Design of Decentralised Urban Energy Systems

Frontiers in Energy Research

Tuesday, 5 May, 2015

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Contents

Introduction

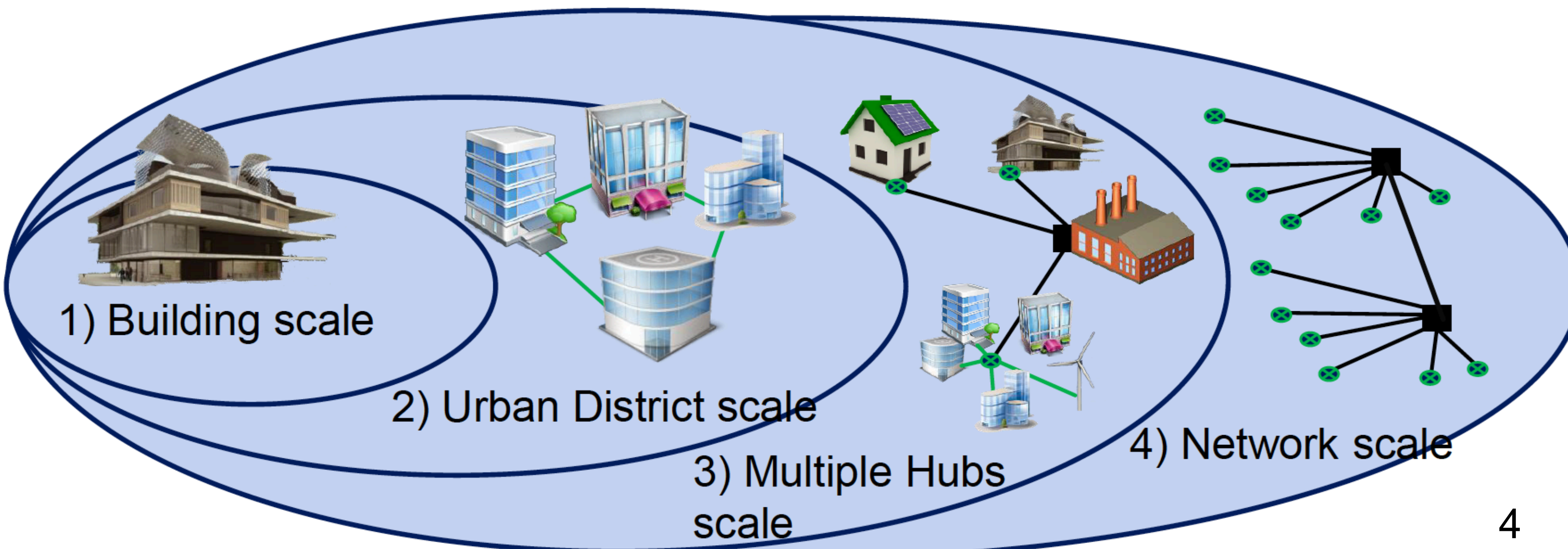
$$CO_2 = Population \times \frac{GDP}{Population} \times \frac{Energy}{GDP} \times \frac{CO_2}{Energy}$$

- Kaya Identity
- Population is increasing
- GDP per capita should increase
- So Energy Intensity and Carbon Intensity must go down significantly
  - Energy Intensity
    - Increase generation efficiencies
    - Reduce transmission and distribution losses
  - Carbon Intensity
    - Integrate large amounts renewable energy resources

Source: Environment, Energy and Economy; Ed. Y. Kaya & K. Yokobori; 1997

Decentralised Generation

- **Paradigm shift:** Centralised generation + T&D → Decentralised generation
- Urban areas give rise to the potential for system integration
- Building orientation, density, and form impact the ability to utilise local renewable energy sources
- Adoption of decentralised renewable energy sources require a re-engineering of the energy infrastructure
- To efficiently integrate renewables into urban areas, energy systems have to be able to manage fluctuating and distributed power sources, store energy, convert energy from one carrier to another



Distributed Energy Resources (DER)

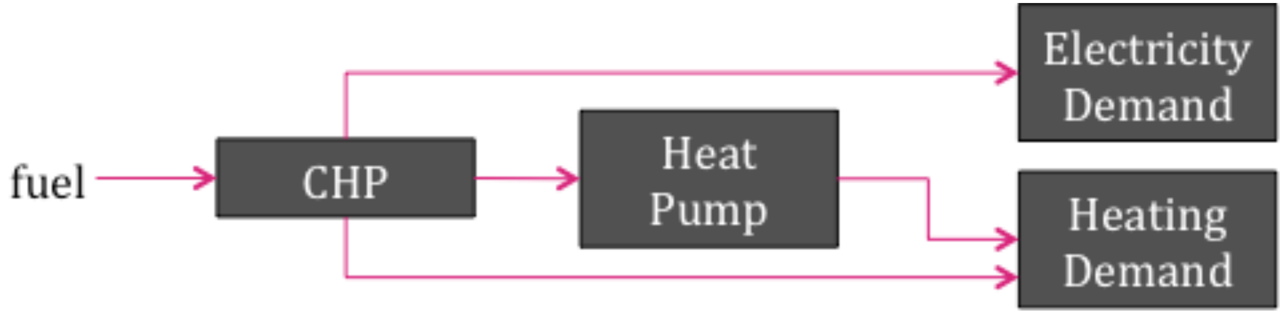
- Small to medium sized power generators that are sited within the electricity distribution systems, near consumers

- DER systems can be made up of a number of technologies including:
  - Combined heat and power (CHP)
  - Photovoltaics (PV)
  - Small wind turbines
  - Micro-hydro
  - Storage

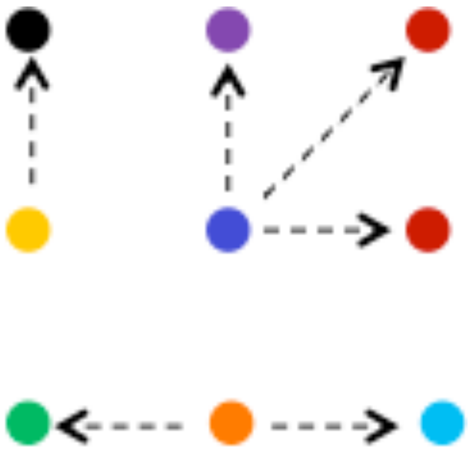
- Also incorporate heating and cooling technologies like ground source heat pumps or absorption chillers in order to create **hybrid polygeneration energy systems**

Supply and Demand Side Integration

– Supply Side

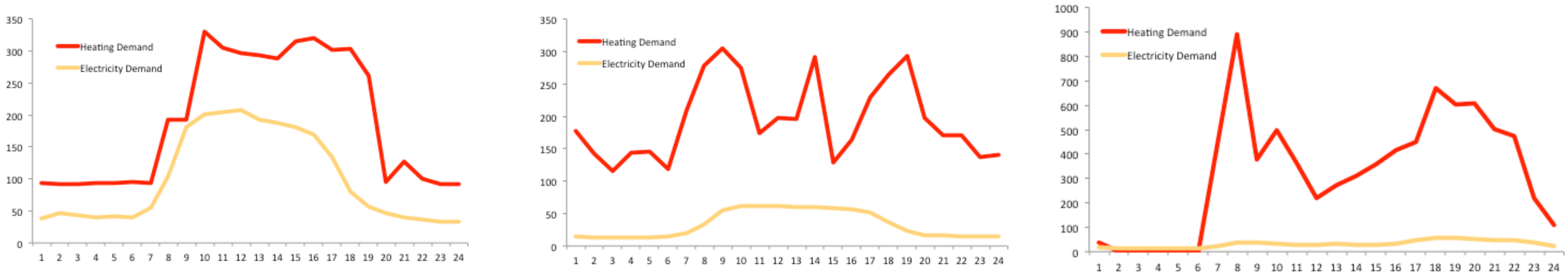


– Demand Side

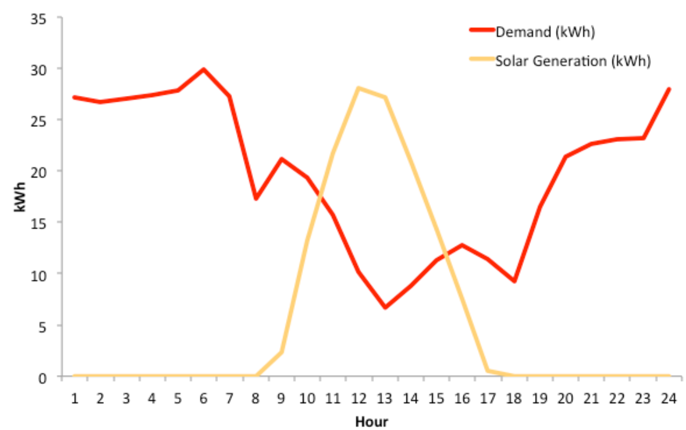


Complexity of Integration

- Temporal and spatial variation in electricity, heating, and cooling demands

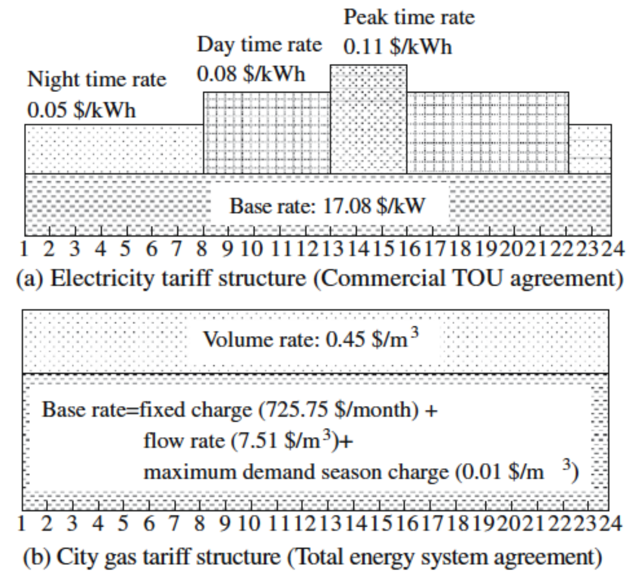


- Intermittency of certain types of renewable technologies (e.g. PV and wind turbines)



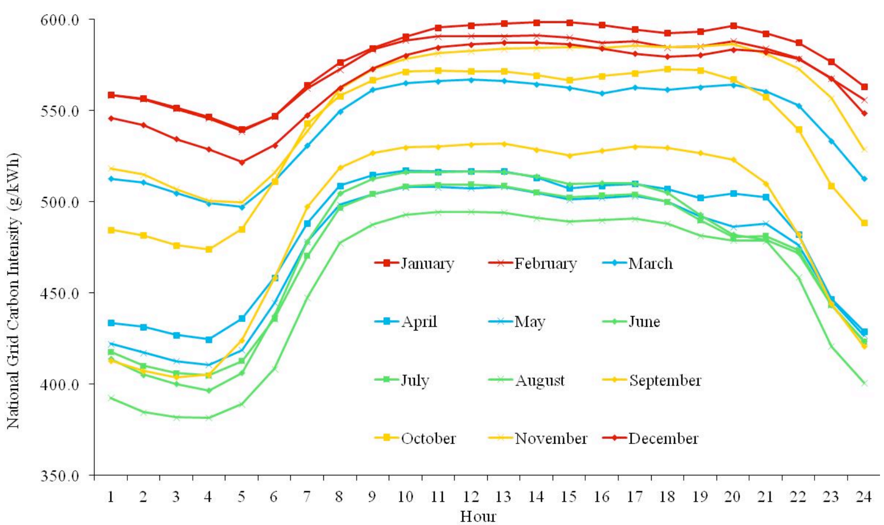
Complexity of Integration

– Variable fuel pricing



source: Ren and Gao, 2010

– Temporal variability in carbon intensity of the grid electricity



Energy Hub Concept

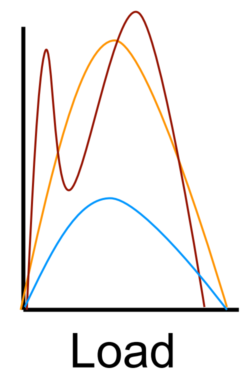
Inputs

e.g. Grid electricity, solar radiation, natural gas, etc.

→ Energy Hub →

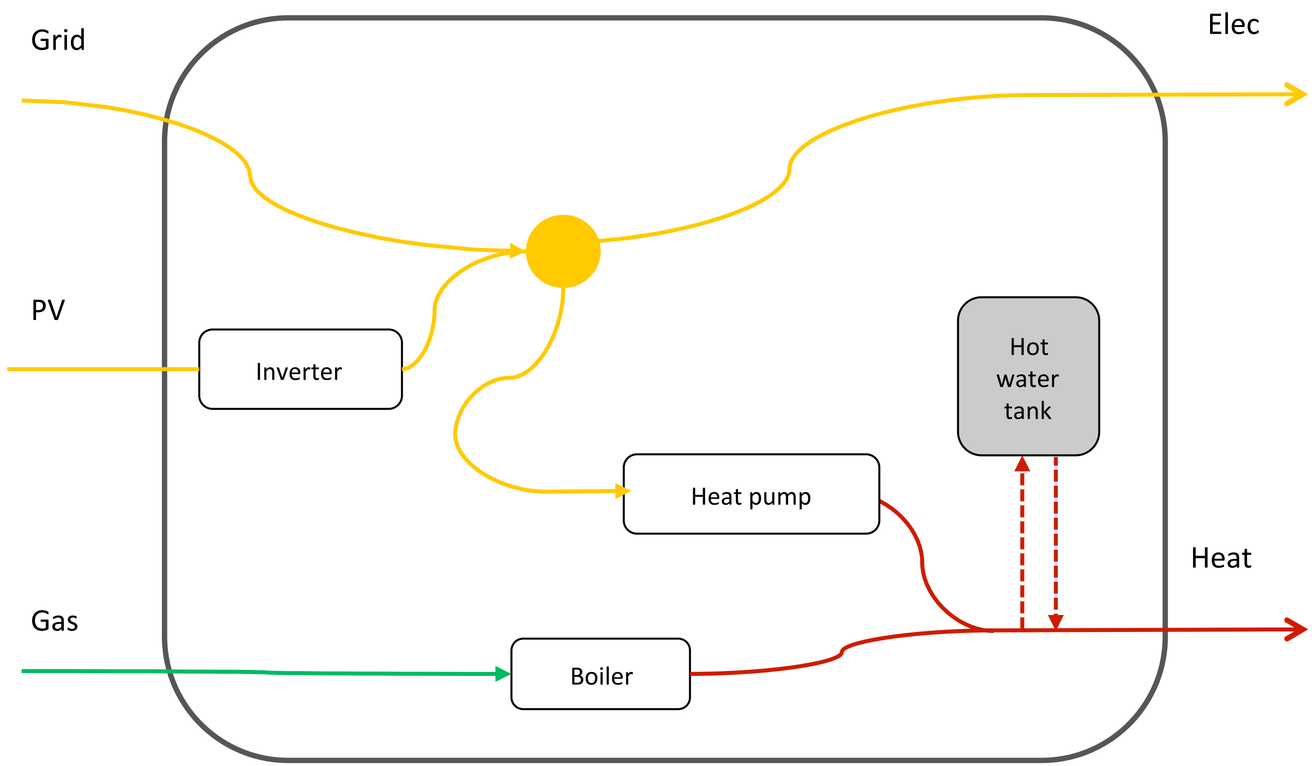
Outputs

e.g. Electricity, Heating, Domestic Hot Water, etc.



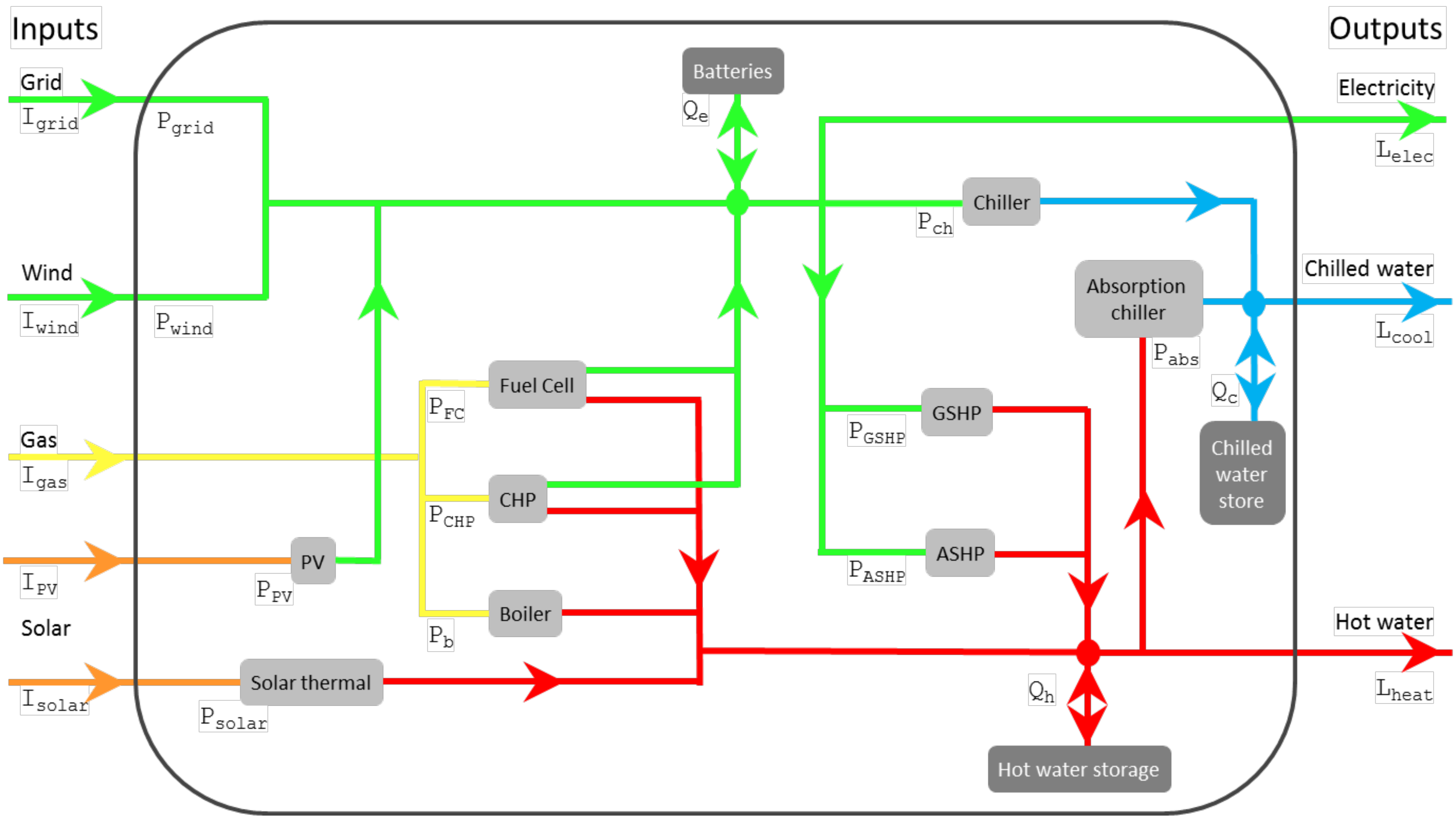
What happens in the black box?

What is an Energy Hub?



- A clearly delineated system to convert and store multiple energy streams
- A physical entity (e.g. energy center with plant and controls) *or* a conceptual formulation for simulation and optimisation
- Applicable at many spatial and temporal scales and resolutions

Energy Hub Superstructure

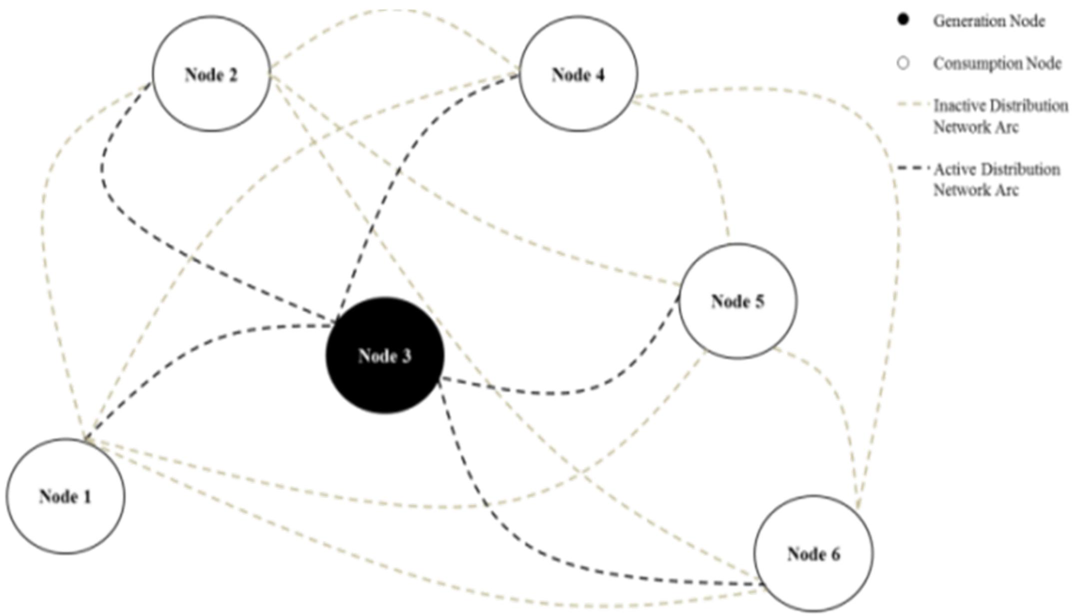


Design, Dispatch, and Distribution

Design of energy hubs (i.e. distributed energy resource systems) must take into account:

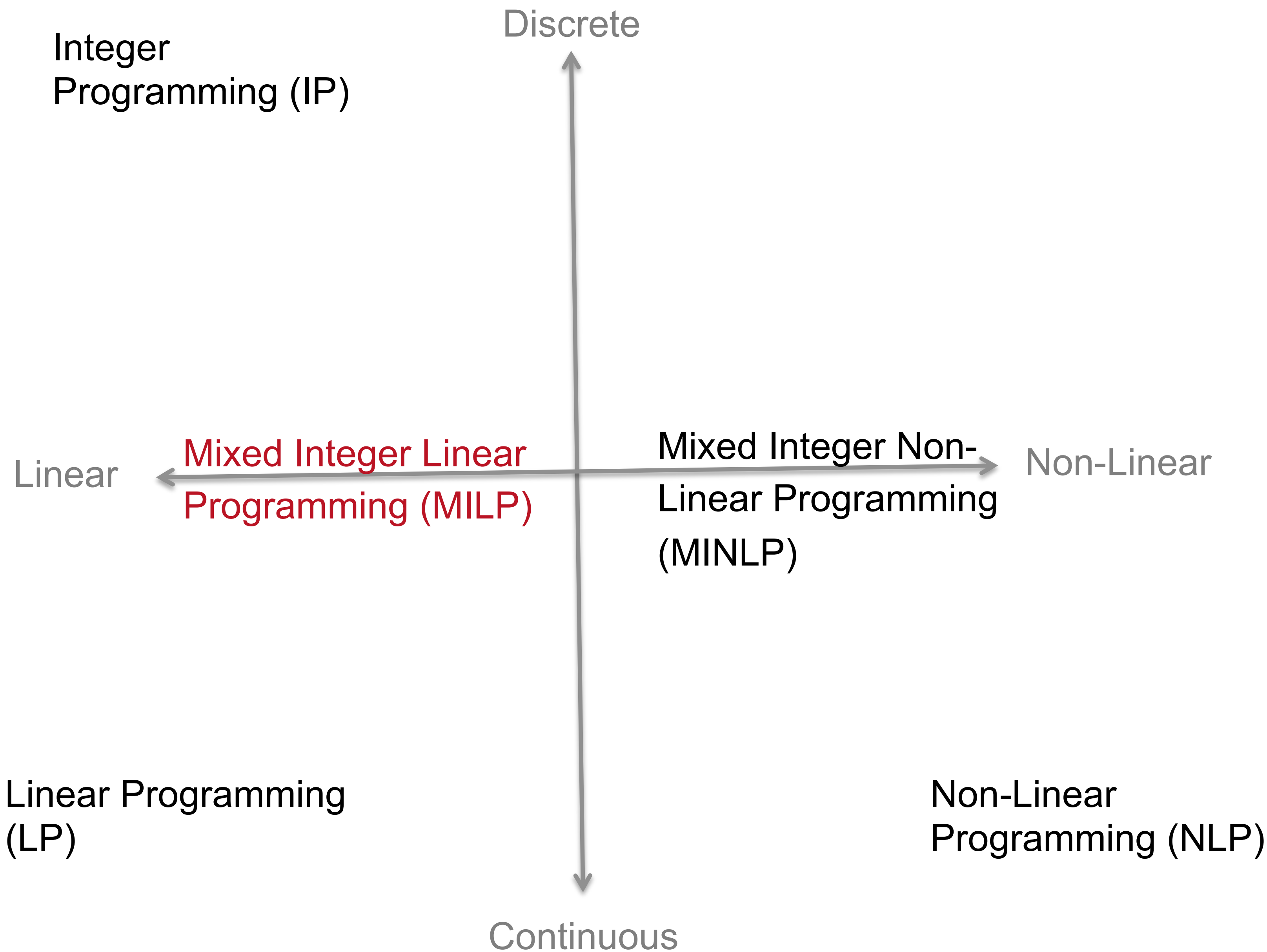
- the choice of generation technologies within the energy system and their unit sizes (**system design)**
- the operational schedule that best matches energy supply with demand **(unit dispatch)**
- the location of the generation units and the structure of the distribution network **(energy distribution)**

Energy Hub Concept

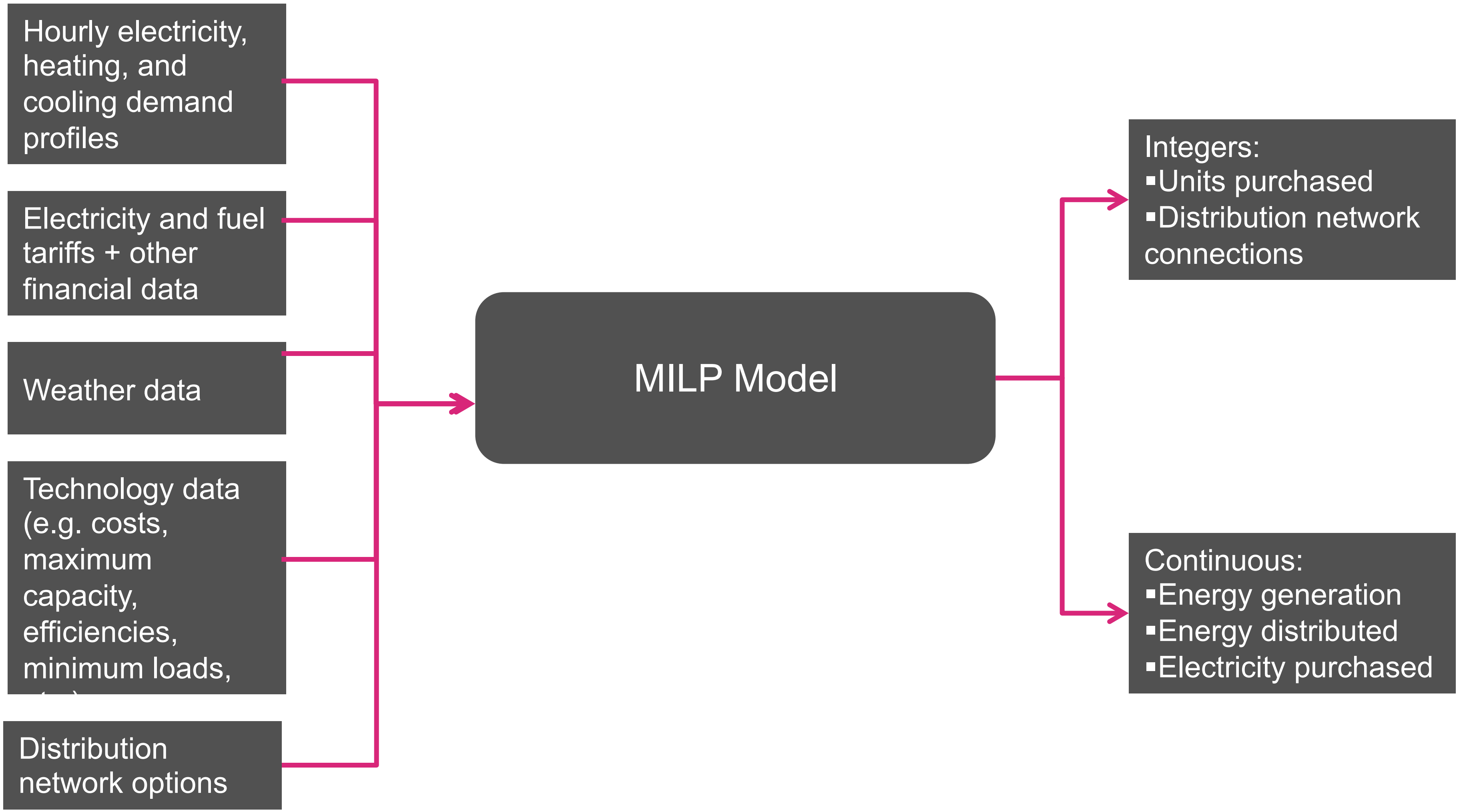


- **Nodes**: Sites of energy generation and/or consumption
- **Arcs**: Flow of energy between the nodes
- Model objective: **Minimise annual cost, primary energy consumption, CO_2 emissions, etc.** by
  - Determining the optimal characteristics of each generation node
  - Identifying the set of active arcs between generation and consumption nodes, and the amount of energy that is distributed along each arc during each time period.

Optimisation Methods



Model Inputs and Outputs



Energy Hub Formulation

MINIMISE

Investment and Operation Cost =

Fuel purchase costs
+ Electricity purchase costs
+ Operational and maintenance costs
+ Technology capital and installation costs
+ Technology retirement costs
+ Distribution network costs
– Electricity sell back revenue
– Energy subsidy revenue

SUBJECT TO

Technology Availability
Technologies can only be used if they are in the set of purchased technologies

Operational Constraints
All technologies must operate within their installed capacity limits

Energy balance
Electricity purchased plus energy generated must equal energy demand in each time period

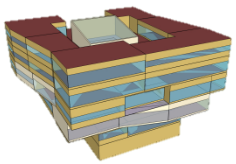
Energy Distribution
Energy distribution from generation sites is bounded by the total amount of energy generated by all technologies at that site

Distribution Network Structure
Energy distribution is to buildings that are connected by the distribution network

Stakeholder Preferences
Specific technologies can be precluded or permitted for the optimal energy system depending on stakeholder preferences

Environmental Targets
Annual CO_2 emissions must be less than or equal target values

Energy Hub Implementation

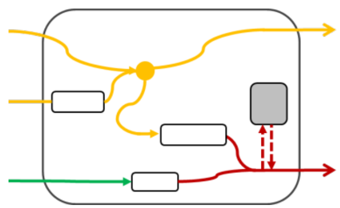


Energy demands from building simulation

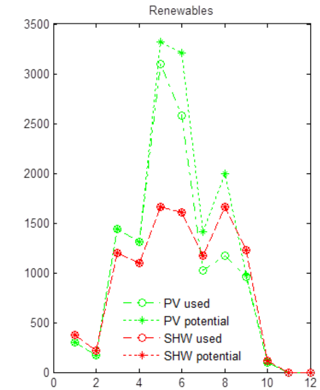
Plant options and performance characteristics

Energy availability from renewables simulations

Energy hub model



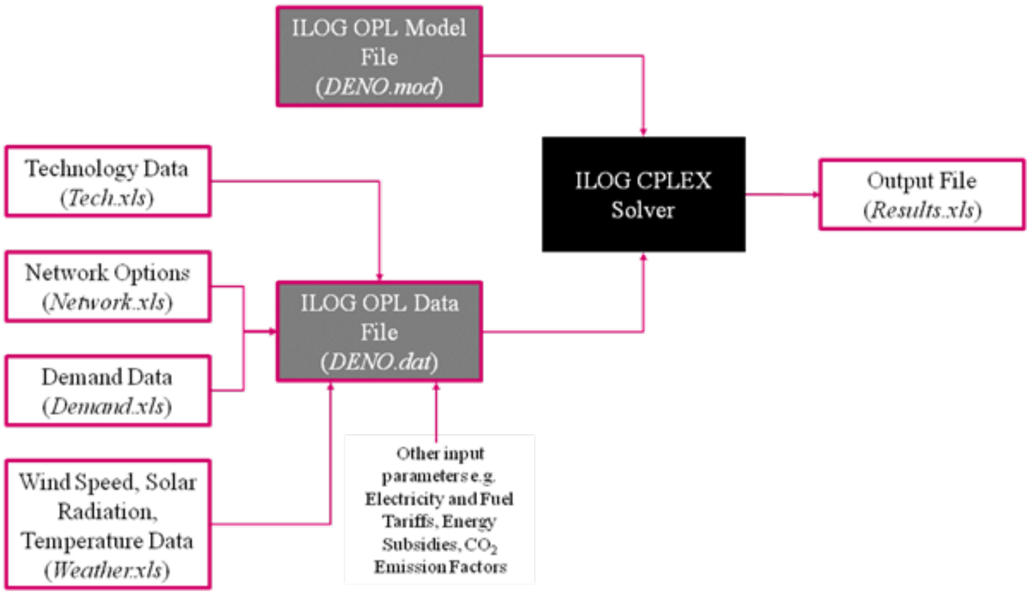
IBM ILOG CPLEX

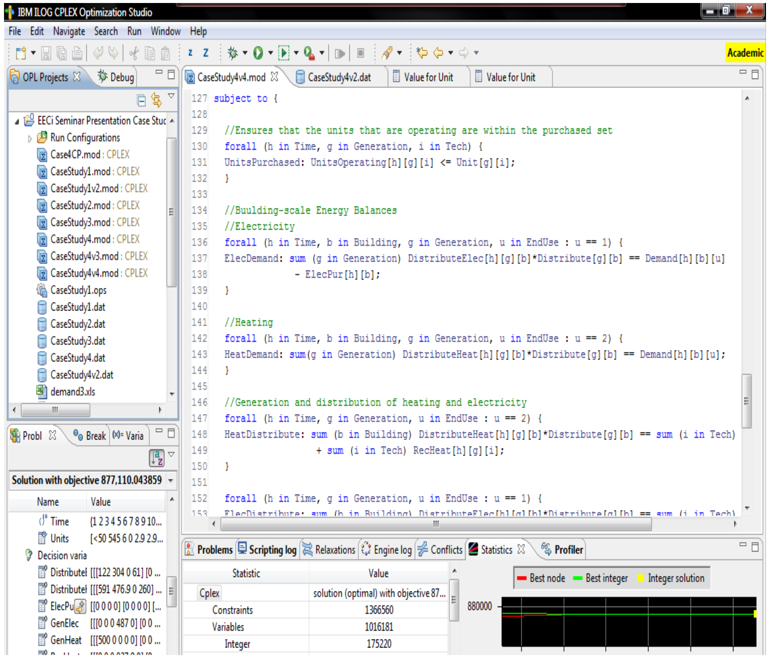


Optimal system design and operation schedules

Energy use & carbon emissions

IBM ILOG CPLEX Optimisation Studio





- The ILOG CPLEX is a commercial optimisation software program that uses the CPLEX solver
- Model is based on set algebraic equations that detail the objective function and equality and inequality constraints
- CPLEX solver uses a branch and cut algorithm to solve MILP

Energy Hub – Benefits and Limitations

Benefits

- Integrated analysis of technologies
- Able to test a large set of technologies
- Analysis of multiple energy carriers
- Optimisation of energy distribution network
- Temporally and spatially scalable
- Can output intermediate technology installation capacities for long-term phased developments

Limitations

- Linear requirement
- Very simplified technology models

Energy Hub Applications

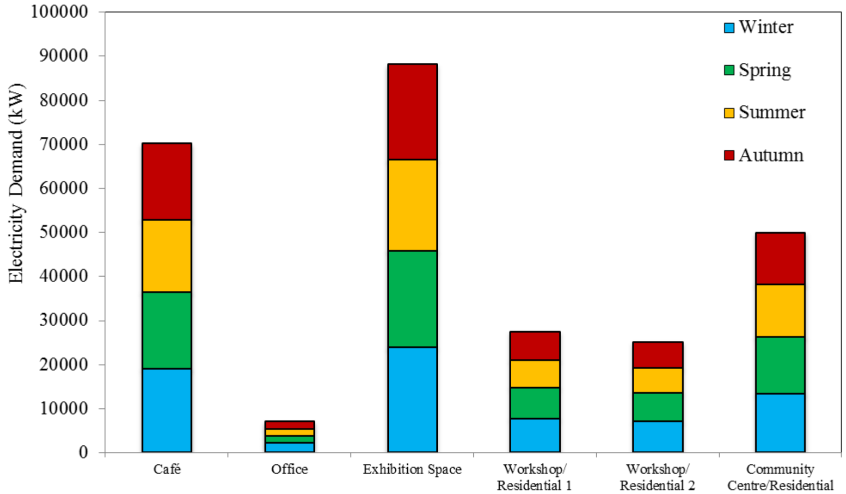
1. **Energy system and network optimisation**
   - What technologies should be installed? Where? How should the generated energy be distributed?

2. **Impact of exogenous variables (e.g. energy subsidies, grid carbon intensity)**
   - What impact do subsidies have on technology selection and economic performance?
   - Can the carbon intensity of the national grid influence the energy planning decisions that are made at the district level?

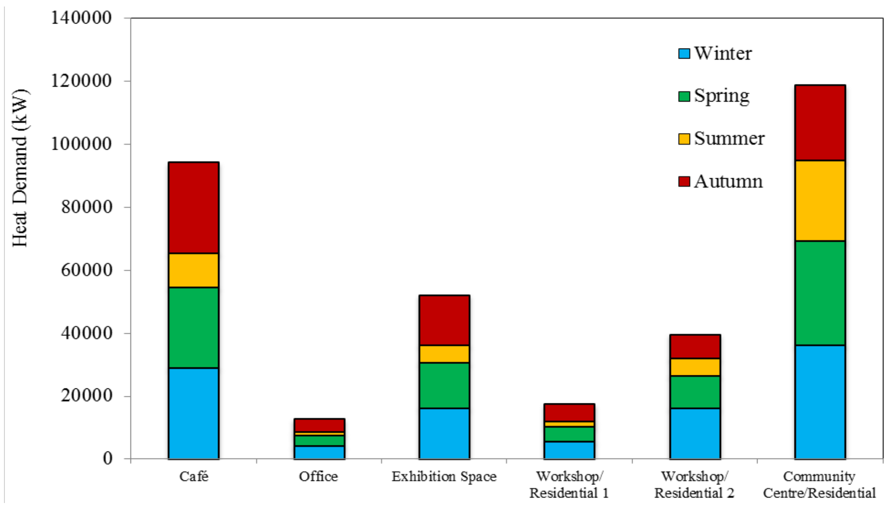
3. **Long-term energy planning**
   - When should DER technologies be installed during phased construction of a new development?

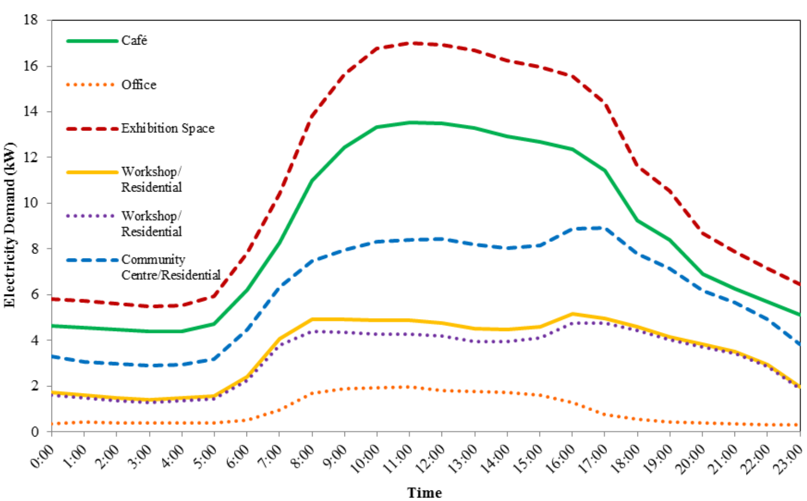
4. **Environmental impact**
   - What are the other environmental impacts of distributed energy systems (e.g. degradation of local air quality)? And how do they influence the overall impact of these energy systems?

Case Study 1 – Site in Cornwall, England

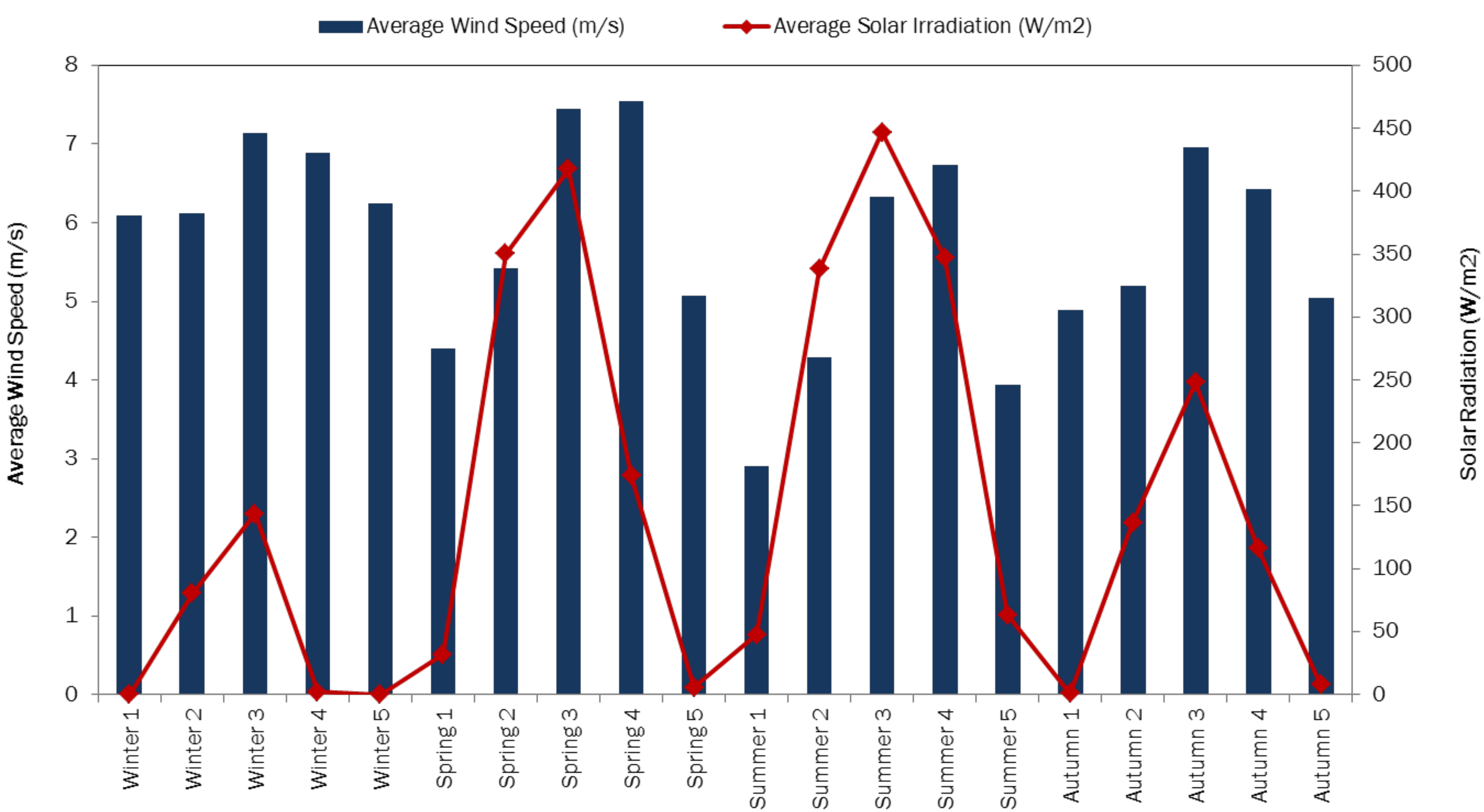


- Highest Electricity Demands:
  1. Exhibition Space
  2. Cafe
  3. Community Centre/Residential
- Highest Heat Demands:
  1. Community Centre/Residential
  2. Cafe
  3. Exhibition Space





Available Solar and Wind Energy



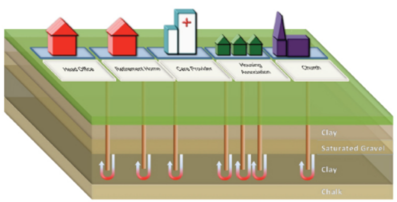
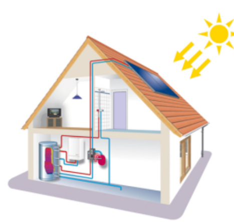
Heartlands District Energy System Analysis

1. Impact of Distributed Energy Resources
   - Technology Selection
   - Distribution Network Structure
2. Influence of Energy Subsidies







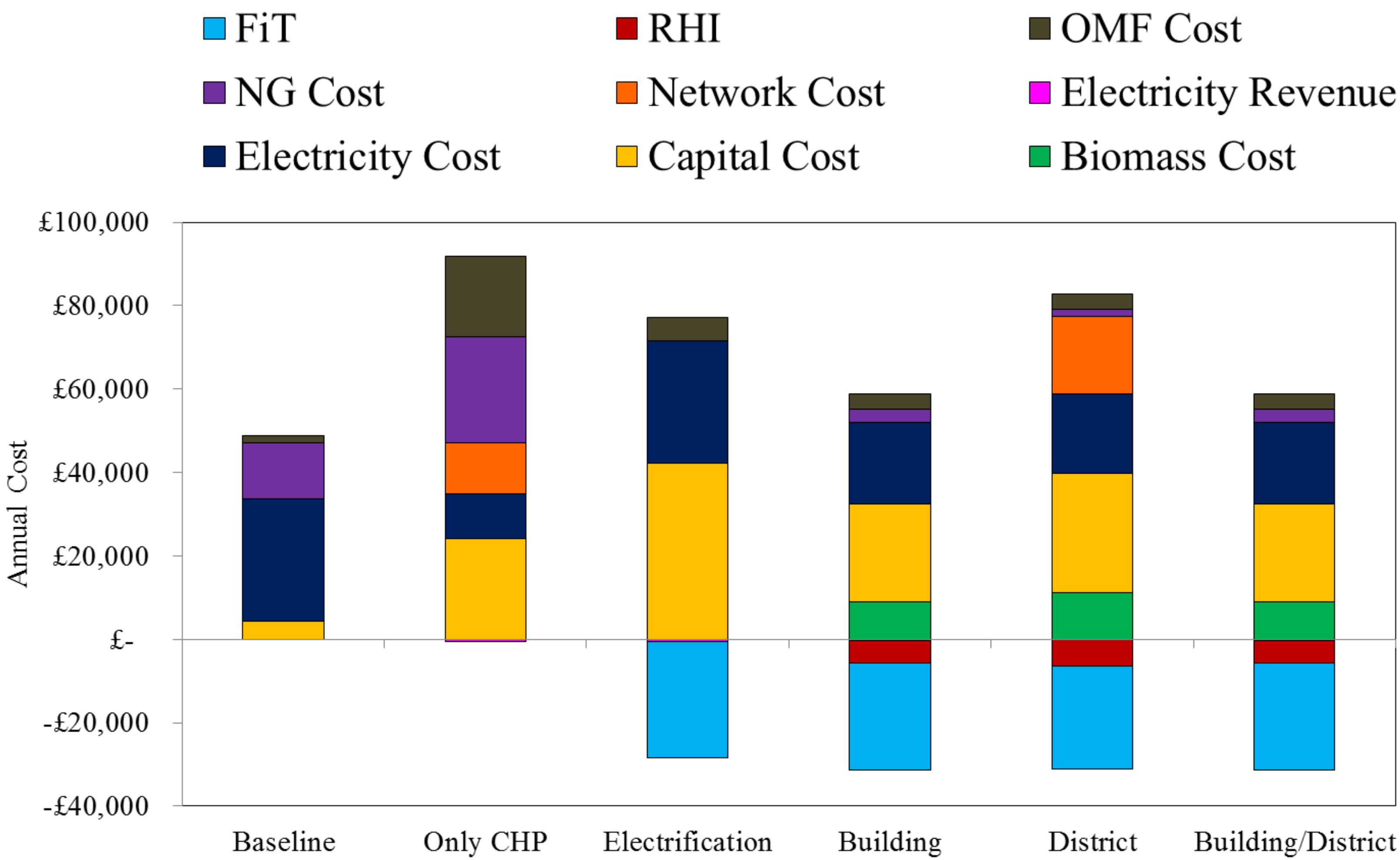

Scenarios

Scenario	Description
1	**Baseline** - Conventional energy generation. Electricity purchased from the national grid and heat generated locally by natural gas boilers
2	**CHP Only** – Distributed energy system that only consists of combined heat and power technologies
3	**Electrification** – Distributed energy system that only consists of non-combustion technologies
4	**Building level generation** – Distributed energy system with any technology, but no distribution between buildings is allowed
5	**District level generation** – Distributed energy system with any technology, but generation can only take place at one location
6	**Building/District generation** – Distributed energy system with any technology, and generation can at any building with distribution between buildings

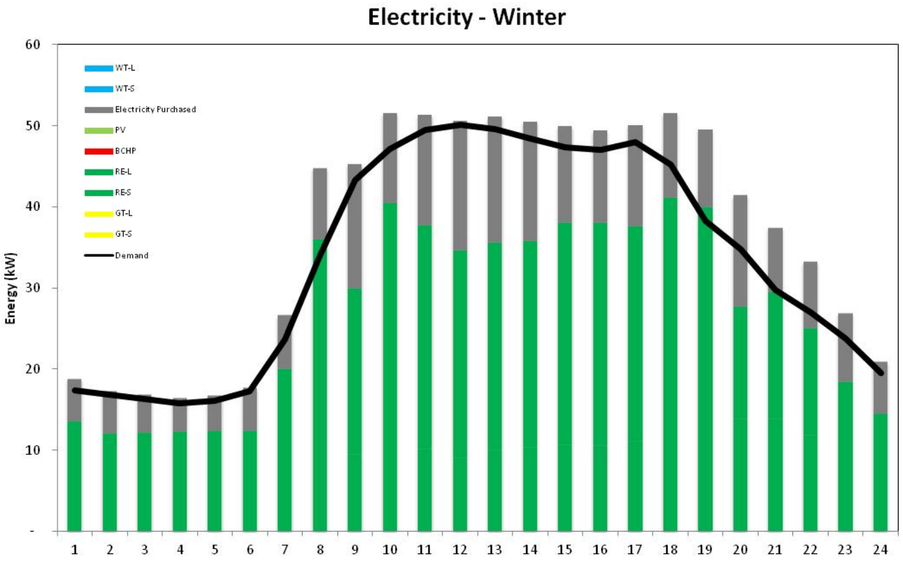
Model Outputs

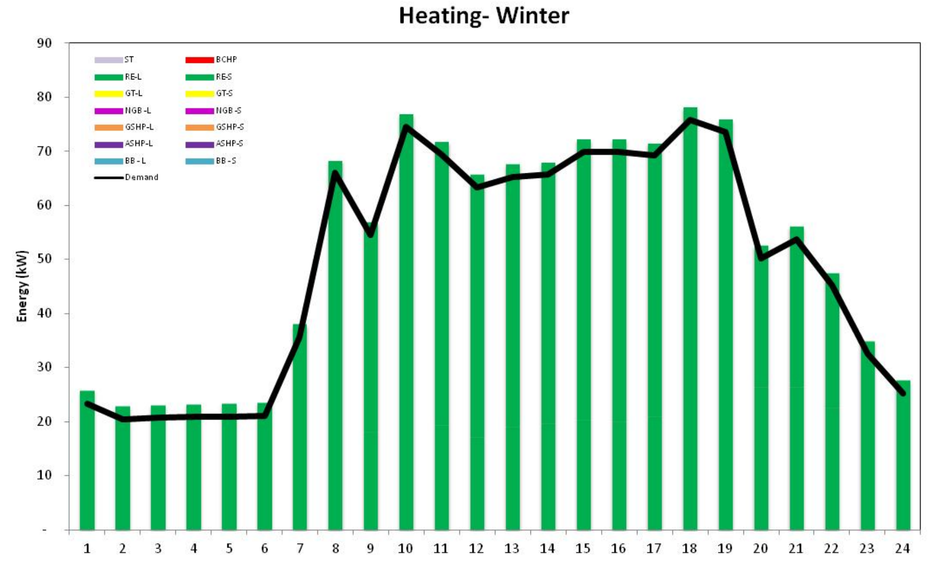
Scenario	Installed Capacity	Objective Function (Annual Cost)	Emissions Change from Baseline	Share of Energy Generation from Renewables
Baseline	NGB: 690 kW	£48,662	NA	0%
CHP Only	RE: 240 kW	£91,225	-6.5%	0%
Electrification	WT: 60 kW GSHP: 50 kW ASHP: 580 kW	£54,046	-36%	16%
Building	WT: 60 kW BB: 150 kW NGB: 480 kW	£29,101	-50%	66%
District	WT: 80 kW BB: 60 kW NGB: 530 kW	£47,980	-53%	70%
Building/ District	WT: 60 kW BB: 150 kW NGB: 480 kW	£29,101	-50%	66%

Breakdown of Annual Cost



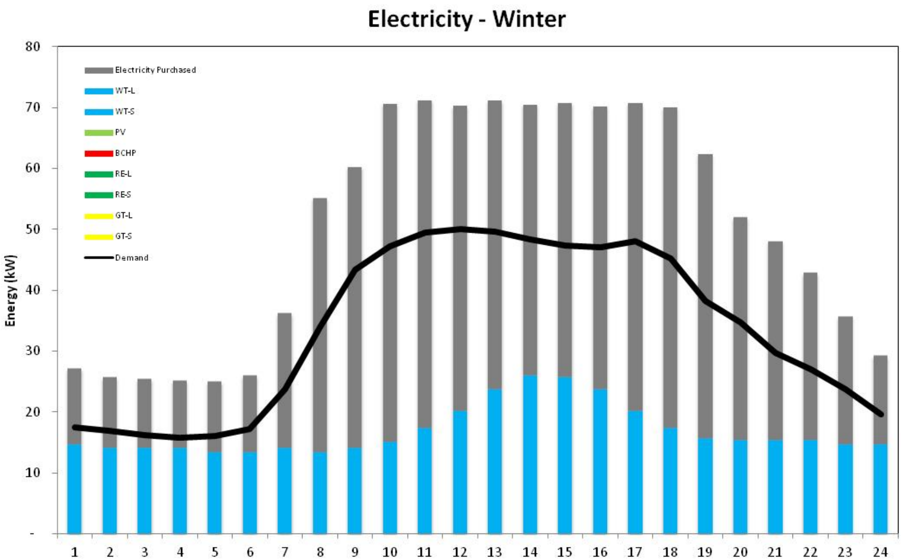
Scenario 2 – CHP Only

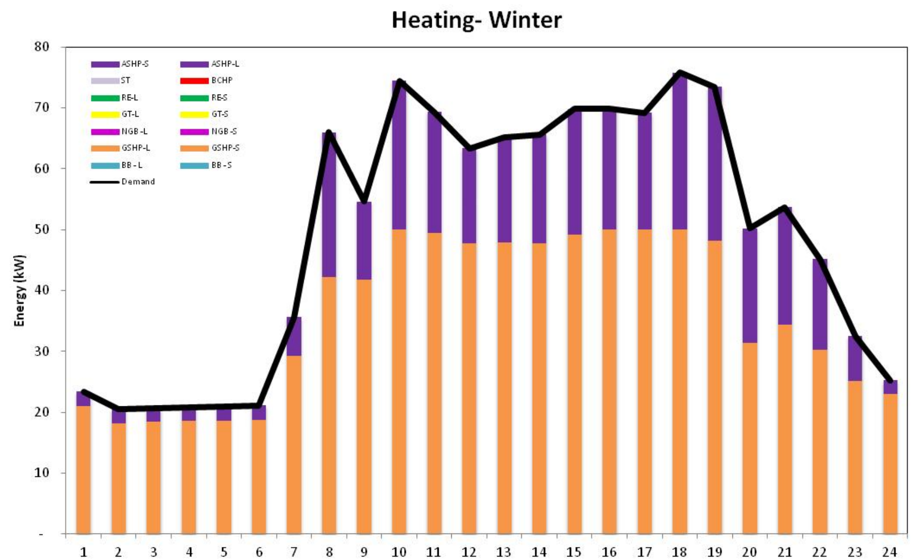




- Electricity and heat provided by heat-led gas engine CHPs at buildings Exhibition Space and Community Centre
- Slight excess heat generation is due to distribution losses (6%)
- Excess electricity is generated in order to produce the required heat (sold back to the grid)
- Some buildings (Office and Workshop 1) are not connected to the CHP systems in the Community Centre, and thus must buy all their electricity from the grid

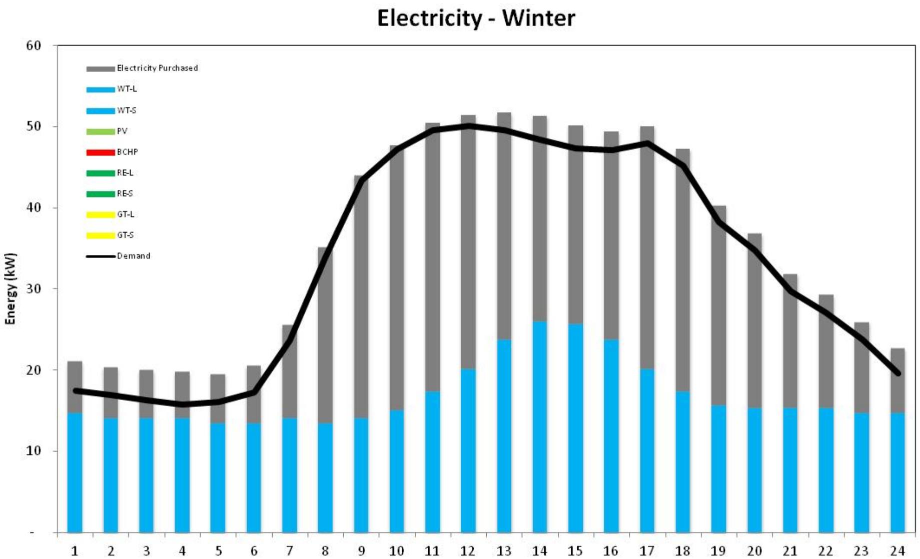
Scenario 3 - Electrification

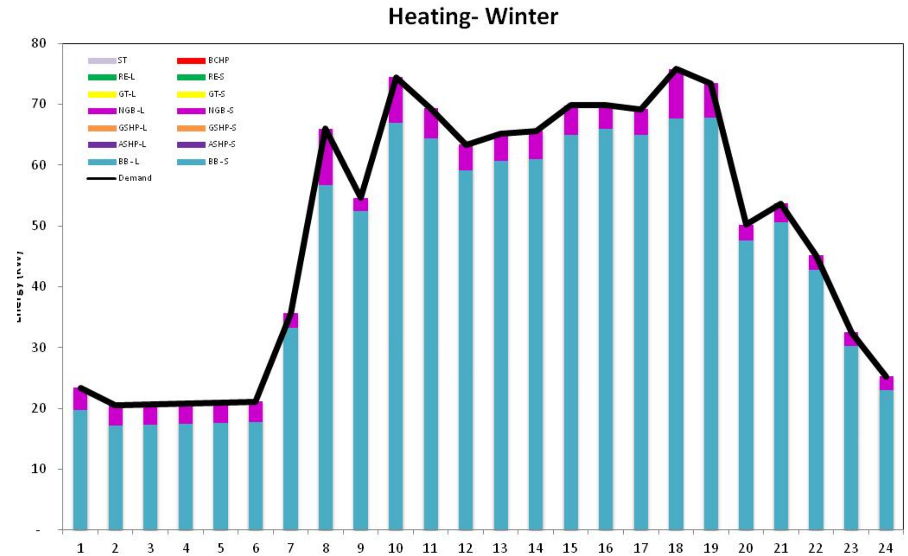




- Electricity from small wind turbines
- Ground source heat pumps supply baseload heat and air source heat pumps provide the peak heat
  - Apart from at the Office and Workshop 1 (which have the lowest heat demands) where all the heat is generated by ASHP

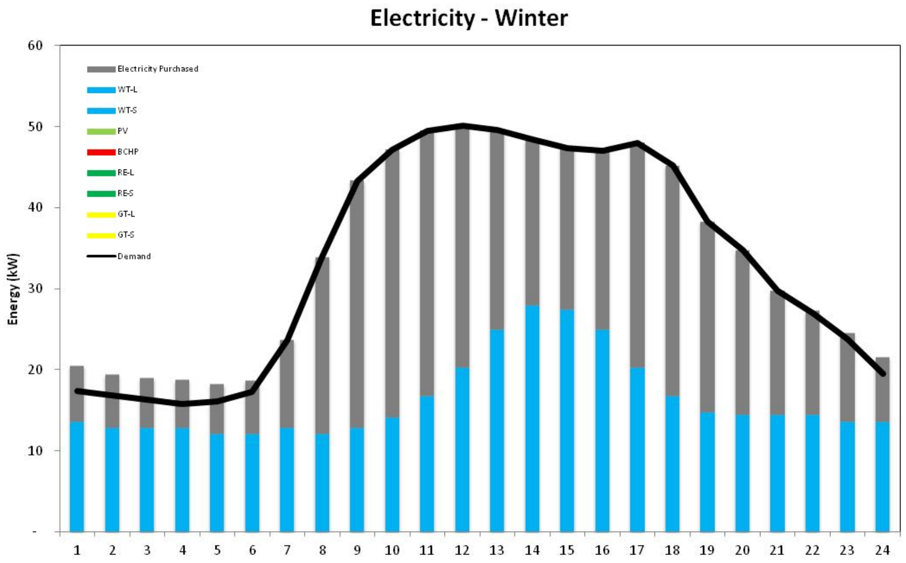
Scenario 4 - Building Level Only

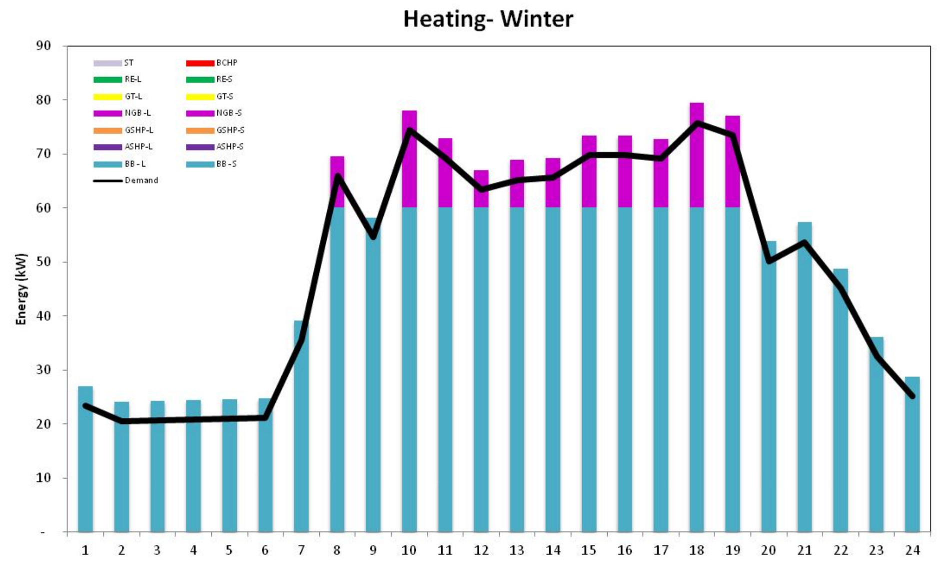




- Small scale wind turbines and grid supply the electricity
- Biomass boilers and natural gas boilers at each building supply the heat
- Excess electricity is sold back to grid
  - Excess electricity at the Office building where the electricity demand is so low that even the smallest wind turbine (10 kW) supplies more electricity than is demanded

Scenario 5 - District Level Only





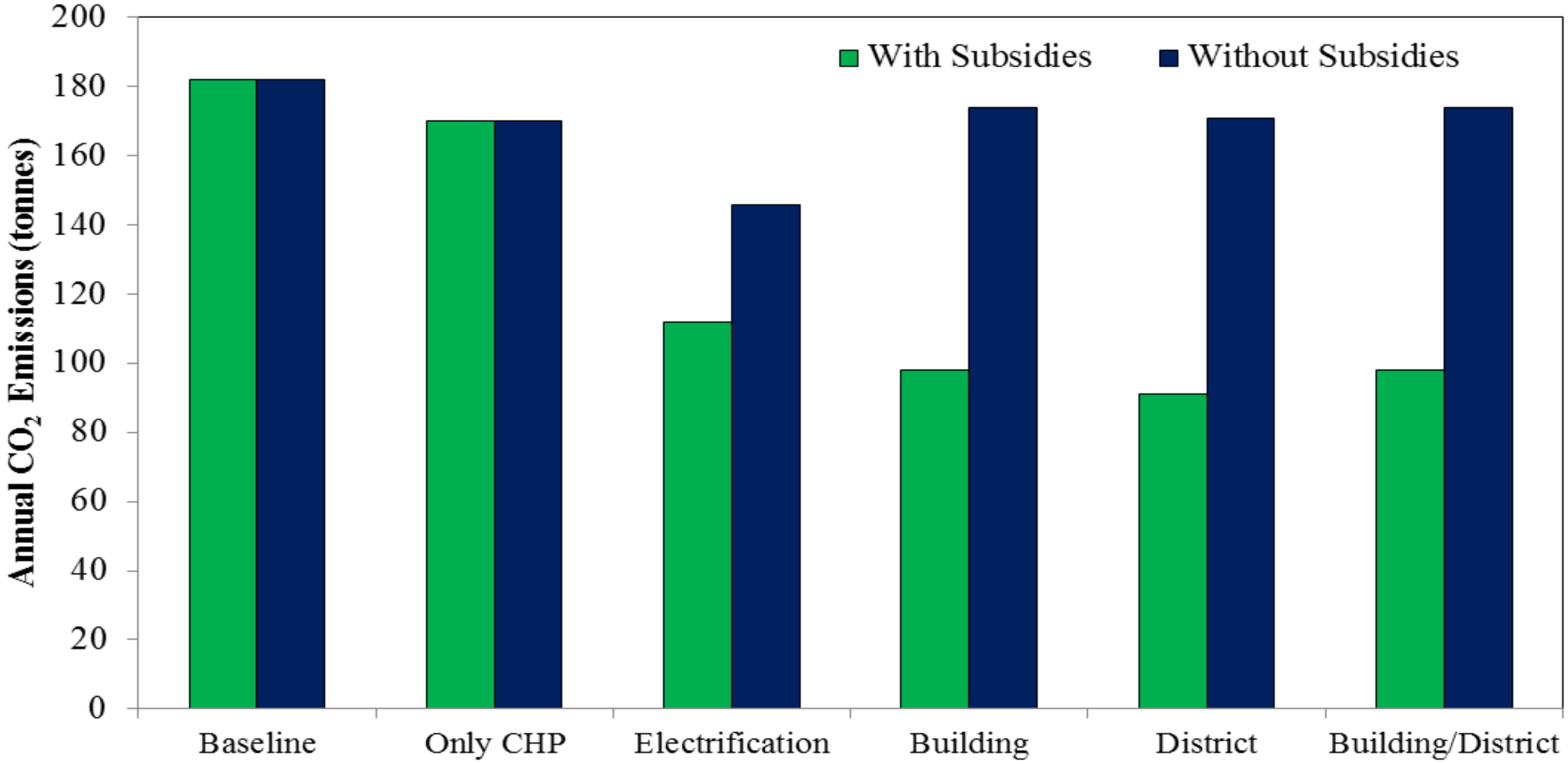
- Electricity supplied from a single 80 kW wind turbine, or purchased from the grid
- Biomass boiler for baseline and natural gas boiler to meet the peak heat demand
- Excess electricity is sold back to grid

Energy Subsidies

Scenario	Installed Capacity (with subsidies)	Installed Capacity (without subsidies)
Baseline	NGB: 690 kW	NGB: 690 kW
Only CHP	RE: 240 kW	RE: 240 kW
Electrification	WT: 60 kW GSHP: 50 kW ASHP: 580 kW	ASHP: 450 kW PV: 192 m^2
Building	WT: 60 kW BB: 150 kW NGB: 480 kW	RE: 20 kW NGB: 630 kW
District	WT: 80 kW BB: 60 kW NGB: 530 kW	RE: 20 kW NGB: 610 kW
Building/District	WT: 60 kW BB: 150 kW NGB: 480 kW	RE: 20 kW NGB: 630 kW

- Subsidies encourage investment in biomass boilers and GSHP
- What is the impact on CO_2 emissions?

Energy Subsidies



Energy Subsidies

Scenario	Subsidy Pay-out	Reduction in emissions (tonnes)	Social Cost of emissions
Electrification	£28,008	34	£2,040
Building	£31,053	76	£4,560
District	£31,028	80	£4,800
Building/District	£31,053	76	£4,560

- Subsidy payouts are significantly higher than the cost of the emissions that they are saving

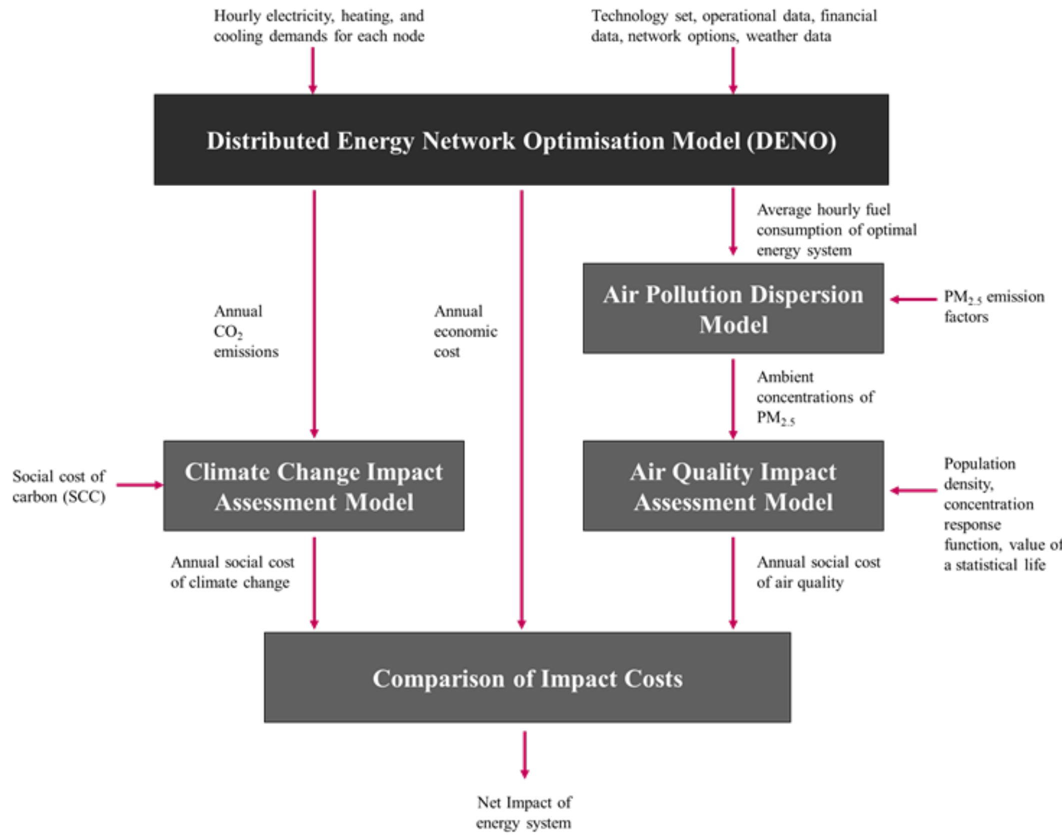
Conclusions

- Distributed energy systems can be cost-effective options for reducing CO_2 emissions
  - 50% reduction in annual CO_2 emissions, with 40% reduction in annual cost compared to baseline
- Imposing specific renewable technologies on a development does not necessarily lead to the most cost-effective, low carbon solution
  - CHP and heat pumps were not optimal for Heartlands, while boilers (biomass and natural gas) and wind turbines were
- District heat networks are not always the most optimal solution, especially for small areas. Extremely site dependent which highlights the value of integrated and flexible analysis tools
- Energy subsidies should be performance driven rather than technology driven

Air Quality Impact of Economically Viable Energy Systems

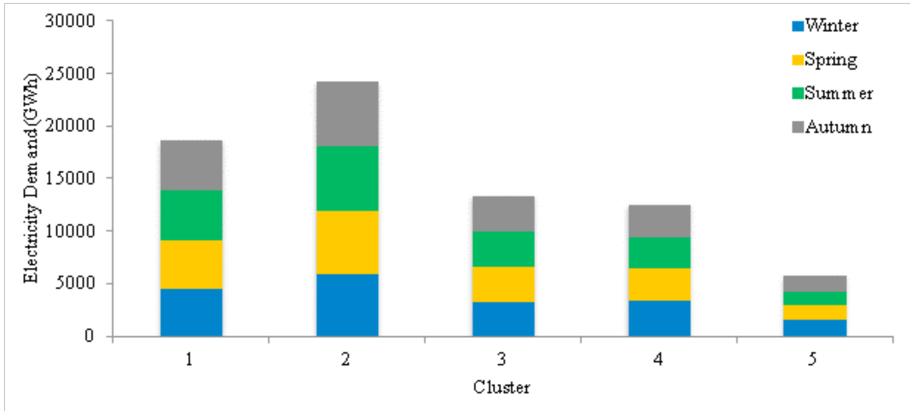
- Biomass Boilers are relatively cheap, renewable technologies
- However their economic feasibility does not take into account other environmental factors including the impact on local air quality
- Compared to gas boilers, biomass boilers can emit at least:
  - 3x NO_x
  - 10x Particulates
  - 20x SO_2
- Centralised biomass technologies facilitate more cost-effective management of air pollutant emissions through centralised particulate filters

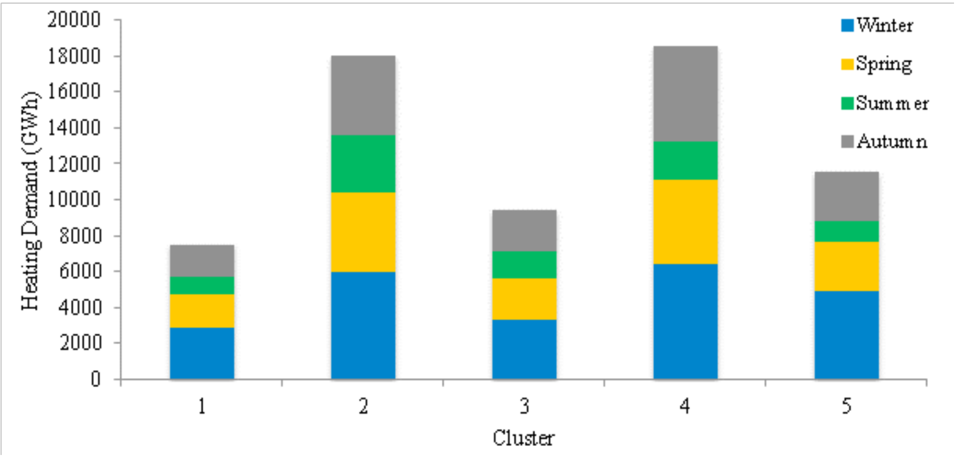
Case Study 2 – Integrated Environmental Assessment

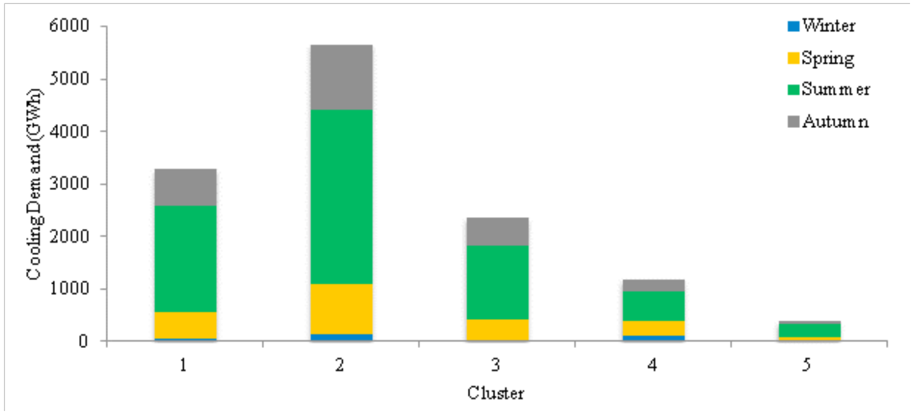


- The cost-benefit assessment framework is used to analyse distributed energy planning options for the area surrounding Paddington station in London, England.
- 75 buildings were identified in the area in the immediate vicinity of the station, bounded by the A40 motorway, Westbourne Terrace and the A4209.

Energy Demands



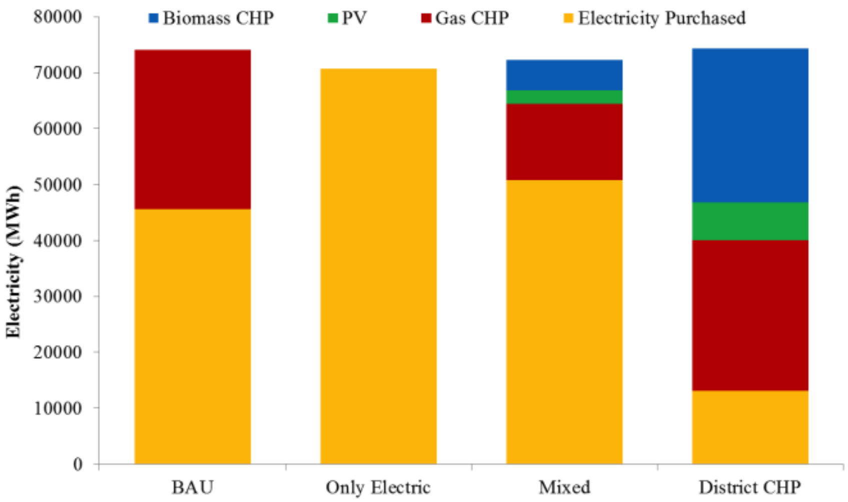


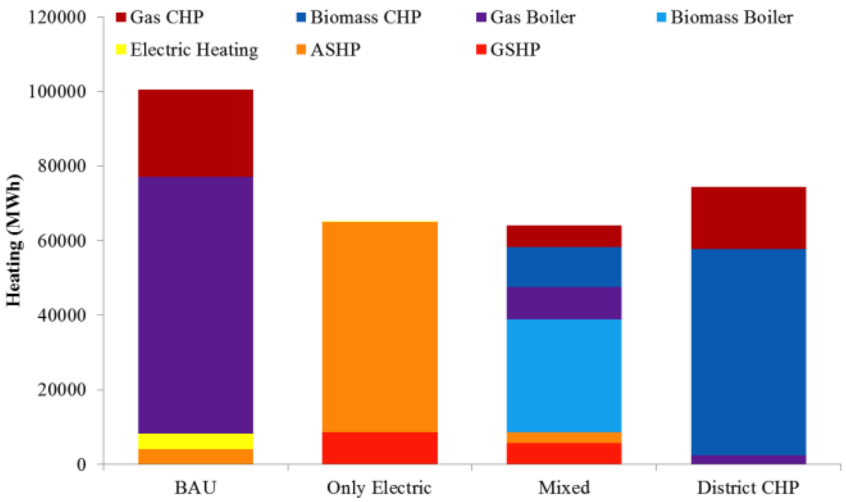


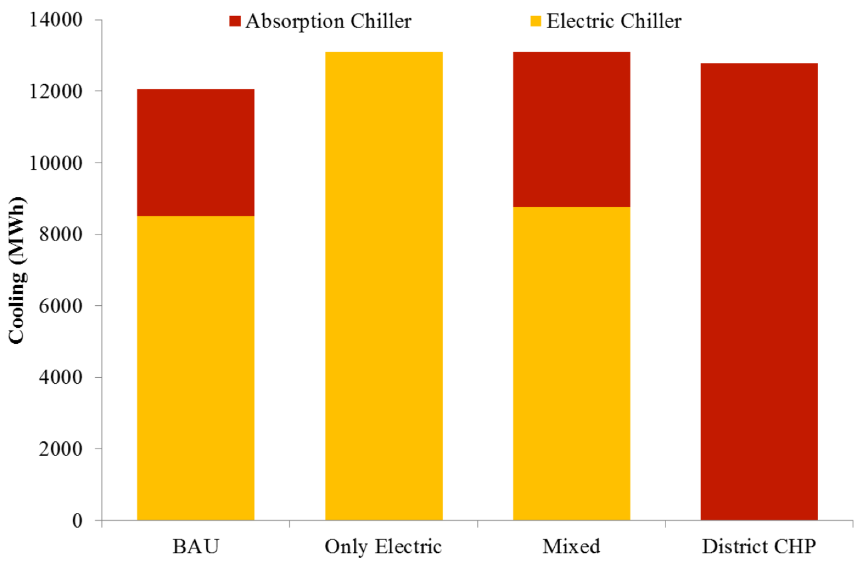
Scenarios

- **BAU** - Energy is supplied using the technology choices that are currently installed at each building
- **Only Electric** - Only heat pumps, electric chillers, electric heaters, PV, and solar thermal systems can be installed in the Paddington area, and the on-site combustion of fuel is not allowed.
- **Mixed** - The adoption level of electricity driven heat technologies is limited to the GLA's expected technology penetration for London by 2030, i.e. 8% of heat generated by GSHP and 4% of heat generated by ASHP.
- **District CHP** - No heat pumps, electric chillers, electric heaters, or solar thermal can be installed in the Paddington area. Only combustion technologies and PV are allowed. The space requirements of a district scale CHP system mean that only one district energy plant can be installed, and this plant is allowed to supply energy to the any of the clusters in the Paddington area.

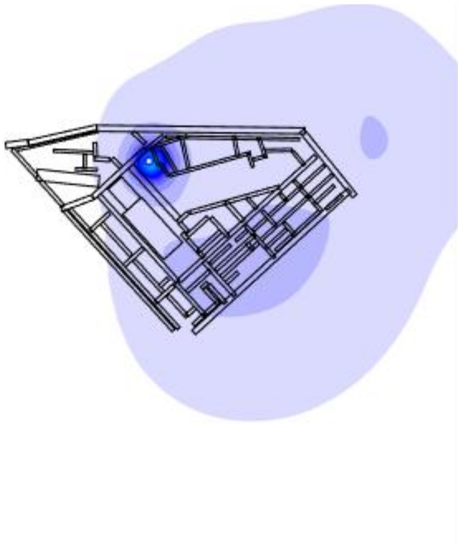
Results – Energy System





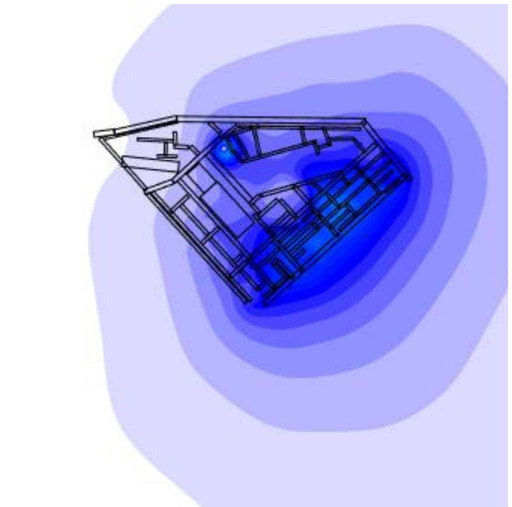


Results – Air Quality



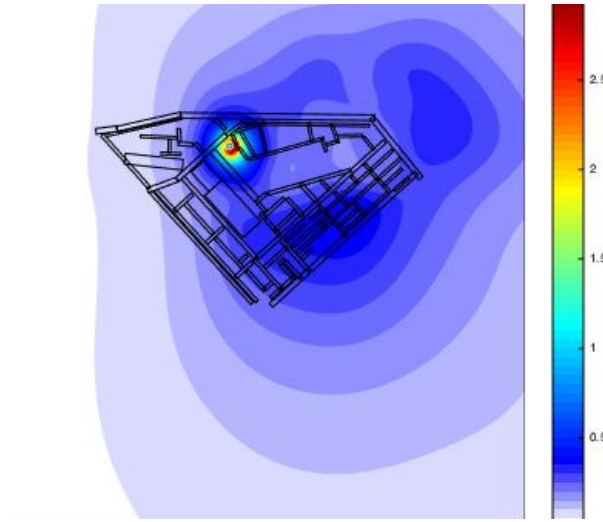
BAU Scenario

Peak pollutant concentrations occur in cluster 2, where the gas CHPs are located



Mixed Scenario

Peak $PM_{2.5}$ concentrations in the Mixed scenario are located in clusters 2 (due to the CHP units) and 5 (due to large number of biomass boilers)



District CHP Scenario

Peak ambient $PM_{2.5}$ concentration in the District CHP scenario is located in cluster 2, where the district biomass CHP plant is sited

Results – Total Emissions

Scenario	Annual Economic Cost (£ millions)	Annual CO_2 Emissions (kt)	Average $PM_{2.5}$ Emissions Rate (kg/s)
BAU	13.4	63.5	1.10×10^{-4}
Only Electric	14.2	54.1	0
Mixed	14.1	41.5	2.55×10^{-4}
District CHP	17.9	25.2	4.94×10^{-4}

	£ thousand			
Scenario	**Annual Economic Cost**	**Annual Social Cost of Climate Change**	**Annual Social Cost of Air Quality**	**Total Impact Cost**
BAU	13,400	906	5.72	14,312
Only Electric	14,200	772	0	14,972
Mixed	14,100	593	191	14,884
District CHP	17,900	359	179	18,438

Conclusions

- Compliance with future carbon targets will require significant decrease in energy demand, increase energy efficiency, and increase in utilisation of renewables
- This is a multi-scale problem and we cannot focus on buildings alone, and should also carry out analyses at the neighborhood and city scale
- Urban areas give rise to significant opportunities for system integration
- Energy hubs are a powerful tool that can handle this multi-scale analysis
- However it is important to look beyond just cost and CO2 emissions as there can be air quality implications of certain low carbon energy systems

THANK YOU. QUESTIONS?

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