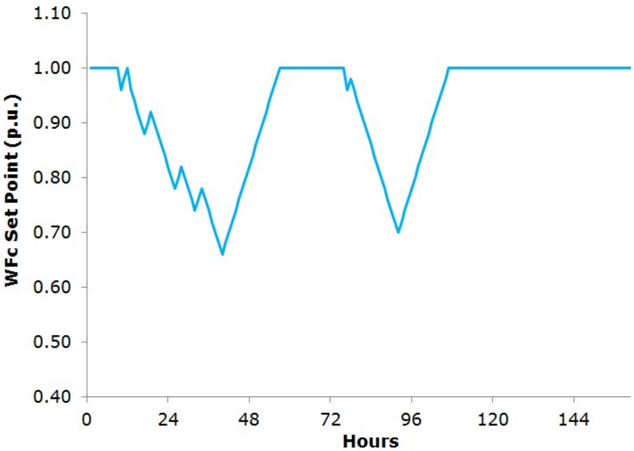
- Number of Overloading Hours/year → 2518 hours.
- Capacity factor → 41.4%.
- Avg Power Output exceeding thermal capacity → 6.42 MVA



Connection of a 24 MW Wind Farm: Rule-Based Active Control

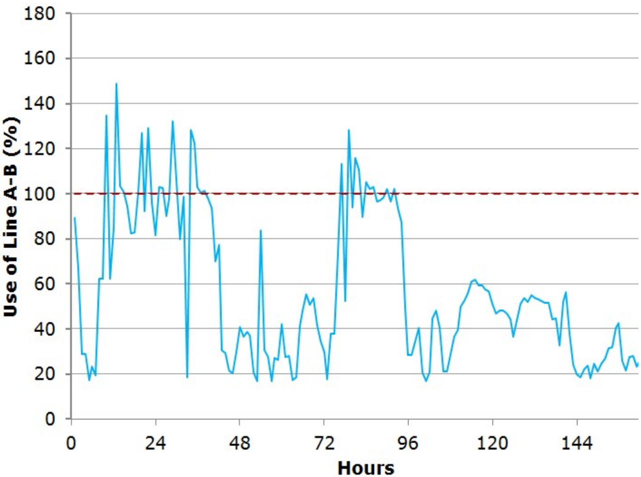
- Deadband +/- 2%
- Number of overloading hours/year → 1930 hours
- Capacity factor → 34.9%
- Avg power output exceeding thermal capacity → 3.17 MVA

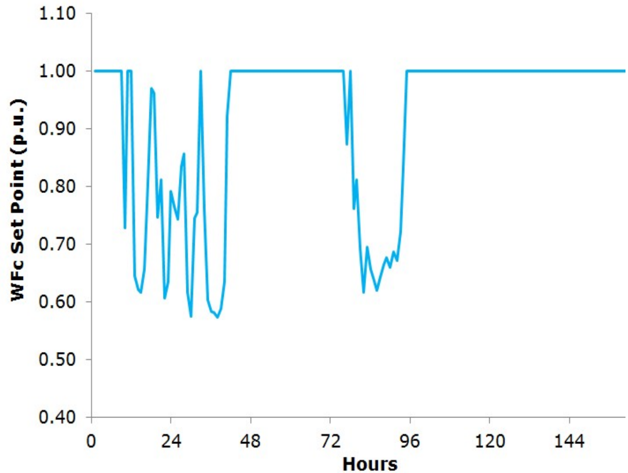




Connection of a 24 MW Wind Farm: AC OPF-Based Active Control

- No deadband
- Number of overloading hours/year → 1443 hours
- Capacity factor → 33.4%
- Avg power output exceeding thermal capacity → 1. 7 MVA

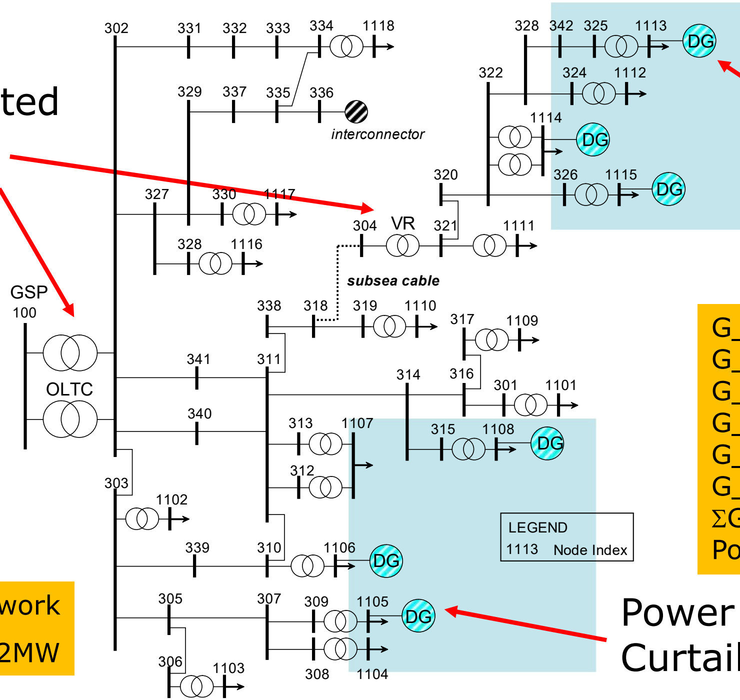




Case Study: UK GDS EHV1

Coordinated Voltage Control

Adaptive Power Flow Control



G_1108: 5.0 MW
G_1106: 14.7 MW
G_1105: 9.5 MW
G_1113: 1.9 MW
G_1114: 8.6 MW
G_1115: 14.8 MW
ΣG: 54.5 MW
Power factor 0.98 ind

132/33/11kV Network

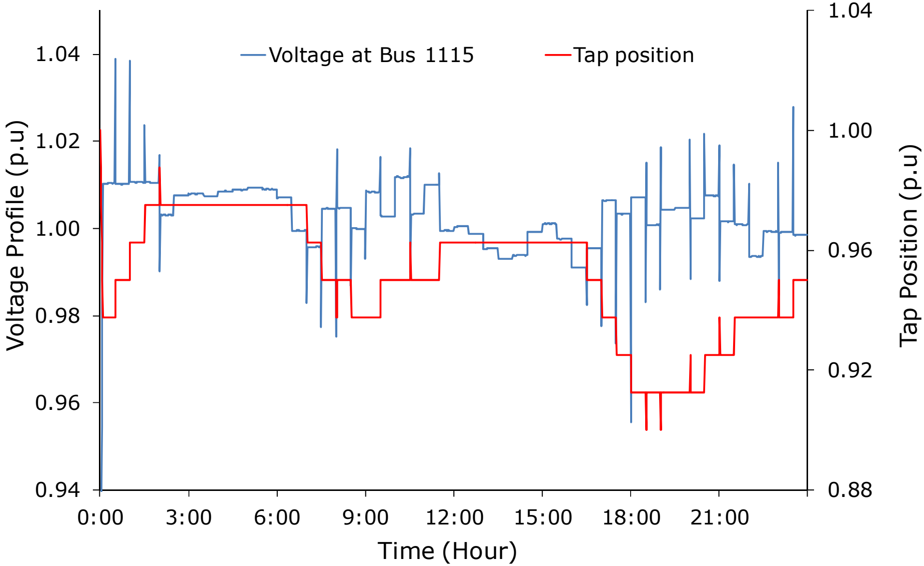
Peak demand 38.2MW

Power Curtailment

PhD Student:
Sahban Al-Naser

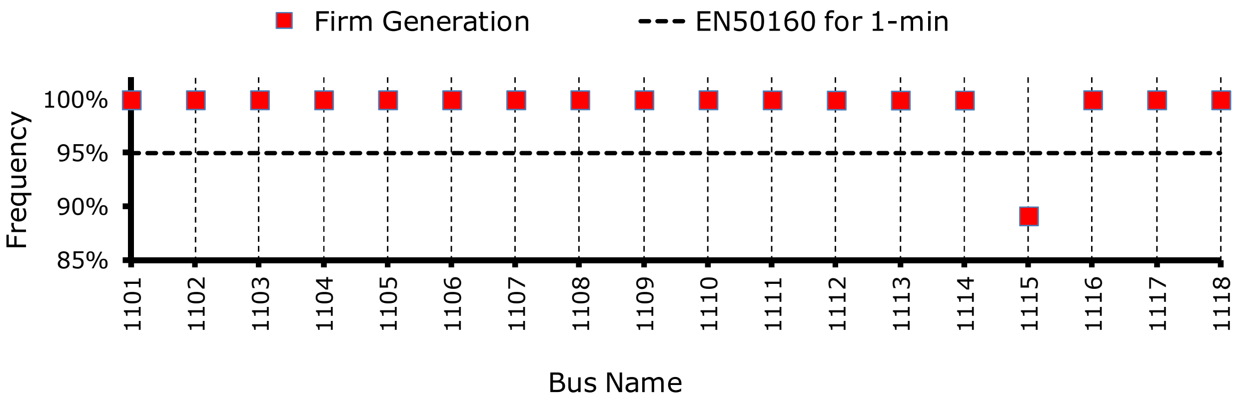
Minute-by-Minute Modelling

- No wind farm (primary 326/1115)
  - Demand for February (Elexon ENWL domestic unrestricted)
  - Target voltage 1p.u., deadband +/- 1%



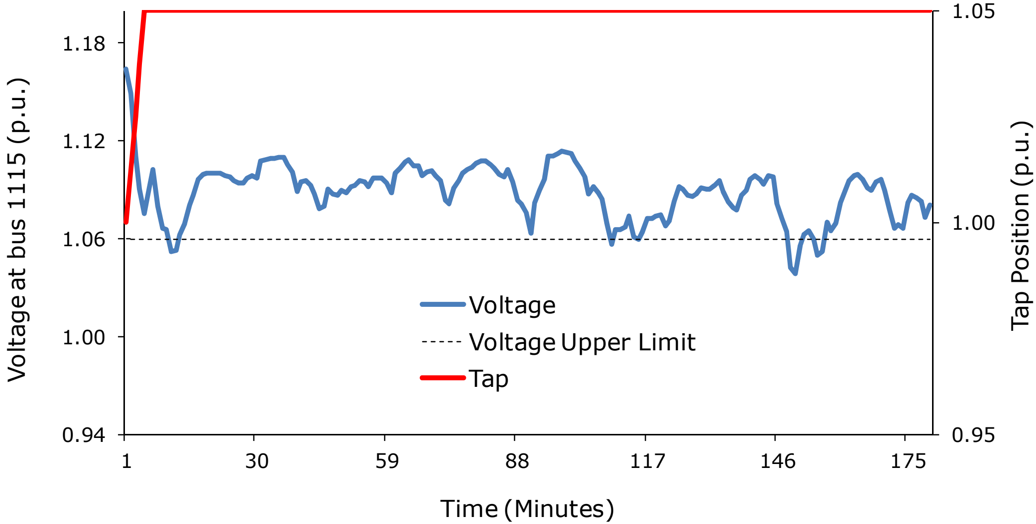
Minute-by-Minute Modelling

- All wind farms (no control)
  - Modified voltage disturbance standard EN50160 (whole month)
  - Voltage limits +/- 6%



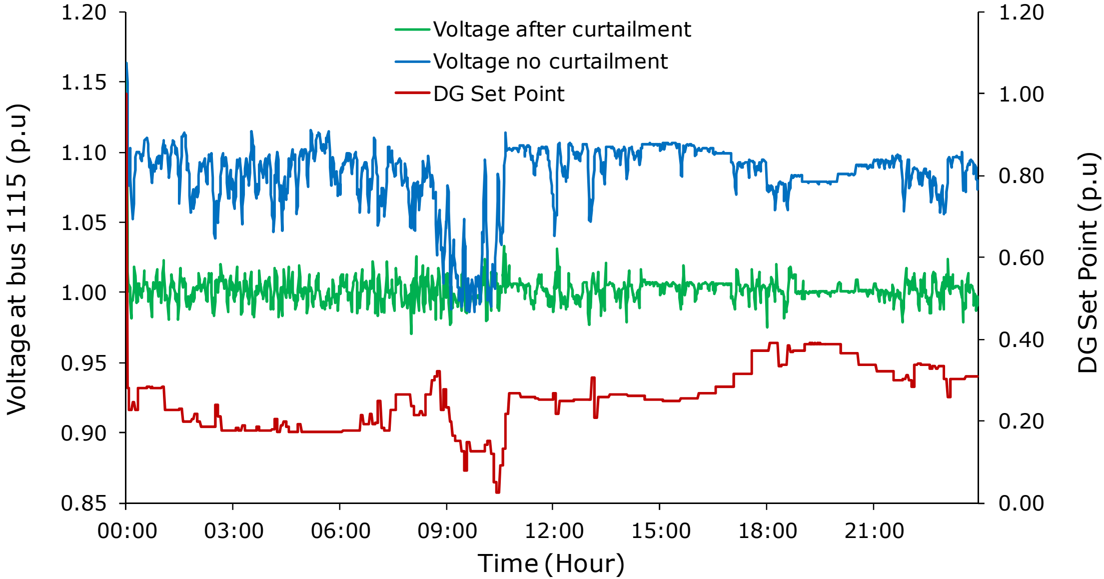
Minute-by-Minute Modelling

- All wind farms (no control)
  - Tap at bus 1115 pushed to its maximum position (target 1.0pu)
  - Voltages above the upper limit (there are also loading issues)



Minute-by-Minute Modelling

- All wind farms (controlling DG output)



Real-Time Control of DER

- It is indeed possible and it is actually becoming more common around the world
  - Thermal management: DG Curtailment
  - Voltage management: On load tap changers (OLTCs)

- However, the business case needs to be clear
  - What is the aim of controlling DER?
    - Cheaper connections (for DG developers)
    - More DG is connected (DNOs need to be seen as enablers)
    - Technical constraints are managed (by the DNO)

… reduction of CO_2 emissions?

… can/should a city control DER?

Active Network Management Applications in Real Time

How are we moving towards more R&D and implementation?

Who is going to invest in this type of solutions?

Incentives to Facilitate DG Connection and Network Innovation (UK)

- **Distribution Price Control Review 4 (2005-2010)** with RIIO (Revenue = Incentives + Innovation + Outputs) model
- Innovation Funding Incentive (IFI) before 2013 (Now Network Innovation Allowance - NIA)
  - R&D, 0.5% of the DNO's invoiced revenue
  - … to have more innovation
- DG Incentive
  - £2.5/kW/year (for 15 years)
  - … for DNOs to have a more proactive approach
- Registered Power Zones (RPZ)
  - +£2.0/kW/year (for the first 5 years). Limit of £0.5m/DNO/year
  - … to develop more cost-effectives ways of connecting DG

RPZ – E.On Central Networks
Thermal Constraints

- Dynamic monitoring of line capacity (132kV) – increases the connection capacity of DG
- Helps transporting energy from off-shore wind farms
- Overhead line capacity calculated by using ambient temperature and wind speeds
- Power donut (www.usi-power.com)

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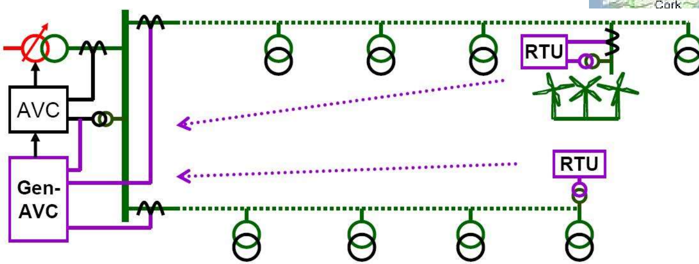
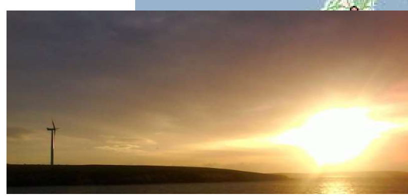
RPZ – EDF Energy
Voltage Constraints

- Coordinated control of OLTC
- Uses (measures/estimates) generation and demand data
- Increases significantly the connection capacity of DG (might double it)



RPZ – Scottish and Southern Energy (SSE)
Thermal Constraints

- The Orkney Islands have great wind resources but are connected to the mainland by subsea cables
- The System uses:
  - circuit availabity
  - wind power variability
  - demand variability
- Increases significantly the export capacity



RPZ – Scottish and Southern Energy (SSE)

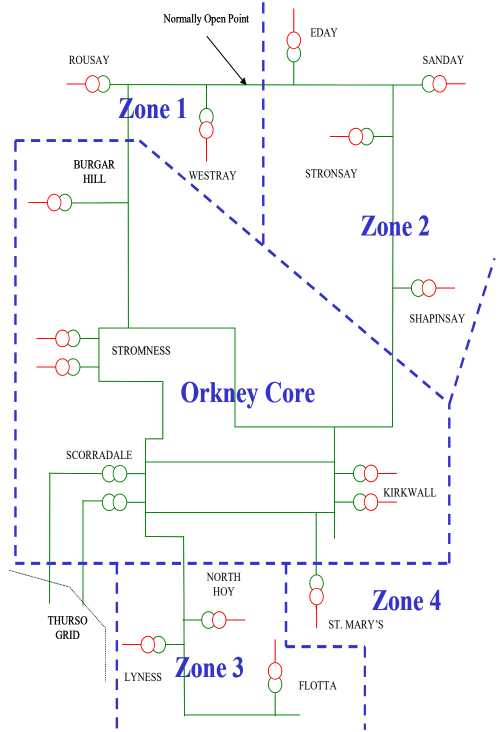
Orkney Islands

- 8MW minimum demand in summer
- 31MW maximum demand in winter
- Two 33kV subsea cables
- Existing generation includes wind, wave and gas
- Exisintg generators have used most of the available capacity of the local network
- There is a lot of interest in connecting more DG, but conventional solutions are too expensive: £30m for distribution and £100 for transmission
- RPZ was registered in 2005. Pilot project successfully run in 2006. Currently is fully implemented

RPZ – Scottish and Southern Energy (SSE)

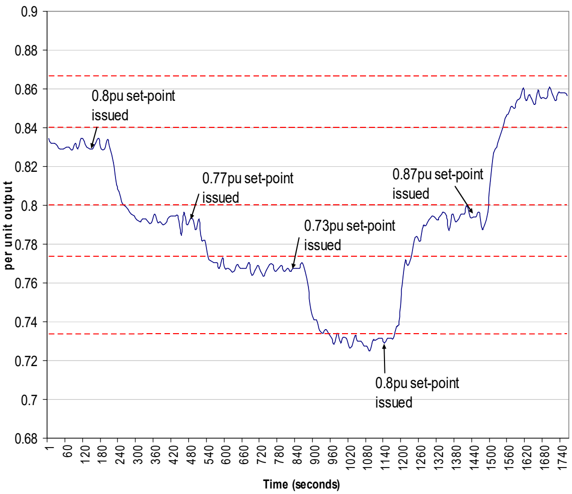
How does it work?

- Real-time control of wind and wave power
- Each zone has thermal limits according to generation levels
- New generation capacity varies with the level of demand and existing generation
- The Orkney system has a limit to protect the subsea cables
- Reactive compensation exists in the area



RPZ – Scottish and Southern Energy (SSE)
Pilot Project

- This project demonstrated the ability of an ANM system to dispatch in real-time the power output of wind farms



- Successful circuit control
- Proven communication systems and logic

RPZ – Scottish and Southern Energy (SSE)
Technical Lessons

- First ANM system in the UK with multiple generators
- Development and implementation of ANM is not trivial
- This is new and different from ‘fit and forget’
- Generation has to be ‘dispatchable’
- Additional cost due to control and communication systems
- Barriers are financial, not technical

RPZ – Scottish and Southern Energy (SSE)

Commercial Lessons

- Ofgem incentives do encourage innovation
- But incentives are not enough
- Dialogue with generator owners/operators is very important
- It is crucial to have partnerships between industry and universities
- Better understanding of participants' liabilities
- Better understanding of risks and gains
- New commercial models need to be developed
- New methodologies for use of system charges are required

Some (Practical) Conclusions About ANM

- Theory is being translated into implementation
- DNOs are becoming more confident about new technologies
- Strong incentives from regulators are very important
- Ideas are relatively ‘easy’, but implementation and commercial application are the greatest challenges

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UK LCNF Tier 2 Projects

www.ofgem.gov.uk/electricity/distribution-networks/network-innovation/low-carbon-networks-fund/second-tier-projects

- 2010
  - Customer-led Network Revolution (CE Electric UK)
  - Low Carbon London (UKPN)
  - Low Carbon Hub (Central Networks)
  - LV Network Templates for a low carbon future (WPD)

- 2011
  - Flexible Plug and Play (UKPN)
  - B.R.I.S.T.O.L. (WPD)
  - Thames Valley Vision 2 (SSEPD)
  - **Capacity to Customers (ENWL)**
  - Flexible Networks for a Low Carbon Future (SPEN)
  - FALCON (WPD)

UK LCNF Tier 2 Projects

www.ofgem.gov.uk/electricity/distribution-networks/network-innovation/low-carbon-networks-fund/second-tier-projects

- 2012
  - Accelerating Renewable Connections (SP Distribution)
  - **Customer Load Active System Services (ENWL)**
  - Flexgrid - Advanced Fault Level Mgmt in Birmingham (WPD)
  - **Innovation Squared (SSEPD)**
  - Smarter Network Storage (UK Power Networks)

- 2013
  - **Eta: Creating efficient distr. networks (ENWL)**
  - Flexible Urban Networks – Low Voltage (UK PN)
  - Solent Achieving Value from Efficiency (SSEPD)
  - Vulnerable Customers and Energy Efficiency (UKPN)

- 2014
  - Network Equilibrium (WPD)
  - **Fault Level Active Response – FLARE (ENWL)**
  - Kent Active System Management - KASM (UKPN)
  - Low Energy Automated Networks – LEAN (SSEPD)

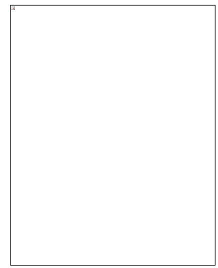
CLASS:
Customer Load Active System Services

- Electricity North West Limited (ENWL)
  - Low-Carbon Network Fund 2012, Tier 2. Total awarded: £7.2m
- Scope
  - Investigating how reducing or increasing voltage on the distribution network can reduce peak demand or increase demand when needed → Services to National Grid
  - Tap Staggering. Use of reactive power capabilities through the use of circulating currents → Services to National Grid
  - Trial to consider only primary substations (33kV to 11kV or 6.6kV)

CLASS customer leaflet

VAr supports to TN by means of DNs

- To apply the tap staggering operation to primary substation transformers in distribution networks.



Network Constraint-Based Quantification of CLASS

- Provision of DSO resource availability to TSO via dashboards
  - Aggregated / Per primary
  - Deterministically / Probabilistically
  - Real time / Forecasting

TSO control room → DSO control room

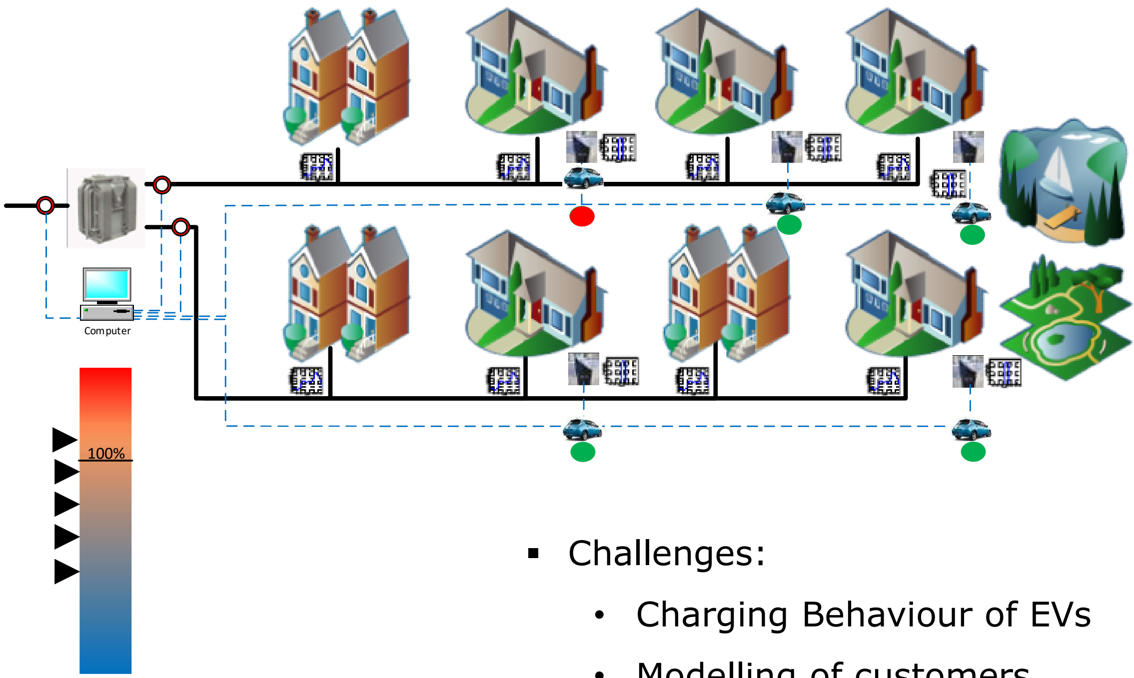
00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00
MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW
Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar

12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW
Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar	Mvar

Innovation Squared: Managing Unconstrained EV Connections

- EA Technology and Scottish and Southern Energy (SEPD)
  - Low-Carbon Network Fund 2012, Tier 2. Total awarded: £4.2m
- Scope
  - Assess the technical and economic impacts of uncontrolled EVs and/or EHPs on real LV networks;
  - Estimate the economic benefits (investment deferral/avoidance), likely effect on EV/EHP uptake, and carbon savings from adopting a control scheme to manage EVs/EHPs; and,
  - Improve the Esprit technology (patented by EA Technology) considering Model Predictive Control (MPC).

General Idea of the Control Algorithm



- Challenges:
  - Charging Behaviour of EVs
  - Modelling of customers

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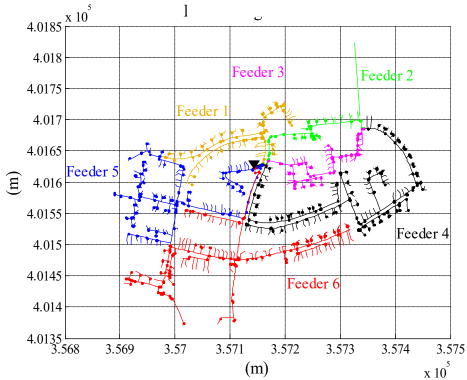
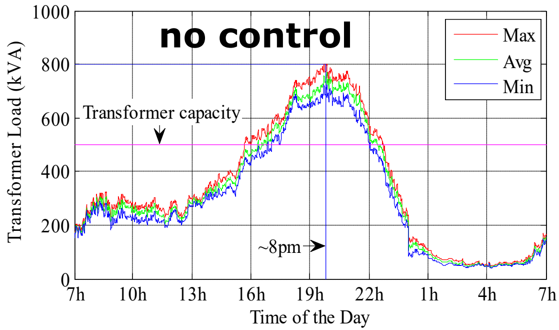
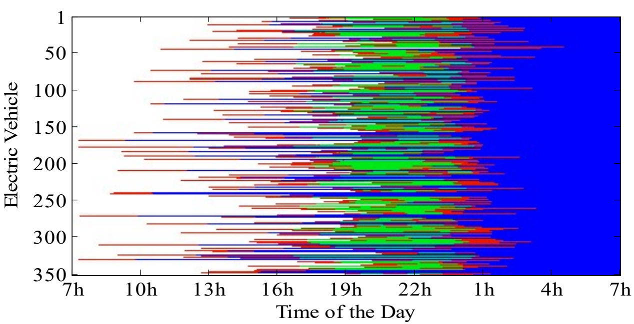
Results: Mini-Stochastic Analysis

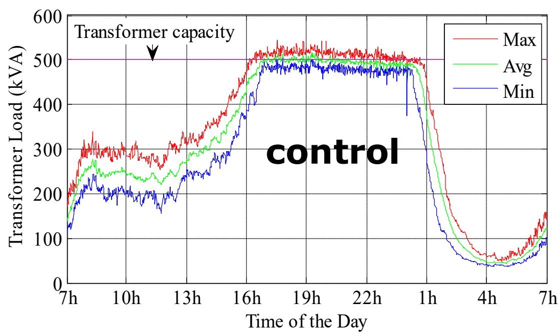
Real UK LV Network



100% EV penetration







eta (aka Smart Street): Creating efficient distribution networks

- Electricity North West Limited (ENWL)
  - Low-Carbon Network Fund 2013, Tier 2. Total awarded: £8.4m
- Scope
  - Using innovative technology to manage voltage on low voltage networks, with the aim of creating capacity for low carbon technologies
  - Dynamic reconfiguration of LV and HV networks
  - Conservation Voltage Reduction by coordinating OLTCs and capacitor banks

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Conclusions

- There are potentially large benefits of implementing Active Management of Distribution Networks
  - increased capacity of DG to be connected to existing networks
- Active Management of Distribution Networks is likely to be particularly beneficial for weak MV rural networks
- Need to demonstrate feasibility of active distribution network management requires:
  - Quantification of cost the of active distribution systems
  - Required control systems to be designed
  - Field tests to be carried out
  - Development of commercial arrangements
- ANM is a building block of Smart Distribution Networks

End of Section 3