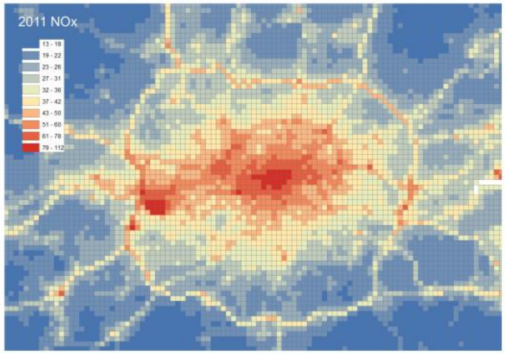
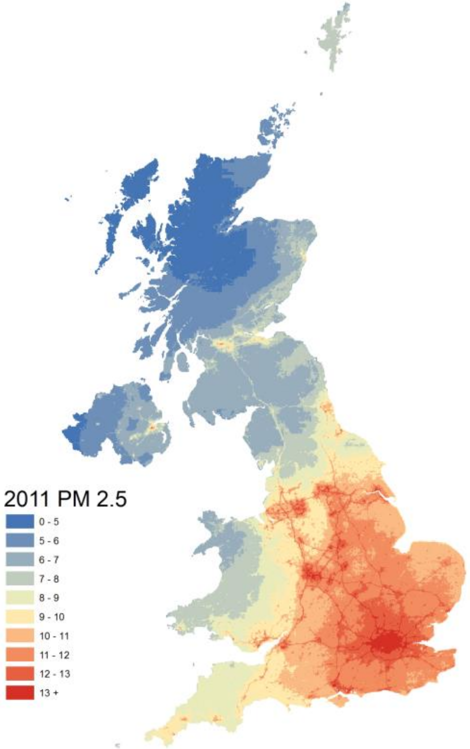


Modelling the effect of low carbon energy strategies on city air pollution

-a focus on fuel synthesis

Mark Barrett

UCL Energy Institute: EnergySpaceTime group



UNECE Air Convention (LRTAP) 4 th Expert Panel on Clean Air in Cities (EPCAC) 16 November 2022 (online)

Outline

Model flow

National energy scenario – Green Light

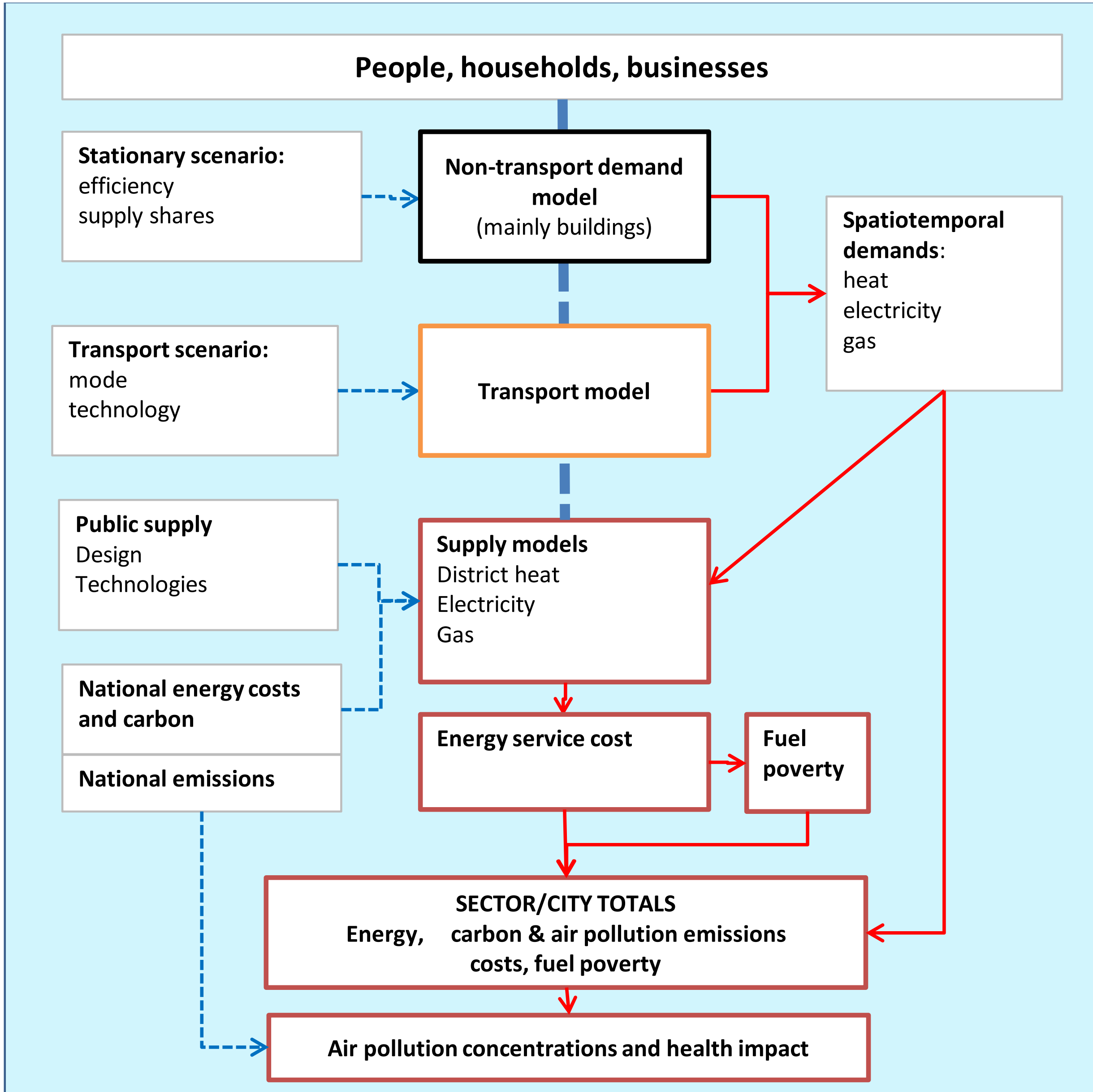
Energy and fuel synthesis related chemical flows

Scenario emissions

Modelling effect in cities

Apologies:
Data to calculate air pollution emissions from fuel synthesis inadequate

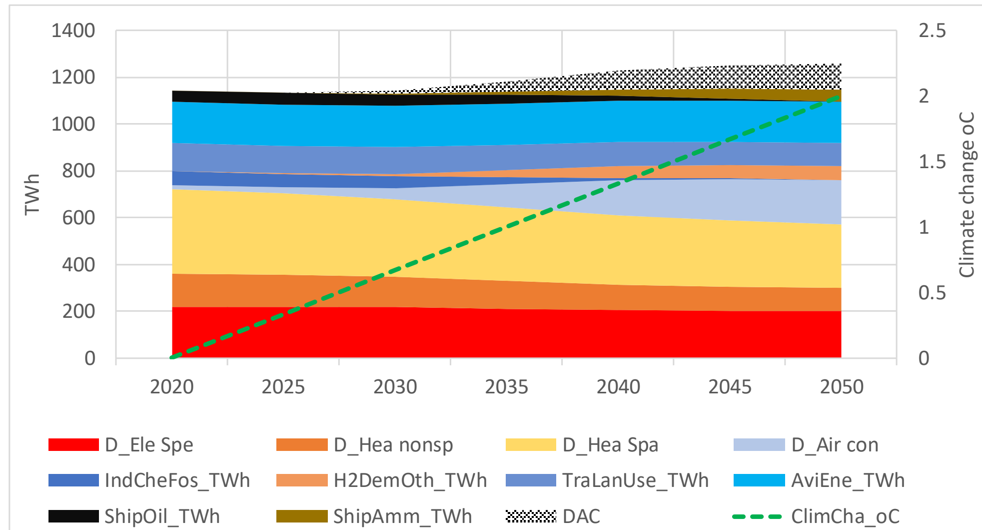
Model and data flow



Green Light transition - demands

- Heat demand decreases because of insulation
- Cooling demand increases because of insulation and climate change
- New demands of EVs, hydrogen, ammonia and DACS

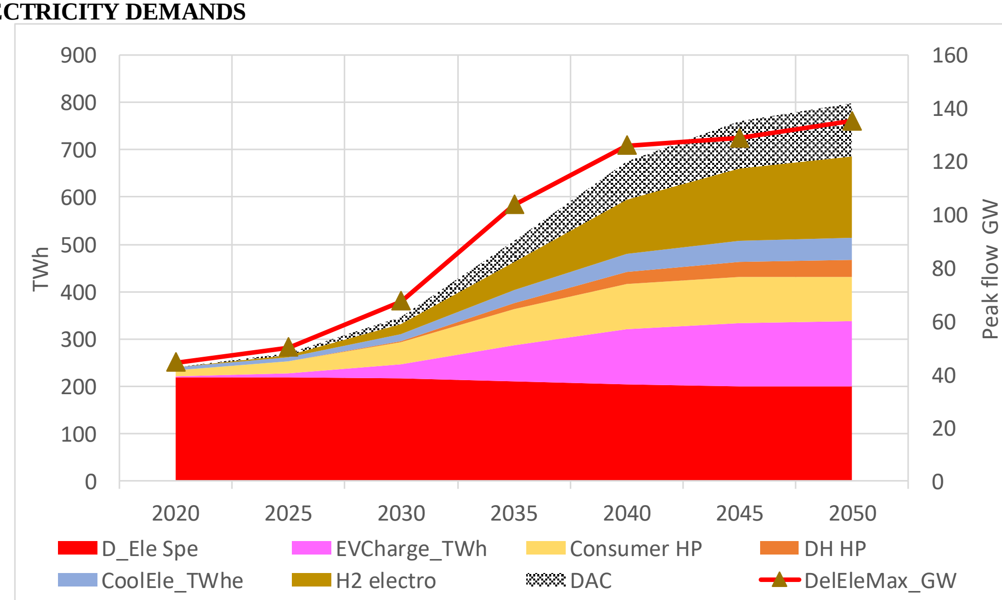
DEMANDS



Electricity demand increases from about 300 to 800 TWh.
Major increases:

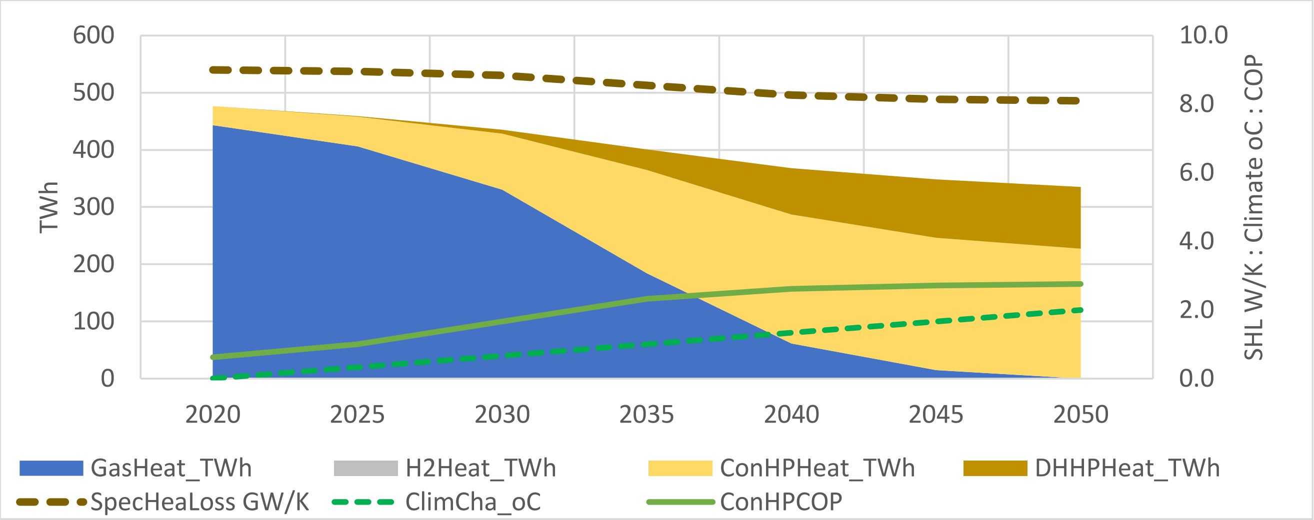
- EVs
- Electric heating and cooling
- Hydrogen
- Direct air capture (DAC)

ELECTRICITY DEMANDS

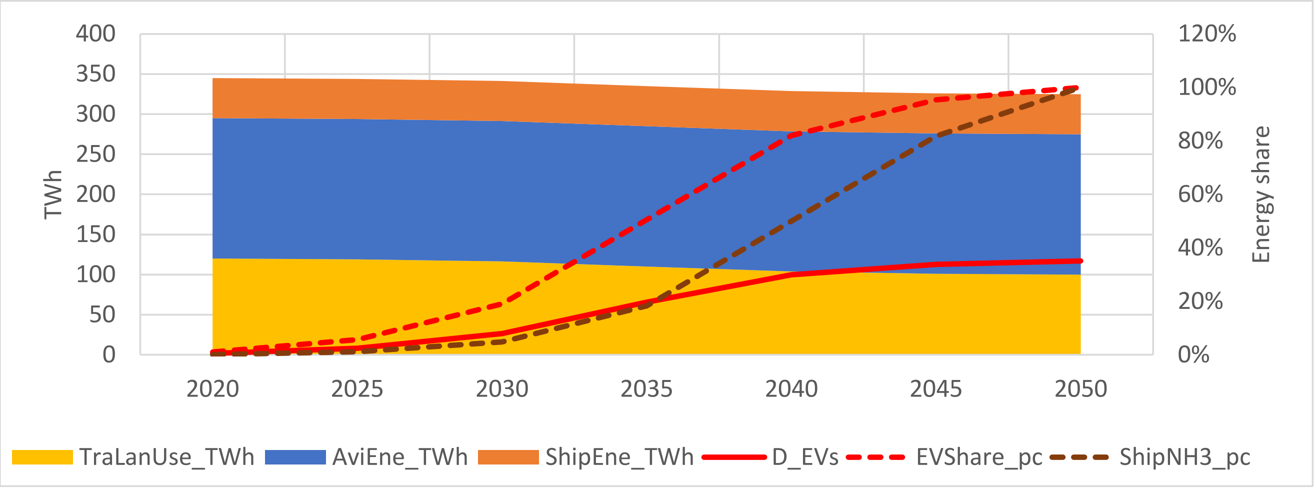


Green Light transition - demands

Heat
- Building efficiency
- Heat and cooling with heat pumps and district heating



Transport
- Land transport more efficient and all electrified
- Shipping fuel demand constant (efficiency gain equals growth) and transition to ammonia
- Aviation fuel demand constant constant (efficiency gain equals growth) and remains kerosene



Transition - electricity

2050

Renewable capacities and generation:

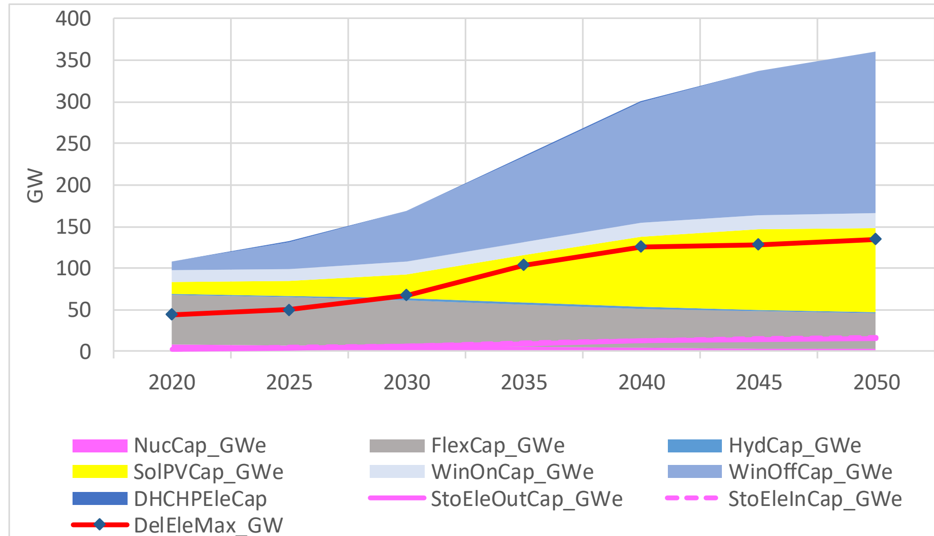
- Offshore wind 200 GW
- Onshore wind 20 GW
- Solar PV 100 GW
- Back up generator 40 GW

Nuclear declines to 3 GW (Hinkley C)

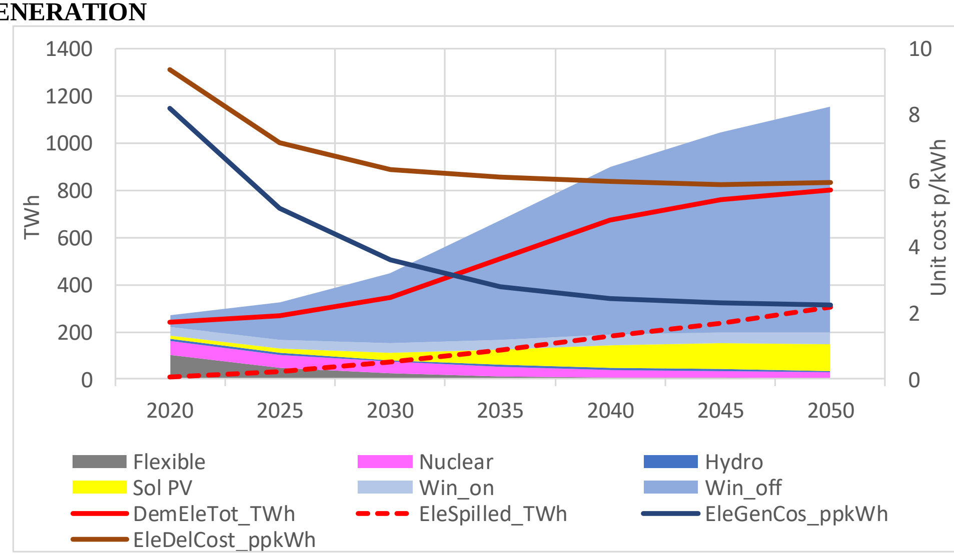
Storage

- Grid
- Hydrogen
- District heat

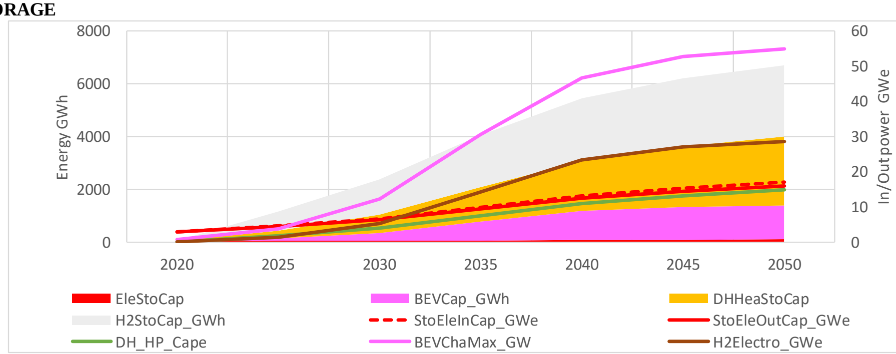
GENERATION CAPACITIES



GENERATION

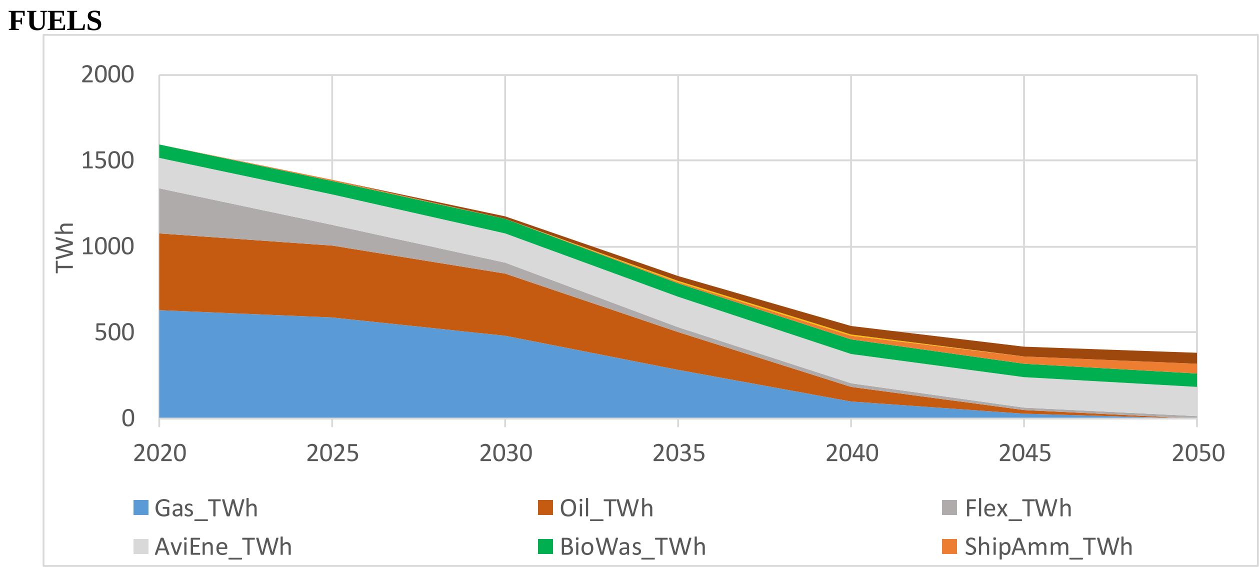


STORAGE

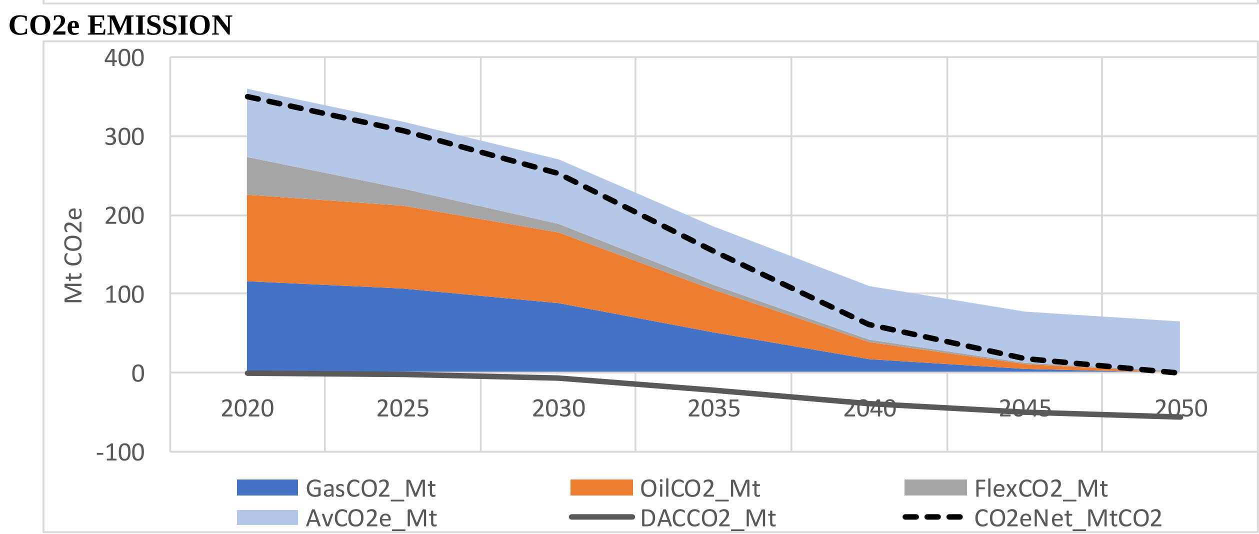


Transition – CO2e emission

Large scale fossil fuel use eliminated except for aviation fossil kerosene



Fossil kerosene CO2 and high altitude aviation warming balanced by 60 MtCO2 negative emissions with DACCS



What if renewable kerosene is made from biomass or atmospheric CO2 and 'green' hydrogen?

Air pollution change by source

Reduction in emission from most sources

Significant uncertainties with newer processes:

- Kerosene synthesis
- Ammonia production and use
- Hydrogen production and use
- Other impacts such as water and chemical inputs, land use

Spatial distribution:

- Location of industry and fuel production

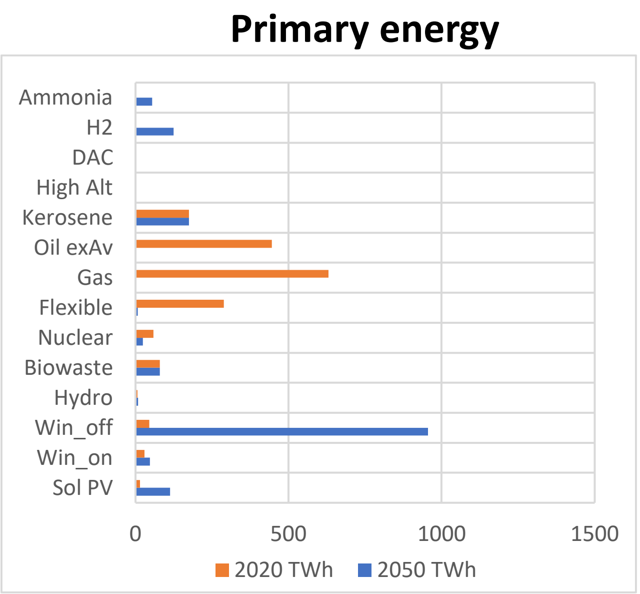
	2050 as compared to 2020 per unit of energy demand					
		PM	NOx	CO	VOC	Other
Buildings	All electric: indoor?	0	0	0	0	
Road and rail transport	All electric	10	0	0	0	
Aviation	Kerosene combustion	10	10	10	10	
Ships	Ammonia: ICE	0	?	0	0	
	Ammonia: fuel cell	0	?	0	0	
Industry	Hydrogen	0	?	0	0	?
	Processes with chemicals	?	?	?	?	?
	New products: batteries etc	?	?	?	?	?
Fuel production	Hydrogen	0	0	0	0	?
	Ammonia	0	?	0	0	?
	Kerosene	?	?	?	?	
	Biofuels	?	?	?	?	
Electricity generation	Renewable	0	0	0	0	
	Hydro	10	10	10	10	
	Nuclear	0	0	0	0	
	Peaking	1	1	1	1	
Bioenergy	Biowaste only	?	?	?	?	?
Negative emissions	Direct air capture	?	?	?	?	?

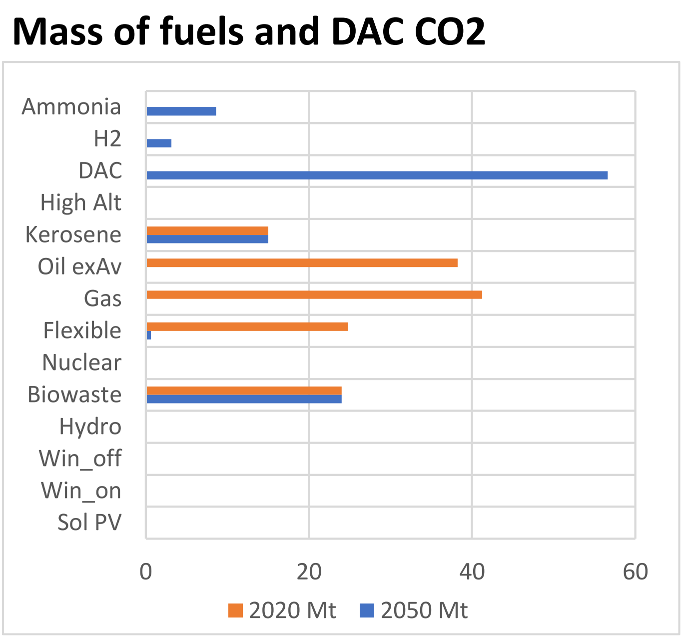
Chemical mass flows

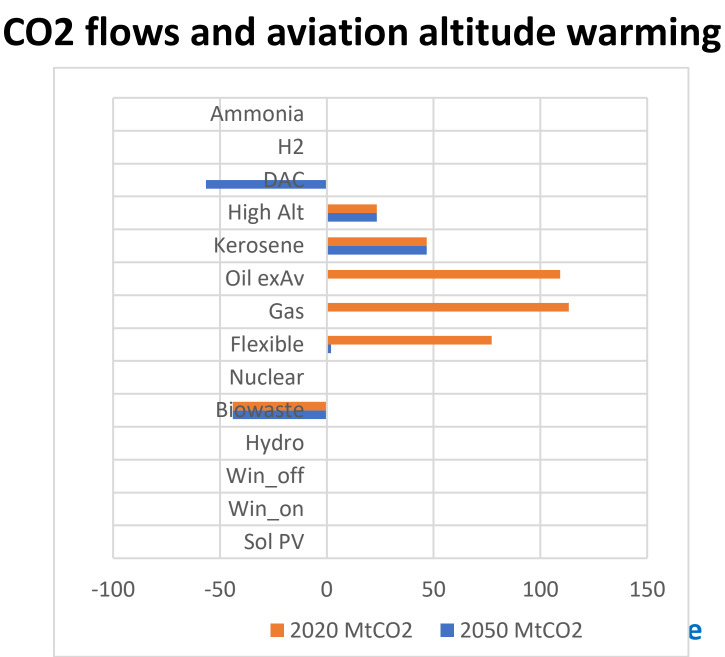
Replacing chemical fuels with renewable electricity.

2020
- 150 Mt of fossil fuels

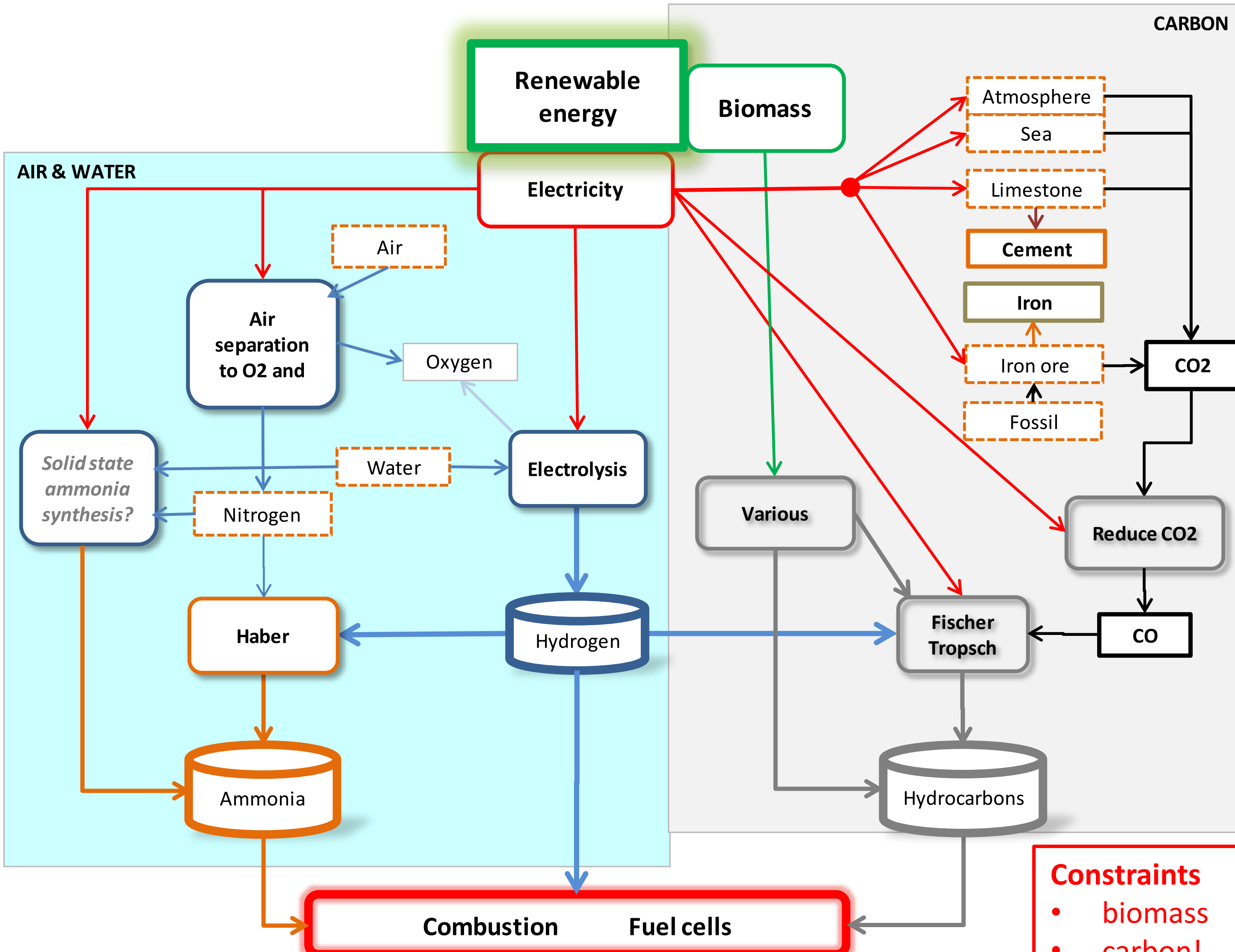
2050:
- fossil fuel is 15 Mt kerosene
- electrofuels - 6 Mt of H_2 and 9 Mt ammonia
- 65% reduction in mass of chemical fuels
- 57 $MtCO_2$ processed with DACCS
- **What if kerosene made from CO_2 and H_2?**







Renewable fuel pathways



Renewable input
- electricity
- biomass
- heat

Feedstocks
- air
- water
- Carbon
- biomass

Products
- hydrogen
- ammonia
- hydrocarbons

Constraints
- biomass
- carbon!

Aviation kerosene from biomass

1. Kerosene demand **15 Mt**
2. Assume no biocrops or biomass import; 300 PJ or **21 Mt** waste biomass
3. About **7 Mt carbon** for a maximum 8 Mt kerosene
4. Perhaps 60 % biomass suitable
5. Fischer Tropsch outputs maximum 70% kerosene
6. Perhaps **4 Mt of kerosene** or 25% of demand can be made from biowastes
7. Is this a good use of diffuse biowastes? What atmospheric emissions?

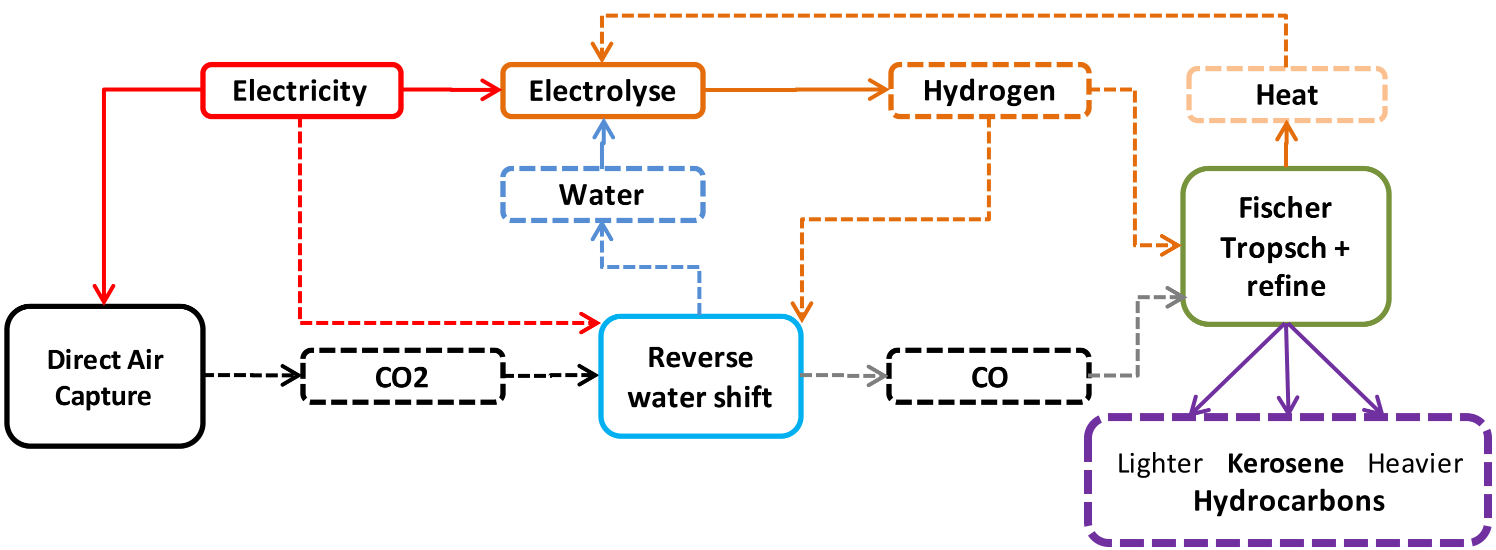
	Energy			Mass	Carbon		Max Ker	Suitable		Ker		Ker	Process ele	
Waste biomass	**PJ**	**TWh**	**GJ/t**	**Mt**	**%**	**MtC**	**Mt**	**%**	**MtC**	**FT prod**	**Mt**	**PJ**	**PJ**	**TWh**
Waste wood	11	3	13	0.8	30%	0.2	0.3	70%	0.2	70%	**0.1**	6	4	1
Wood	31	9	13	2.4	30%	0.7	0.8	70%	0.5	70%	**0.4**	17	13	3.6
Animal/anaerobic	73	20	13	5.6	30%	1.7	2.0	30%	0.5	70%	**0.4**	17	13	3.6
Plant biomass	128	36	12	10.7	30%	3.2	3.8	80%	2.6	70%	**2.1**	89	66	18.5
Sewage gas	21	6	50	0.4	75%	0.3	0.4	90%	0.3	70%	**0.2**	10	7	2.0
Landfill gas	49	14	50	1.0	75%	0.7	0.9	90%	0.7	70%	**0.5**	23	17	4.7
Other waste	0	0	10	0.0	30%	0.0	0.0	30%	0.0	70%	**0.0**	0	0	0.0
TOTAL	**312**	**87**		**20.9**		**6.9**	**8.1**		**4.7**		**3.9**	**162**	**121**	**34**
% UK 2019 kerosene consumption							**54%**		**31%**		**26%**			

Aviation kerosene synthesis

from renewable electricity, atmospheric CO2 and electrolytic hydrogen

For 15 Mt aviation kerosene

1. Absorb **50 M**t atmospheric CO2 with direct air capture (DAC) and **130 TWhe** electricity
2. Generate **4 Mt hydrogen** with **330 TWhe** renewable electricity
3. Produce syngas (**22 Mt CO** + H2) with hydrogen using reverse water shift
4. Input syngas to Fischer Tropsch to produce 70% **15 Mt kerosene** and **7 Mt other hydrocarbons**
5. **Total inputs 73 Mt chemicals and 460 TWhe total, or 221 TWh (25%) additional electricity**



Aviation and shipping fuels - what air pollution implications?

Aviation kerosene demand 15 Mt kerosene

Fossil kerosene + negative emission with DACCS:

40 Mt CO2 to balance fossil kerosene

20 Mt CO2 to balance high altitude warming always needed

Biowaste route: 10 Mt waste biomass for **4 Mt** kerosene (25% demand)

Atmospheric carbon route:

inputs 73 Mt chemicals, 460 TWhe total, or 221 TWhe (25%) additional electricity

Shipping oil demand 5 Mt: replace with ammonia

- 60 TWh energy
- **9 Mt** ammonia
- **8 Mt** nitrogen
- **2 Mt** hydrogen
- **90 TWh electricity**

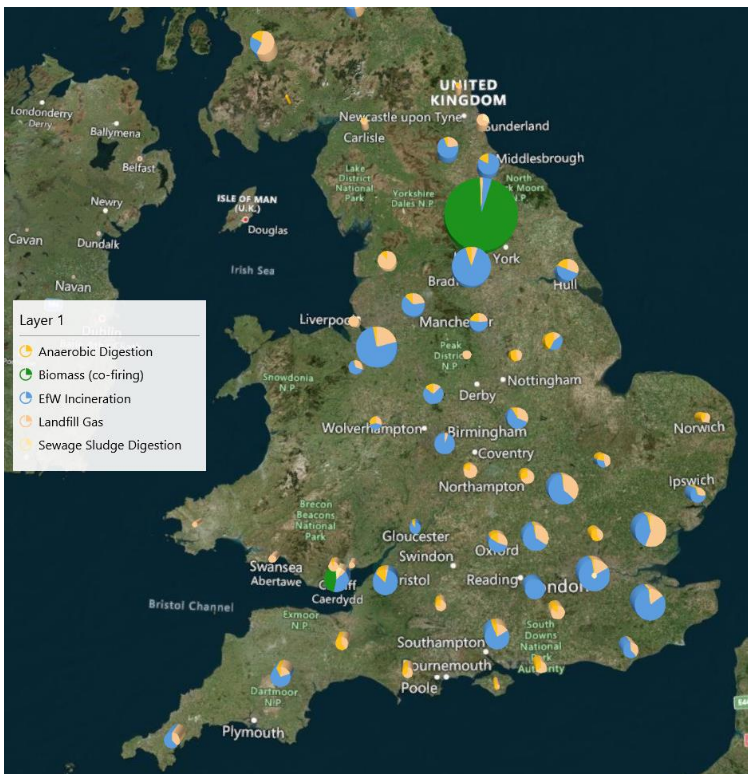
Aviation and shipping fuels 40 – 80 Mt chemical processing

- **0-10 Mt waste biomass**
- **20 Mt to 70 Mt CO2** from direct air capture
- **6 Mt of hydrogen**
- **8 Mt nitrogen**

Spatiotemporal emission pattern

How will patterns of energy demand and supply change and accompanying pollution emission?

UK biomass plant map

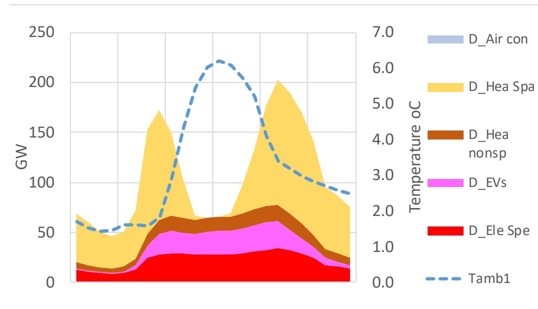


2050 operation

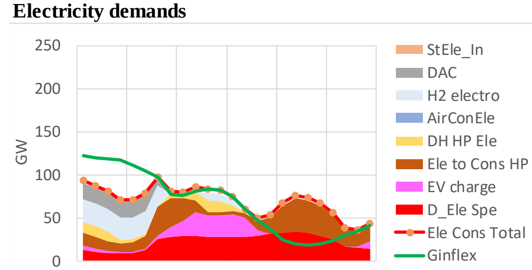
Winter

Day of year 51 February

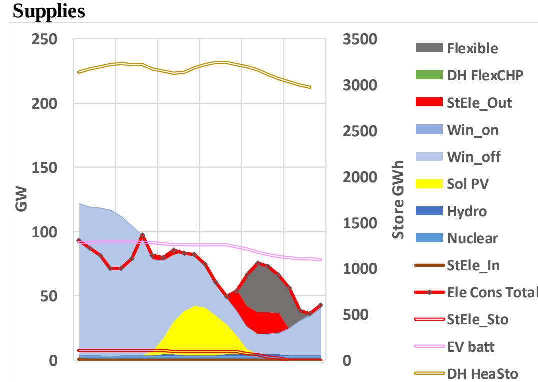
Demands



Electricity demands



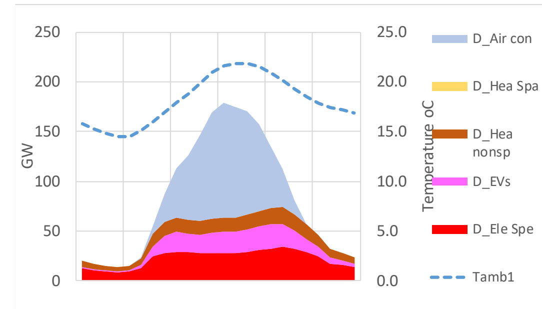
Supplies



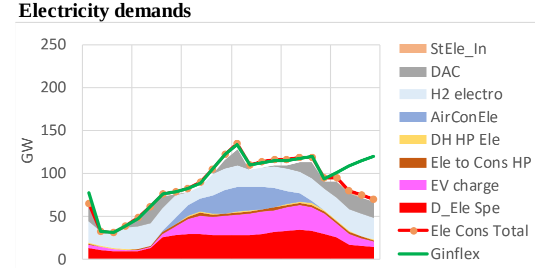
Summer

Day of year 194 July

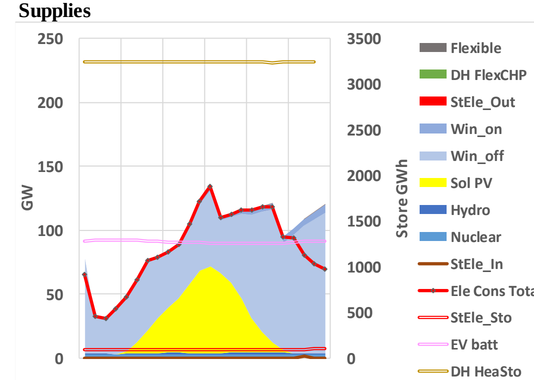
Demands



Electricity demands



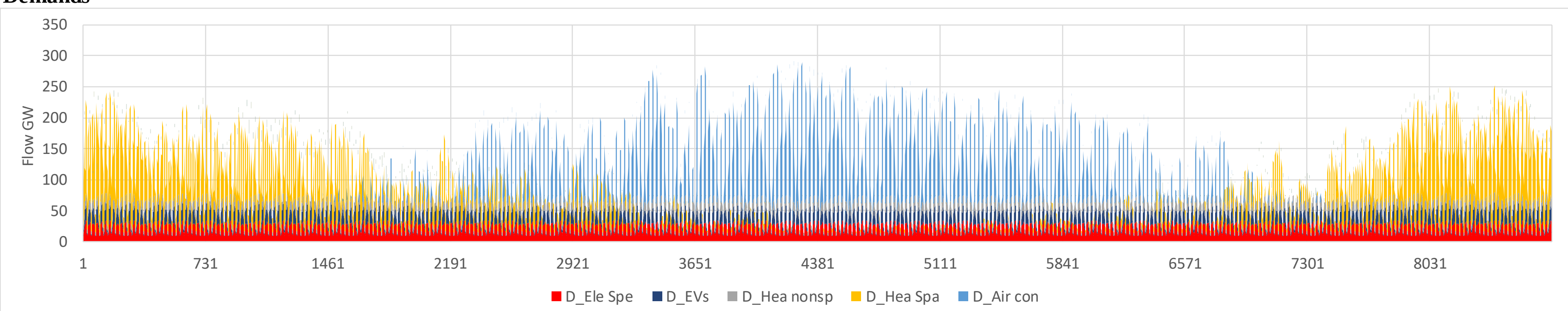
Supplies



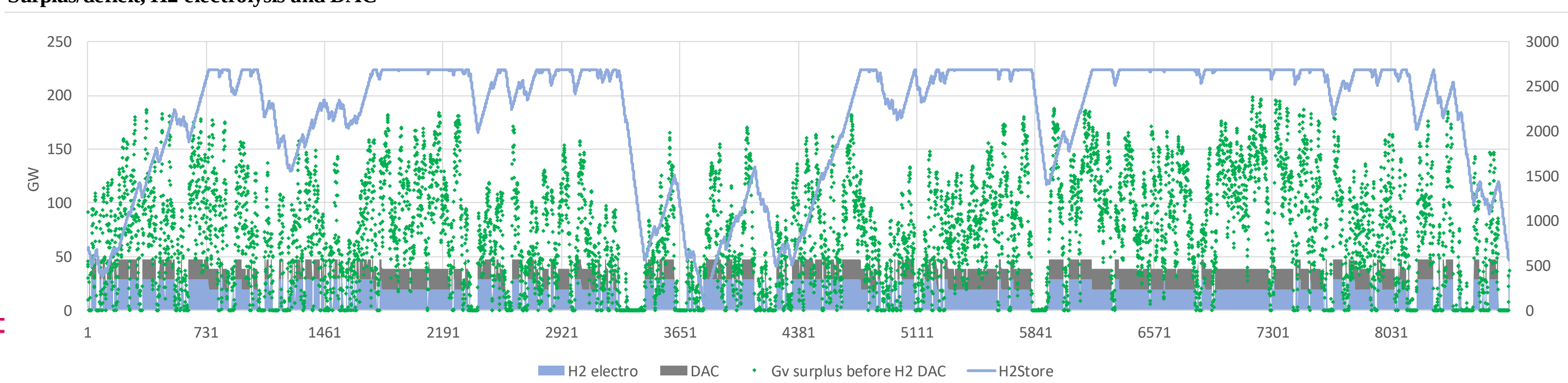
Year

What temporal variation in demands and fuels synthesis?

Demands

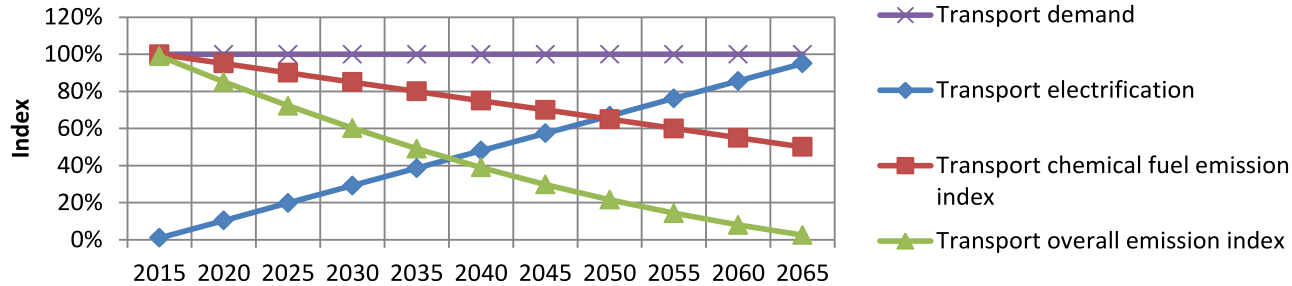


Surplus/deficit, H2 electrolysis and DAC

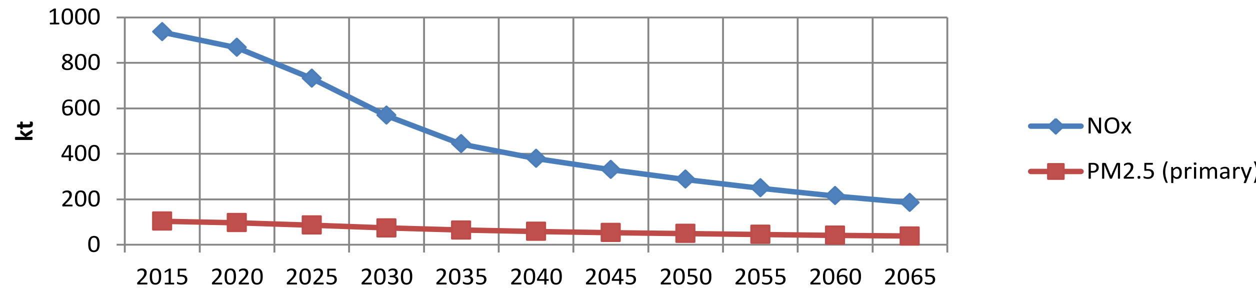


Air pollution projections – national - needs updating with fuel data

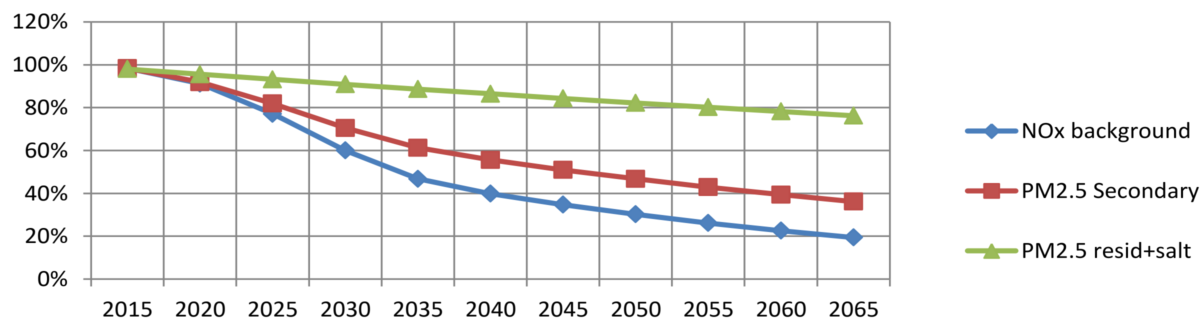
Transport



National primary emissions

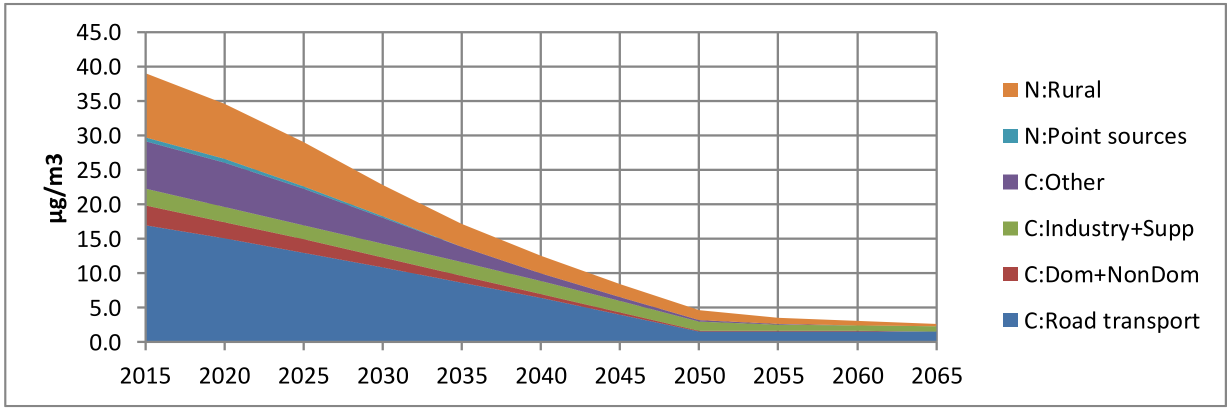


Background concentration indices

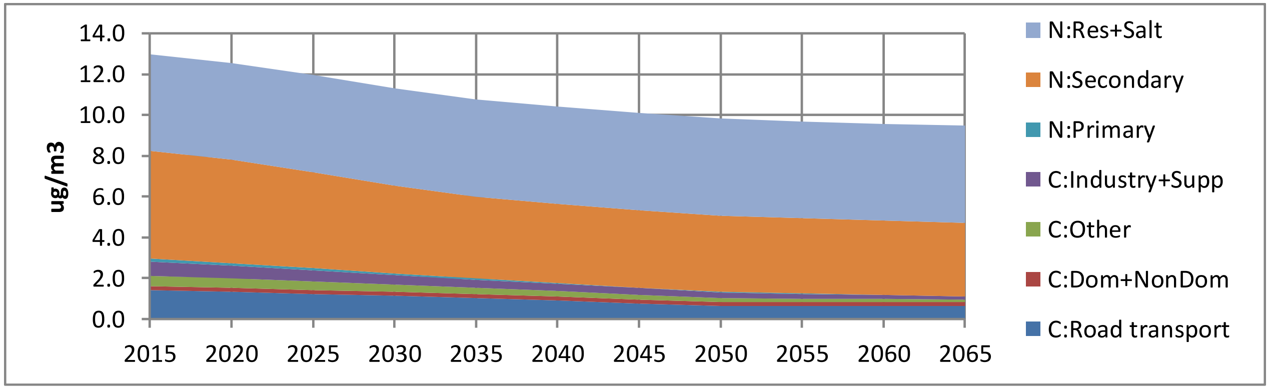


Air pollution concentration projections

NOx
(NO2 similar change)



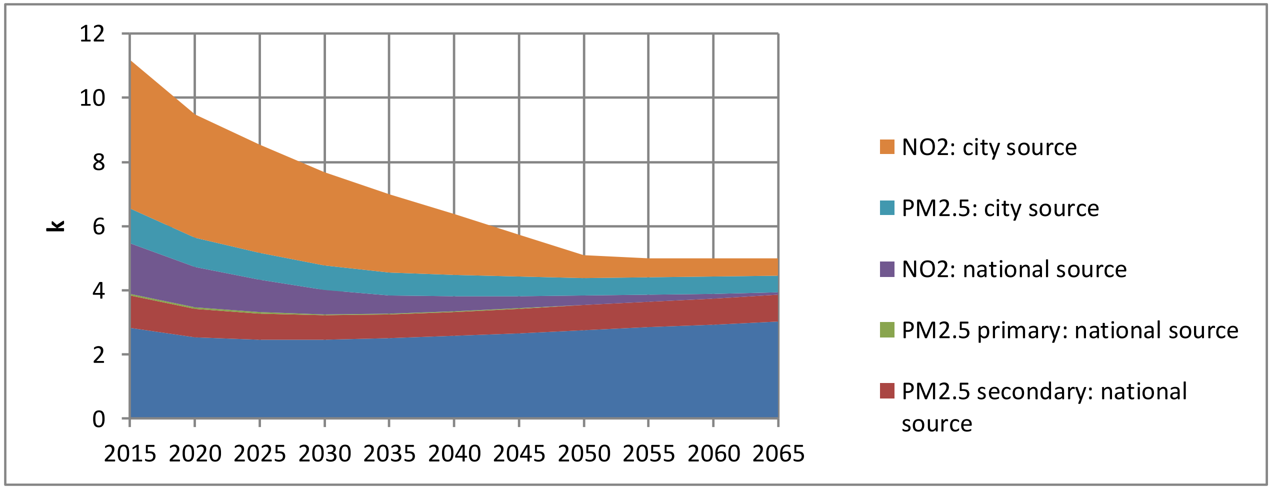
PM2.5



Air pollution health impacts: Birmingham

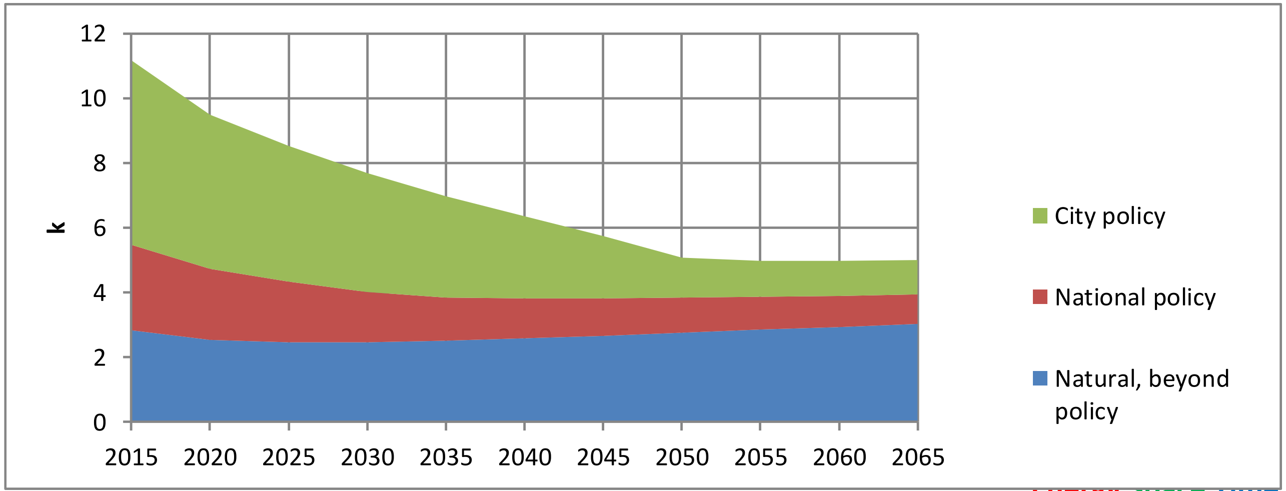
(any increasing trends are due to increasing population)

Premature deaths by pollutant and source



NB: assumption that natural sources have heath impacts

Premature deaths affected by policy



Thanks for listening

Questions?

Aviation kerosene synthesis

from renewable electricity, atmospheric CO2 and electrolytic hydrogen

	Kerosene	C14H30								
	Atom	**N**	**At Wt**	**%Ker Wt**	**Kerosene Mt**	**FTtotal Mt**	**TWhe**		**Energy per mass**	
			226		**15.0**	**21.4**			12	kWh/kgKer
Process	C	16	192	85%	12.7	18.2				
FT input	H	34	34	15%	2.3	3.2	169	Electrolysis	53	kWhe/kgH2
RWS input	CO2		704	312%	46.7	66.8	134	DAC	2	kWhe/kgCO2
RWS input	H		32	14%	2.1	3.0	159	Electrolysis	53	kWhe/kgH2
FT input	CO		336	149%	22.3	31.9				
Refining						**21.4**	*21*	Refine	*1*	kWhe/kgHC
						21.4	**484**			
Total HC out							**257**	TWhc	12	kWh/kgHC
DAC not required for negative emission							-93	TWhc		
Residiual mixed HC							6	Mt		
Residiual mixed HC							-77	TWhc		
H2 electrolysis displaced by RMHC							-103	TWhe		
Aviation fuel net additional electricity							**287**	TWhe		
Efficiency hydrocarbon out/Electricity In							53%		23	kWhe/kgHC

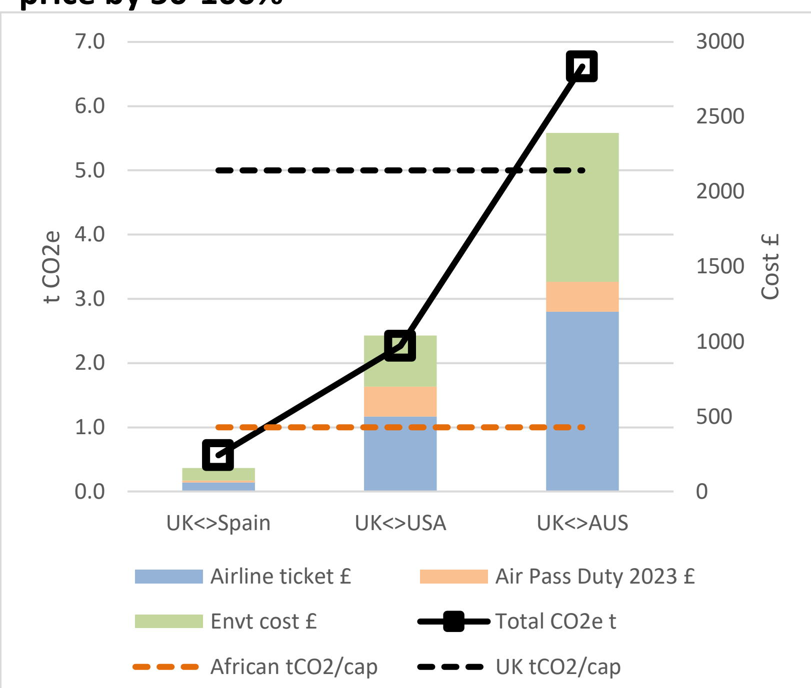
Aviation kerosene synthesis

from renewable electricity, atmospheric CO2 and electrolytic hydrogen

Synthetic kerosene about 2x fossil price

		Negative emissions	Synfuel	Difference	Cost extra £/kW	Capital G£	Annual G£/a
Fossil kerosene	*TWh*	*180*	*0*	***-180***			*-15*
RMHC	*TWh*	*0*	*-77*	***-77***			*-7*
DACS	*TWh*	*67*	*134*	***67***			
	GW	*14*	*28*	***14***	*7000*	*97*	*36*
Electrolysis	*TWh*	*0*	*226*	***226***			
	GW	*0*	*47*	***47***	*350*	*16*	*6*
Fischer Tropsch	*TWh*	*0*	*257*	***257***			
	GW	*0*	*37*	***37***	*350*	*13*	*5*
Generation	*TWh*	*67*	*287*	***221***			
	GW	*14*	*60*	***46***	*1400*	*64*	*24*
					Total net	***190***	***48***
					Net cost	***19***	***p/kWh***

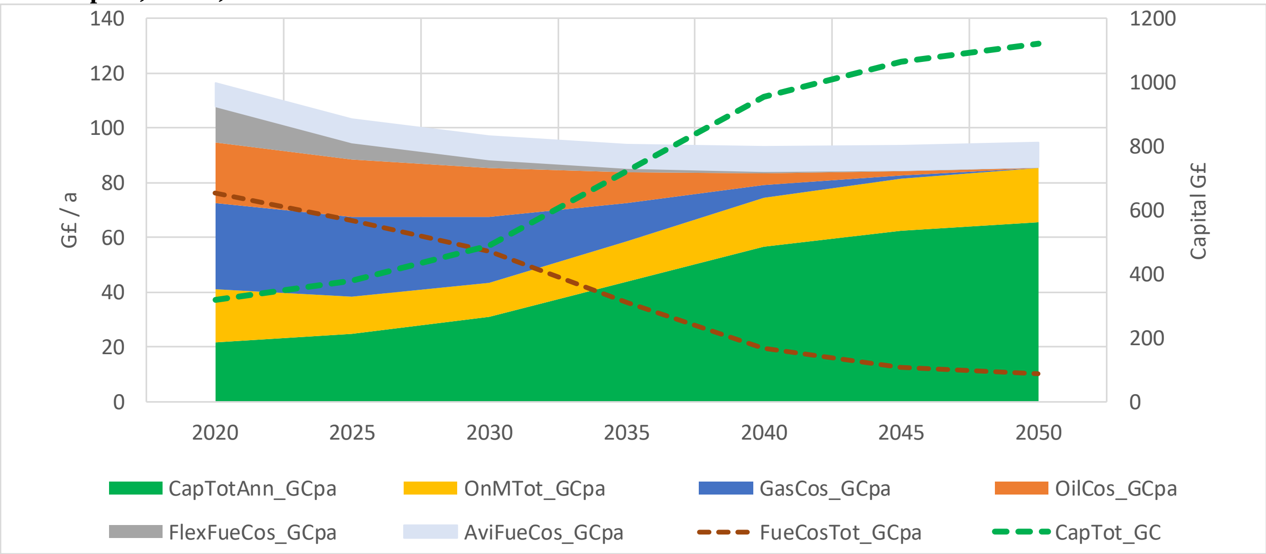
300 £/tCO2e tax kerosene increases ticket price by 50-100%



Transition – costs

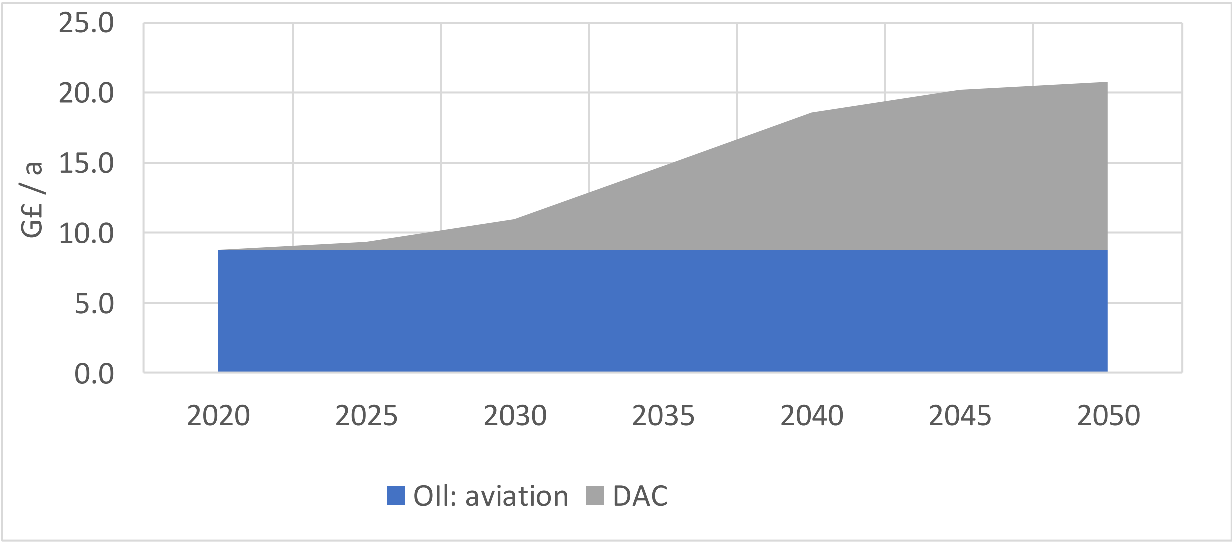
- At recent fossil prices, net zero system costs less
- 90% of system costs are fixed capital and O&M so little volatility

COSTS - capital, O&M, fuels



- Aviation about 20% of total system cost

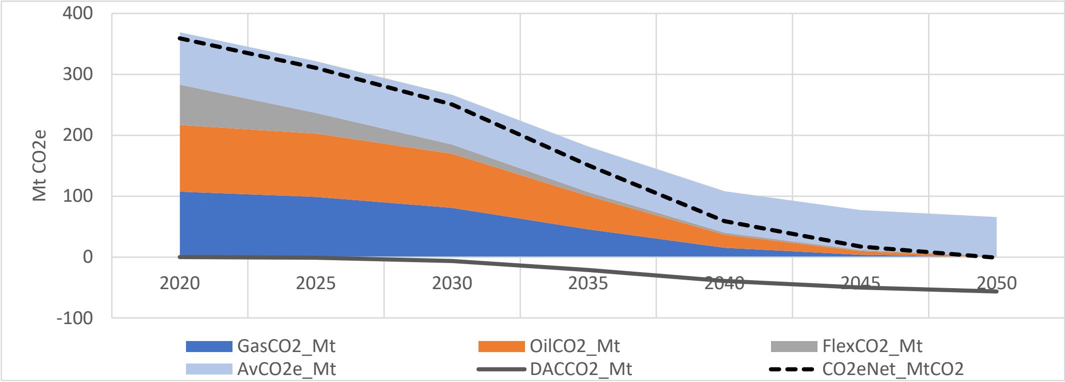
AVIATION



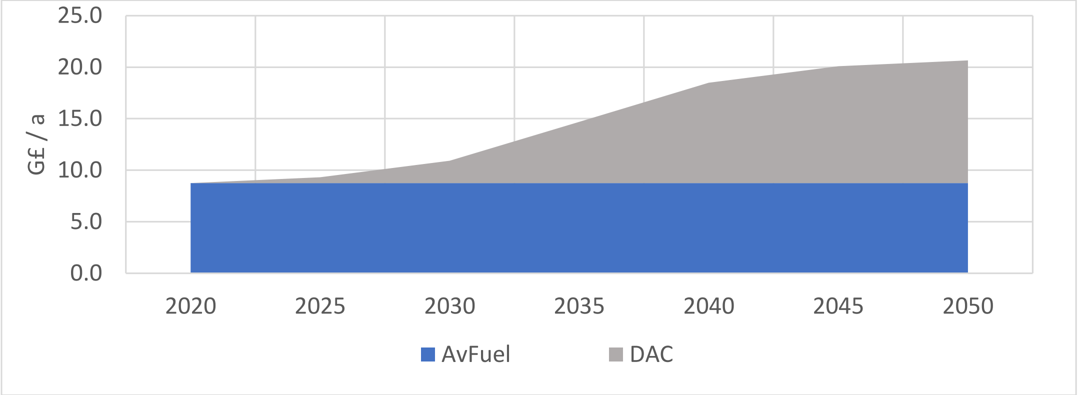
Aviation – the fly in the ointment

Long range aircraft require kerosene – fossil with DACS negative emissions cheaper than renewable kerosene?

Aviation is the main CO2 emitter



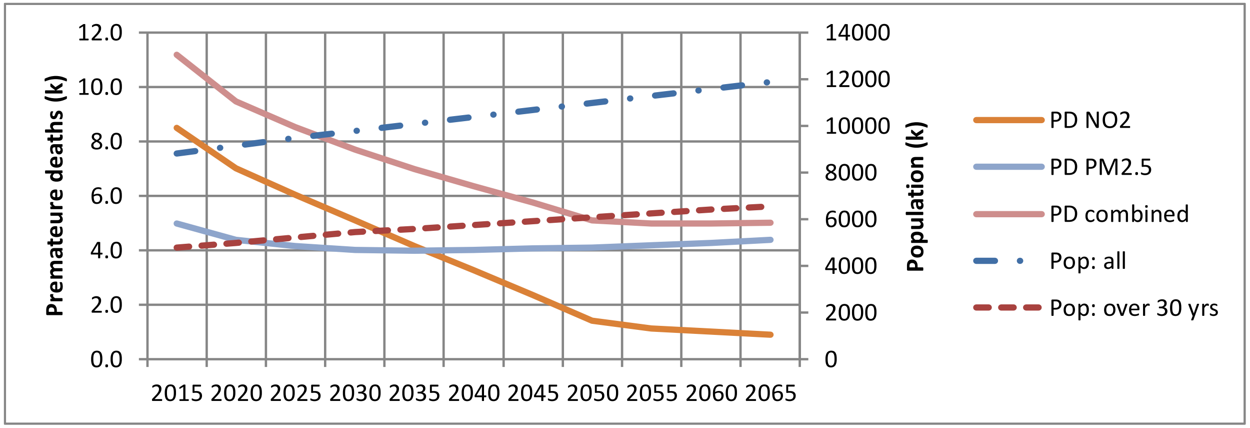
Aviation about 25% of total system cost



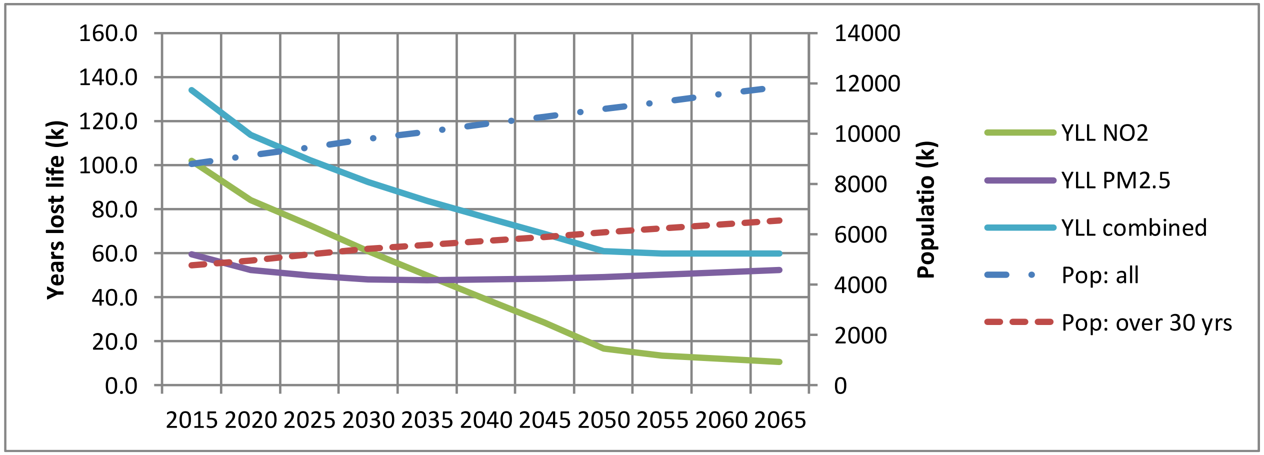
Imposing CO2 costs on aviation would increase ticket prices by 100-300 %

Air pollution health impacts

Premature deaths



Years of lost life



Health model

The relative risk RR (a fraction) is the concentration response factor CRF raised to the power ((change in concentration dC)/10):

$$RR = CRF^{(dC/10)}$$

The attributable fraction AF due to air pollution is calculated:

$$AF = (RR-1)/RR$$

The premature deaths PD per year is the population over 30 yrs old Pop30 times the baseline mortality rate Mb times the attributable fraction AF:

$$PD = Pop30\ Mb\ AF$$

The years of life lost (years) YLL is the premature deaths PD times the years of life per premature death YLLd (assumed to be 12 years)

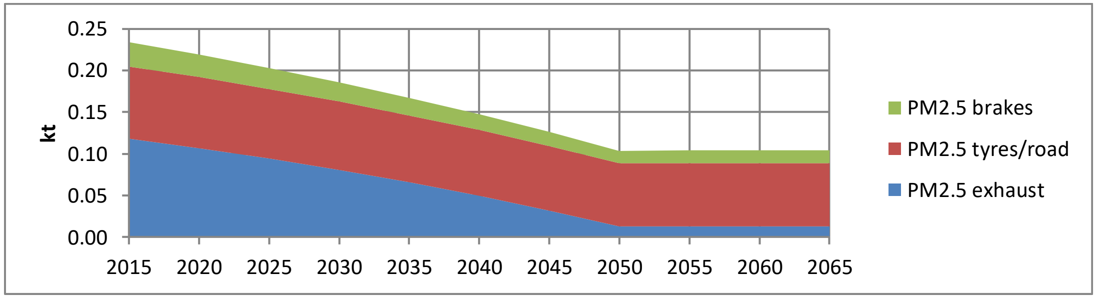
$$YLL = PD\ YLLd$$

Notes:

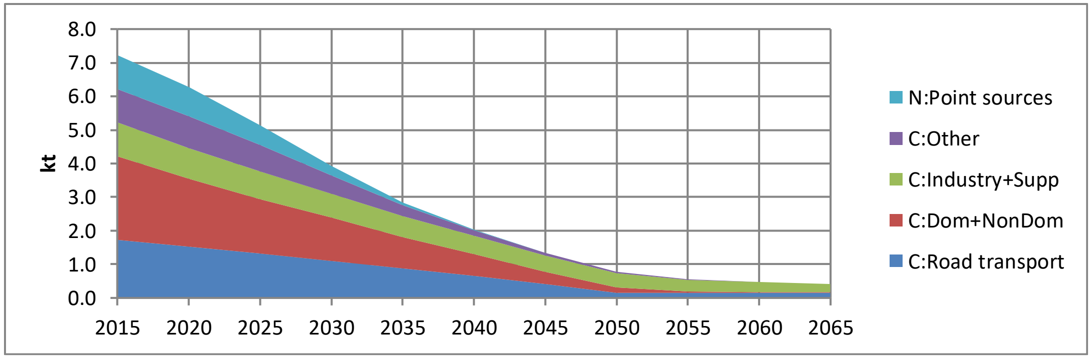
- It is conventionally assumed that the combined impact of several pollutants is less than the sum of the individual impacts.
- Currently natural particulate pollutants (dust, salt etc.) are assumed to have the same impacts as anthropogenic pollutants

Birmingham emissions air pollution and CO2

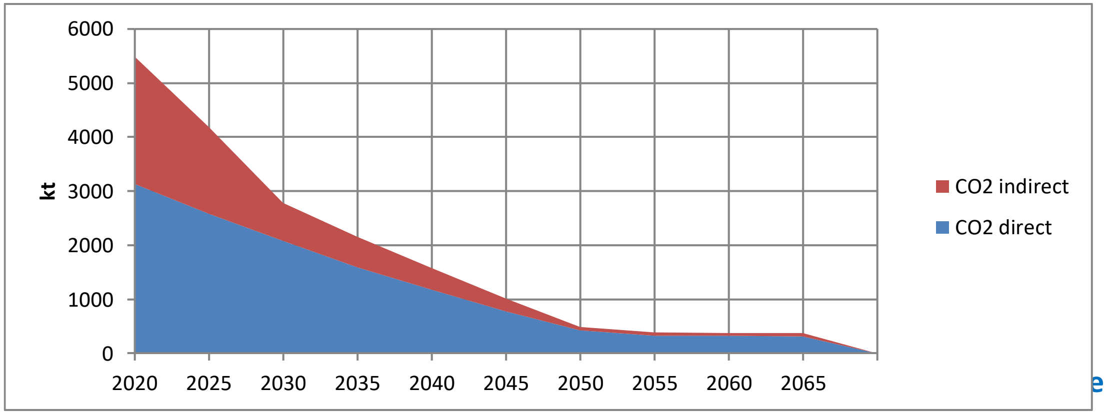
PM2.5
Excluding dust resuspension



NOx



CO2

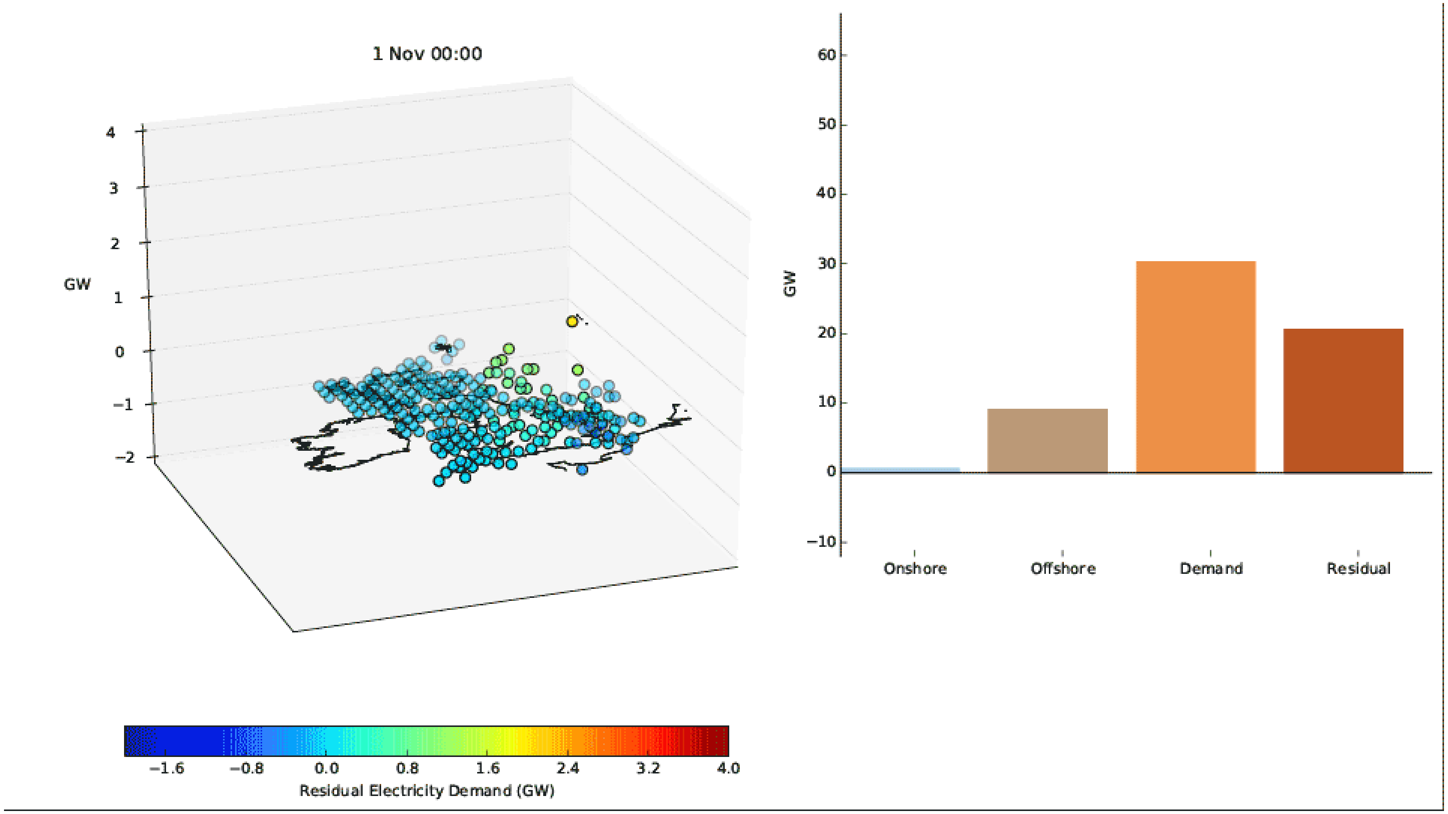


Outline: combining spatial and temporal variation

London's contribution to residual demand

- As a results of its large resident population and workforce London inevitably has a significant effect on the national system

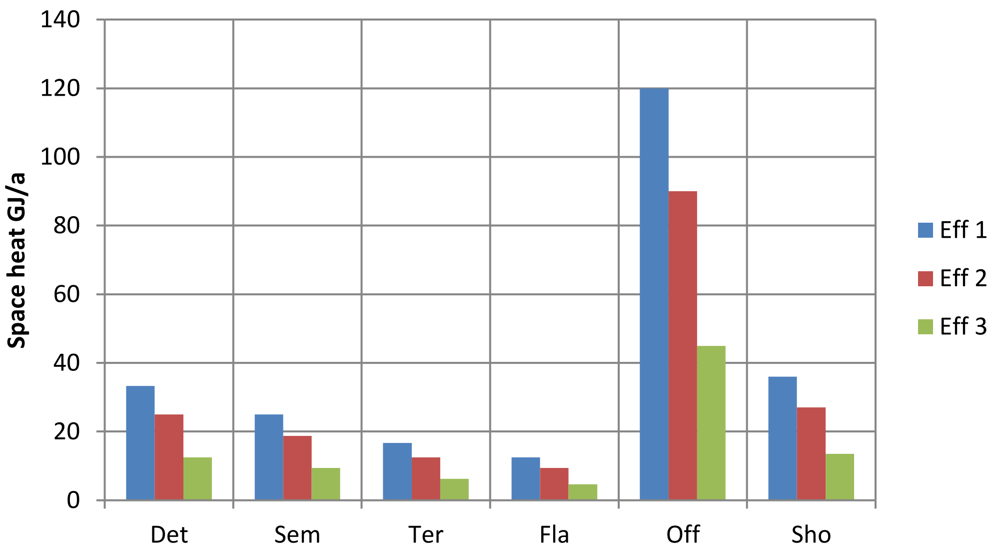
- The animation shows the magnitude of this demand relative to other areas of the country of the same geographical size.



Stationary Demand

People-Building archetypes database (illustration)

- People
- Form
- Area
- Heat loss
- Demands
- Costs
- Network lengths



Acronym	Description	% of stock	Sector	Subsector	Npeople	SolarArea (m2)	SpecLoss0 (W/oK)	3 efficiency levels, Annual demands: GJ/a Space heat 1	2	3	GJ/a Other heat 1	2	3	GJ/a Elec non heat 1	2	3	GJ/a AirCon 1	2	3
Det		15%	D	Det	4	4.0	400	33	25	13	8	7	6	24	22	17			
Sem		30%	D	Sem	2.5	3.0	300	25	19	9.4	5	5	4	15	14	11			
Ter		30%	D	Ter	2.2	2.0	200	17	13	6.3	4	4	3	13	12	10			
Fla		25%	D	Fla	1.5	0.5	150	13	9.4	4.7	3	3	2	9	8	6			
Off		50%	N	Office	10	5.0	700	120	90	45	50	45	36	100	90	72	5.0	4.0	3.6
Sho		50%	N	Shop	3	2.0	500	36	27	14	15	14	11	30	27	22	1.5	1.2	1.1

Acronym	3 efficiency levels, Peak demands: kW Space heat 1	2	3	kW Other heat 1	2	3	kW Elec non heat 1	2	3	kW AirCon 1	2	3	Capital cost Efficiency k£ 1	2	3	Network External m/consumer: Elec	Gas	District heat
Det	10	8	4	2	1	1	5	4	3				0.0	13	38	10	10	10
Sem	8	6	3	1	1	1	3	3	2				0.0	10	28	8	8	8
Ter	5	4	2	1	1	1	3	2	2				0.0	7	19	7	7	7
Fla	4	3	2	1	1	0	2	2	1				0.0	5	14	5	5	5
Off	18	14	7	10	9	7	20	18	14	1.0	0.8	0.7	0.0	48	135	5	5	5
Sho	13	10	5	3	3	2	6	5	4	0.3	0.2	0.2	0.0	14	41	5	5	5

Building efficiency packages

Incremental installation costs of efficiency packages for reducing:

- Reducing space heat loss with insulation and ventilation heat recovery for existing and new buildings
- Reducing electricity use for lighting, computing etc.

Costs will depend on details of buildings and equipment use.

For domestic:

- Unit costs per dwelling (£/W/oK, £/kWhe/a)
- Multiply by number of dwellings for total capital cost

For non-domestic:

- Unit area costs (£/W/oK/m2, £/kWhe/a/m2) highly variable and uncertain because of heterogeneity and lack of data about buildings
- multiply costs per m2 by floor areas of buildings to get total capital cost

Scenario settings

For:

- Demand drivers
- Efficiency (buildings)
- Heat shares
  - Boiler
  - Electric
  - Heat pump
  - CHP
- District heating
  - Minimum density
  - Take up
  - Heat input shares
- Transport
  - Efficiency
  - Mode
  - Technology

Specify

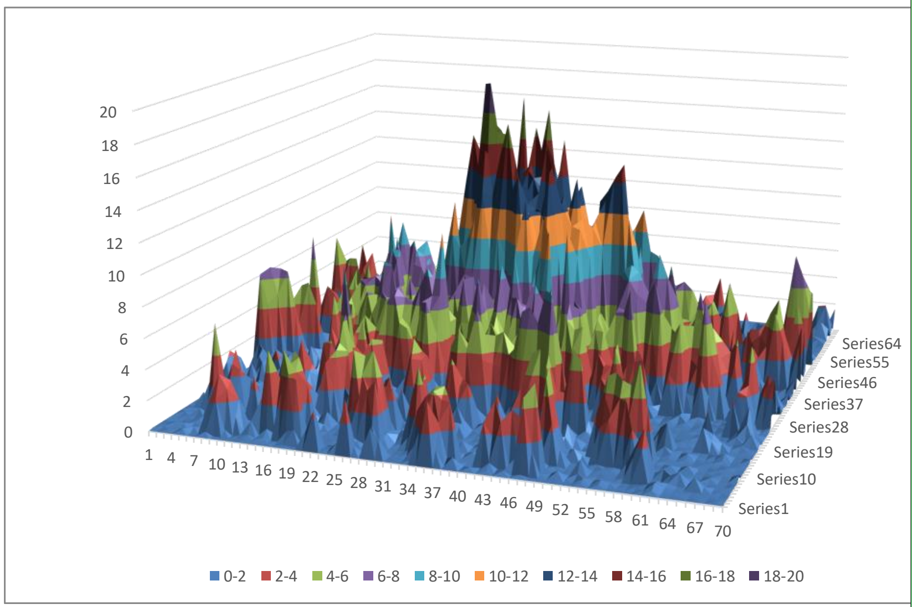
- Initial and final values
- Years to final
- Interpolation (linear, other)

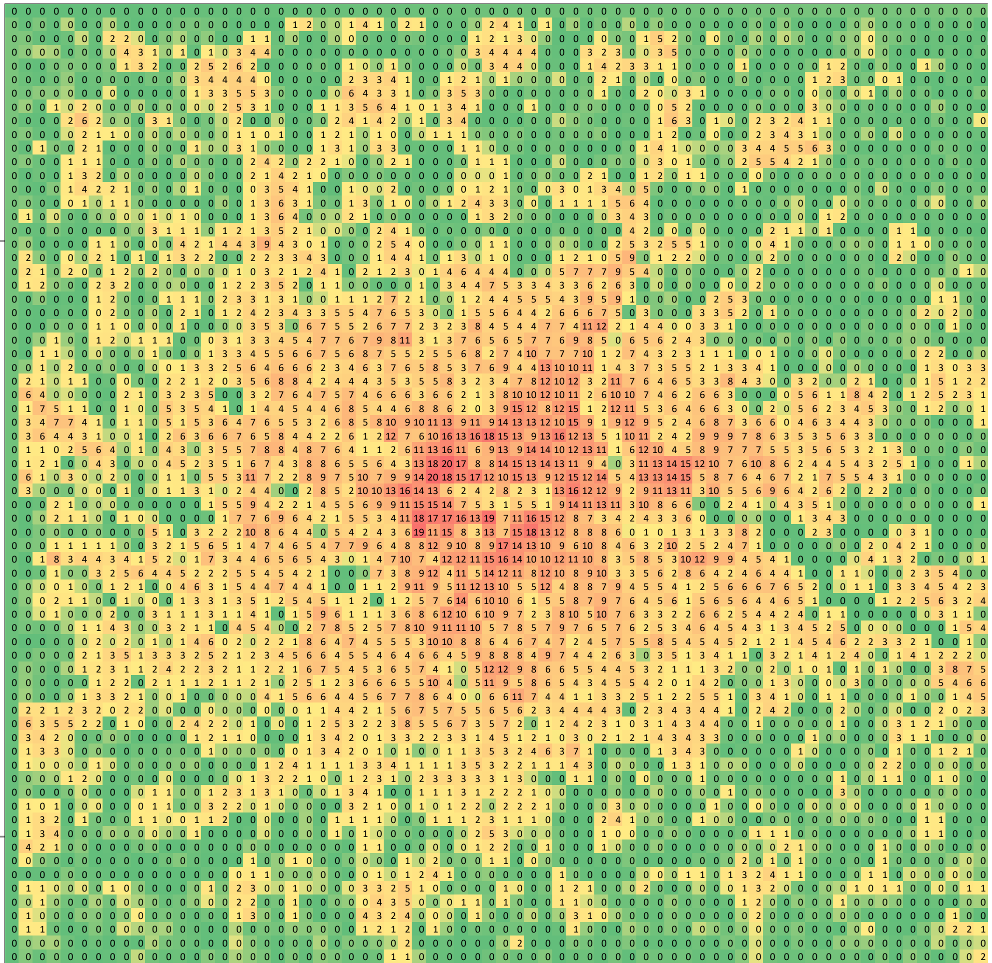
Category	Description		Variable	Initial	Final	Yrs	Shape	Exp
Demand	Population	%	PopCh_pc	0%	10%	50	Lin	0
	People per household		HHSize_p	2.3	1.8	50	Lin	0
	Economy	%	EcoCh_pc	0%	5%	50	Lin	0
Transport	Passenger	%	TrDemPas_pc	0%	10%	40	Lin	0
	Freight	%	TrDemFre_pc	0%	1%	40	Lin	0
Efficiency	Fractions		Eff1_pc	50%	5%	40	Lin	0
			Eff2_pc	48%	5%	40	Lin	0
Heating			Eff3_pc	2%	90%	40	Lin	0
Non-DH Shares	Gas boiler	%	GasBoi_pc	90.0%	1.0%	30	Lin	0
	resistance heating	%	EleRes_pc	3.0%	5.0%	30	Lin	0
	resistance heating	%	EleOff_pc	3.0%	10.0%	30	Lin	0
	Heat pump	%	HPInd_pc	0.5%	82.0%	30	Lin	0
		%	CHPInd_pc	3%	2%	30	Lin	0
District heat	ıeat density	TJ/km	DHMin_TJpkm2	300	15	40	Exp	-0.075
	DH take up	%	DHTakeUp_pc	80%	98%	45	Lin	0
	Heat input	%	DHCHP_pc	85%	3%	40	Lin	0
		%	DHHP_pc	5%	96%	40	Lin	0
		%	DHGasBoi_pc	10%	1%	40	Lin	0
Transport	Efficiency	%	TrEffYr_pc	100%	100%	40	Lin	0
	Mode	%	TrModeYr_pc	100%	50%	40	Lin	0
	Technology	%	TrFuelYr_pc	100%	50%	40	Lin	0
Generation	SolarPV	%	SolarPV_pc	1%	50%	40	Lin	0
Pollution		%	NOxRed_pc	100%	50%	25	Lin	0

London: population

Population (res)

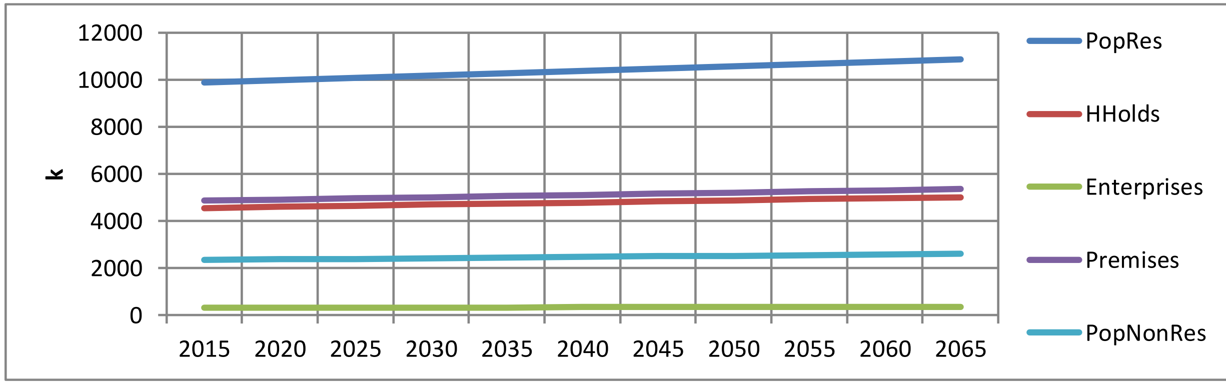
Total 9899 k



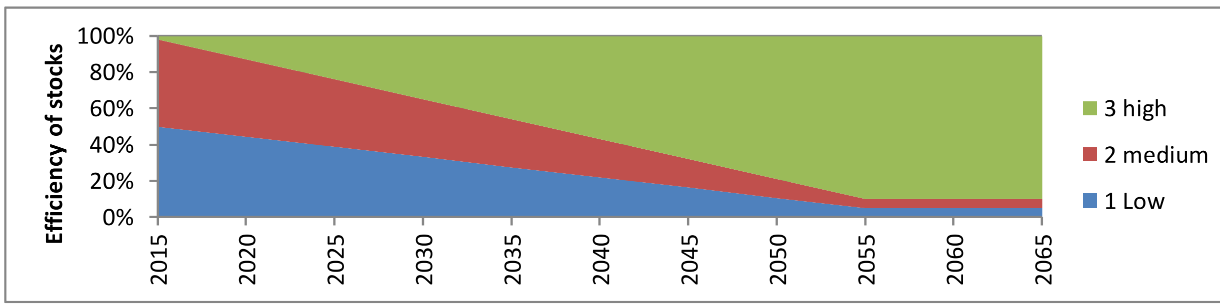


Scenario (London) – demand

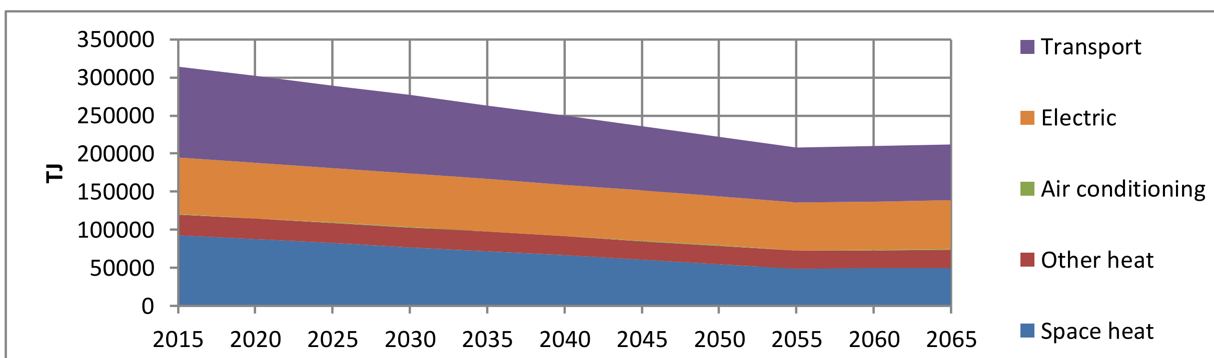
Drivers



Building efficiency

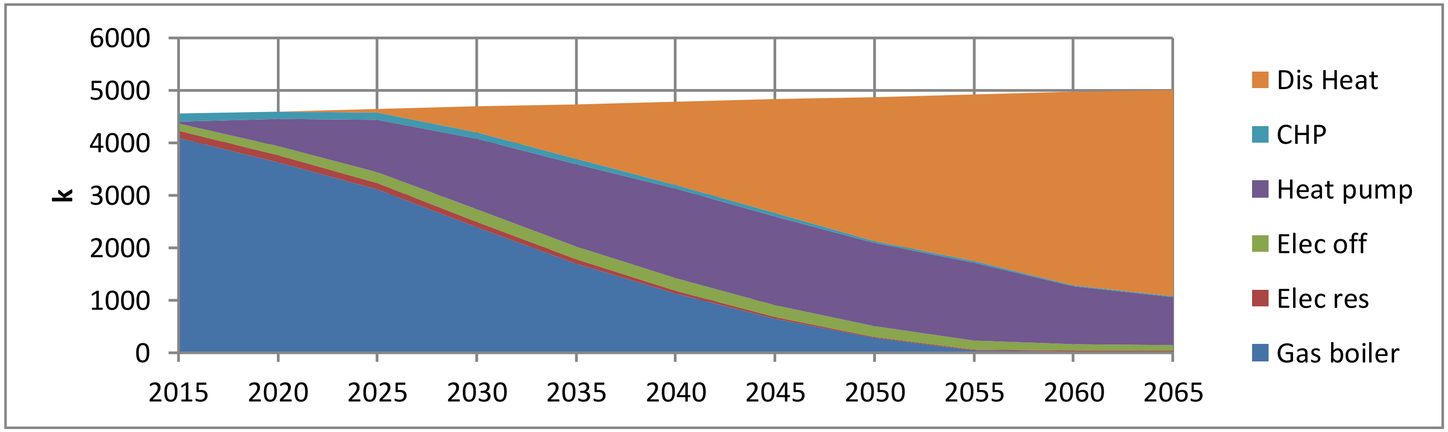


Services

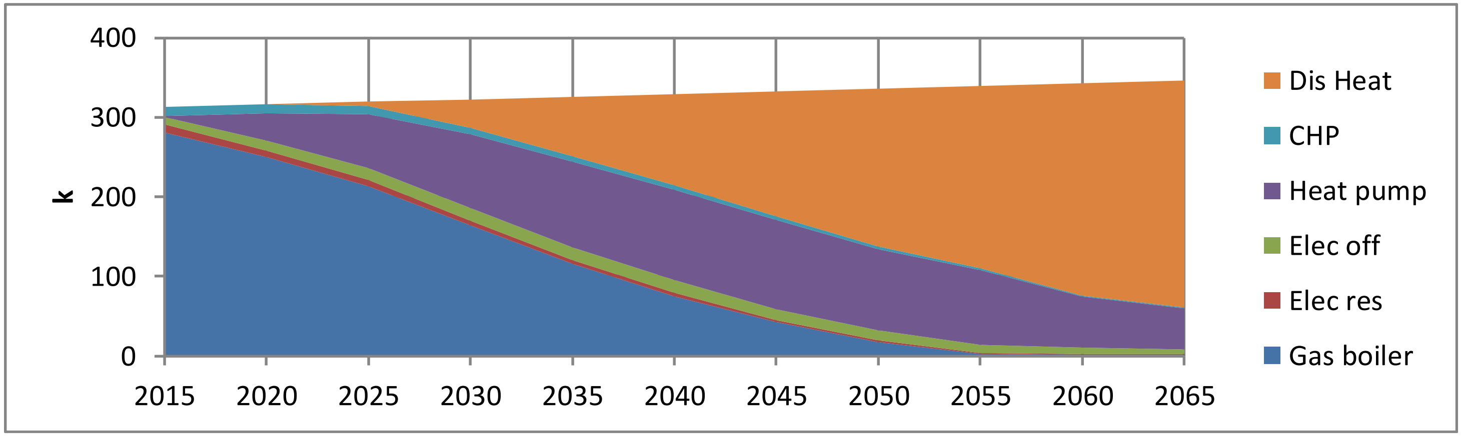


Scenario (London) – heating systems
(gas, electric, district heat only)

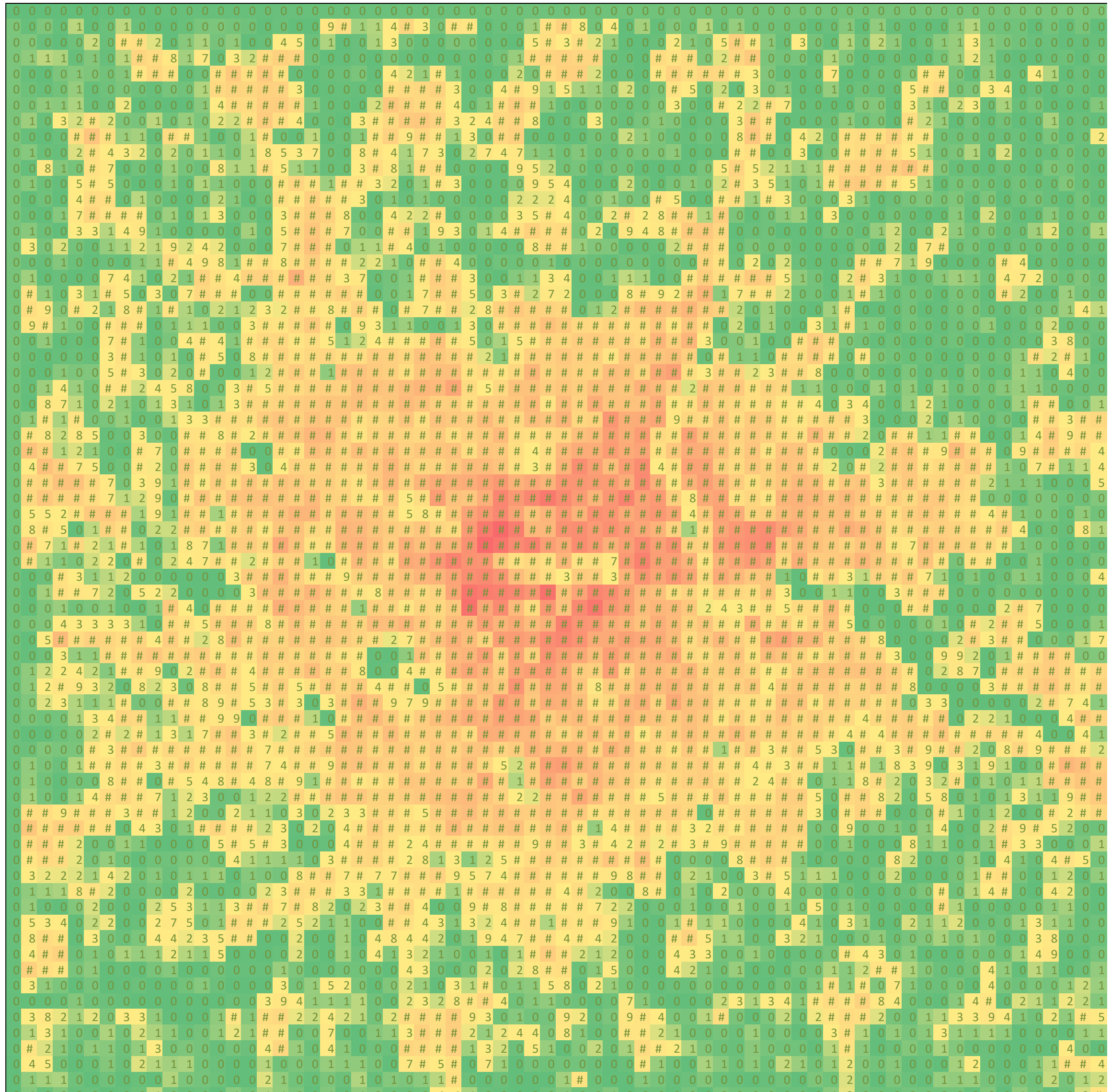
Domestic



Non domestic



London: heat load illustration



District Heating

Algorithm

Specify

- minimum heat load density (TJ/km2) for DH across future years
- percentage of heat load connected at minimum density
- fraction of heat mix (HP, CHP, boiler) across future years
- performance of components
- costs with scale economies of network, HP, CHP, heat store

Calculate

- which heat load km2 are connected to DH
- generate schemes: if adjacent km2 connected join them into one scheme
- heat demands, energy inputs, capital and operating costs of each scheme

Scenario (London) – district heat

Density and consumers

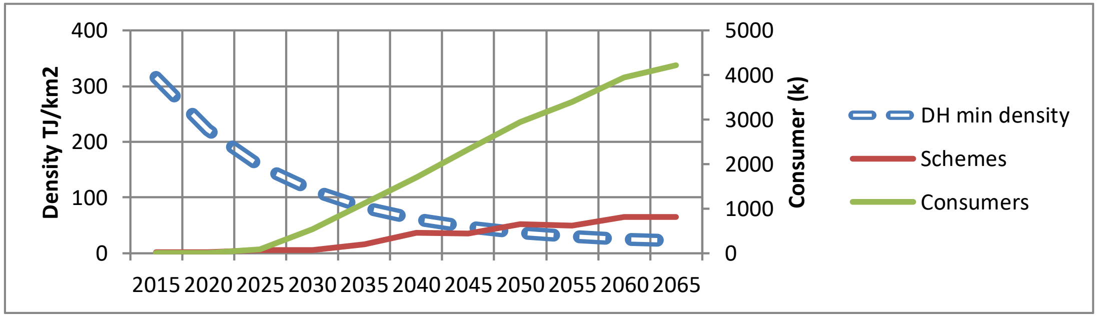
- as minimum heat load density decreases, more consumers connected

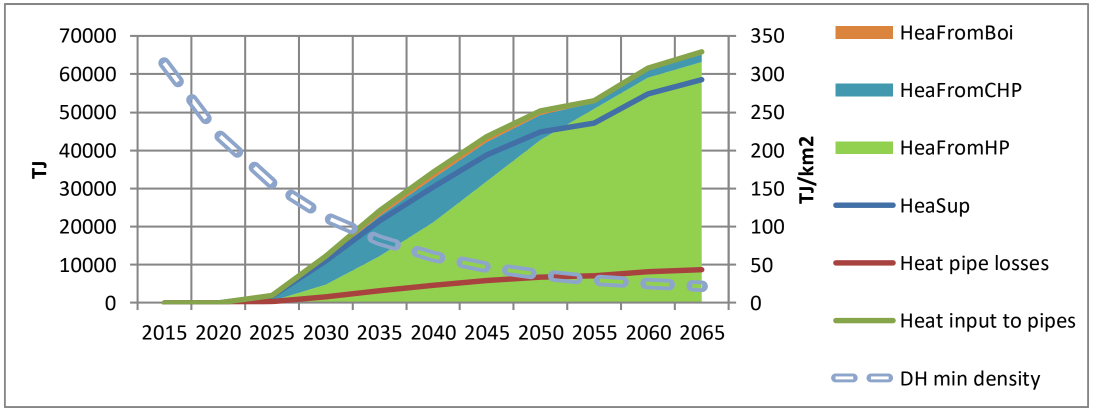
Heat mix

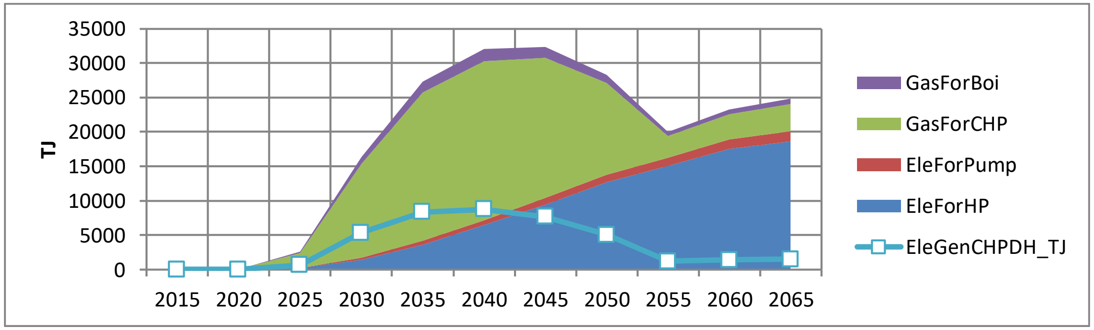
- Decreasing CHP and increasing heat pump fractions of heat supply as national renewables/ nuclear increase

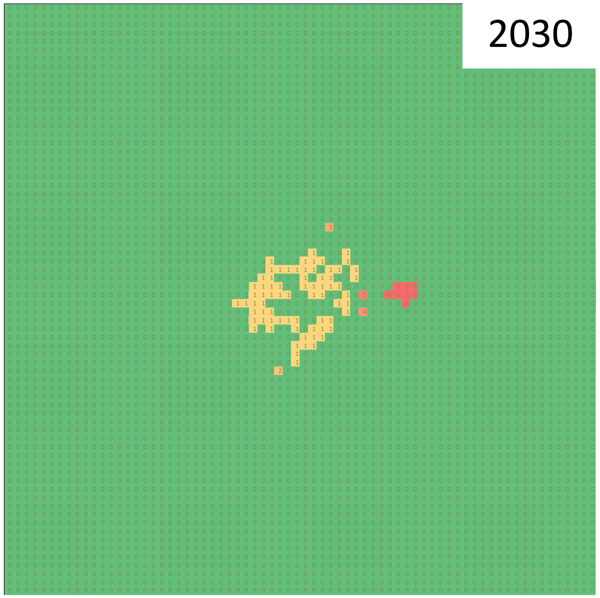
Energy inputs and generation

- Gradual growth in heat pump electricity input as national renewables/nuclear increase





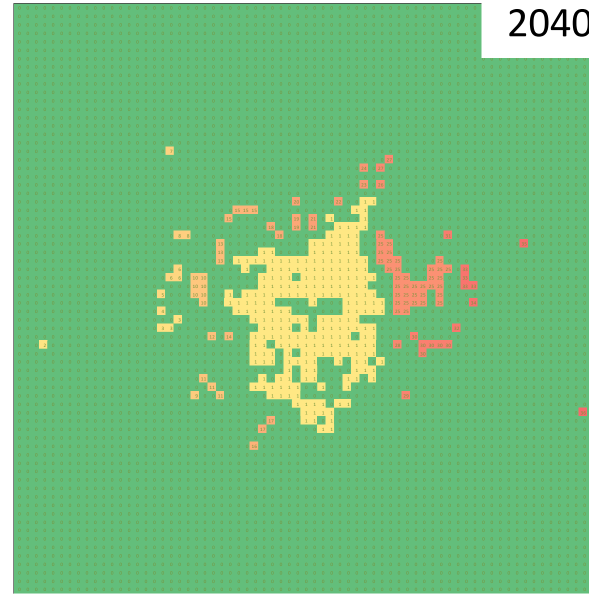


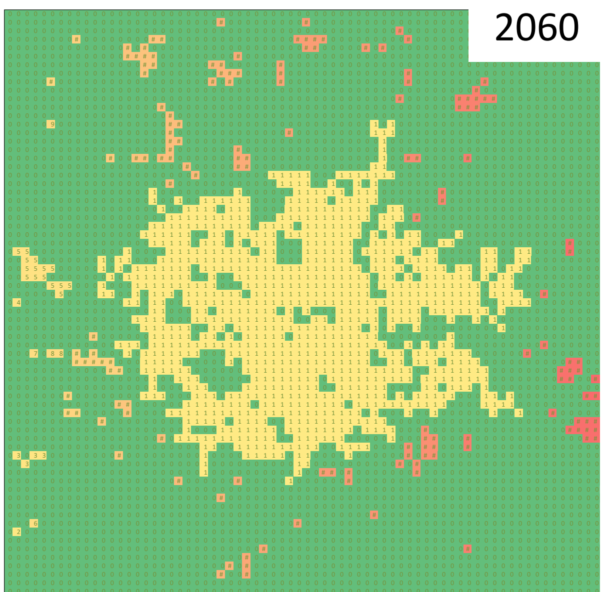


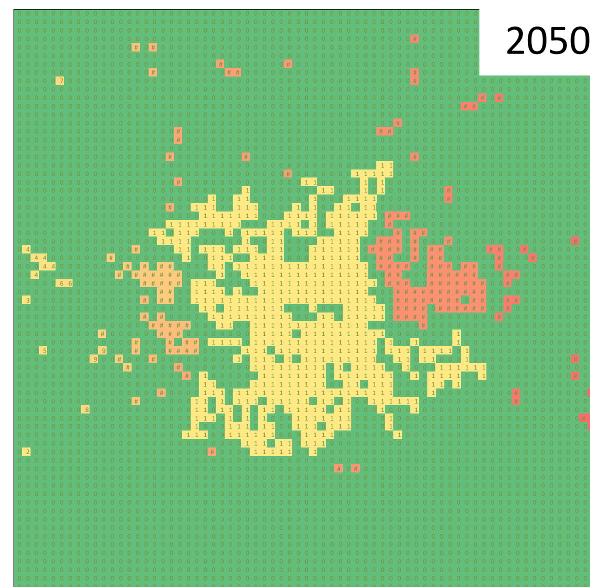
London

District heating development Illustration using algorithm.

As lower heat load densities connected 2030-2060, schemes grow in number and integrate







District heating scenario (London 2050)

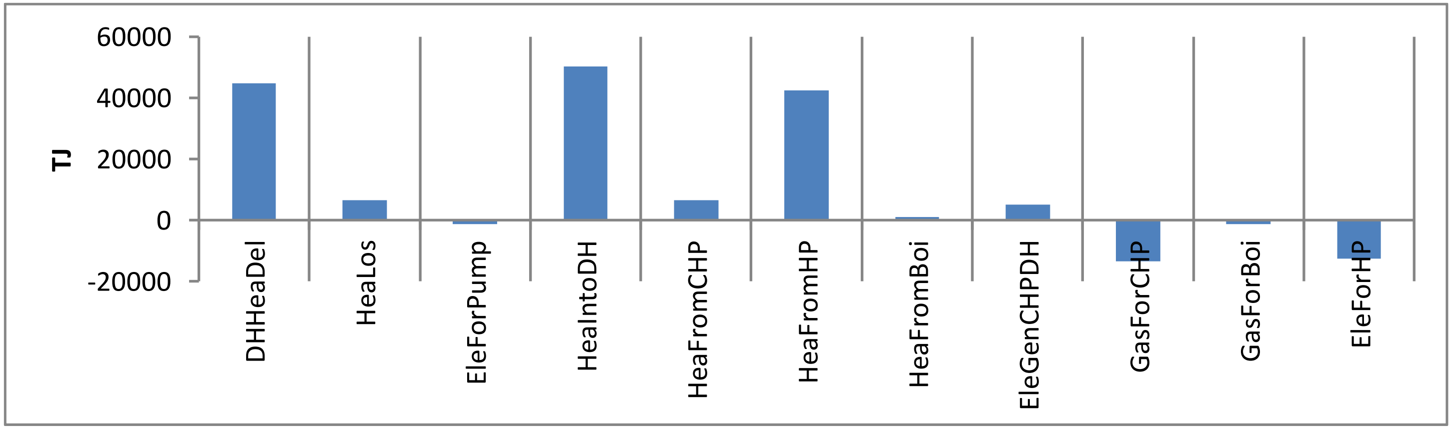
Energy, engineering and cost of each scheme calculated

Economies of scale mean larger schemes have lower unit costs

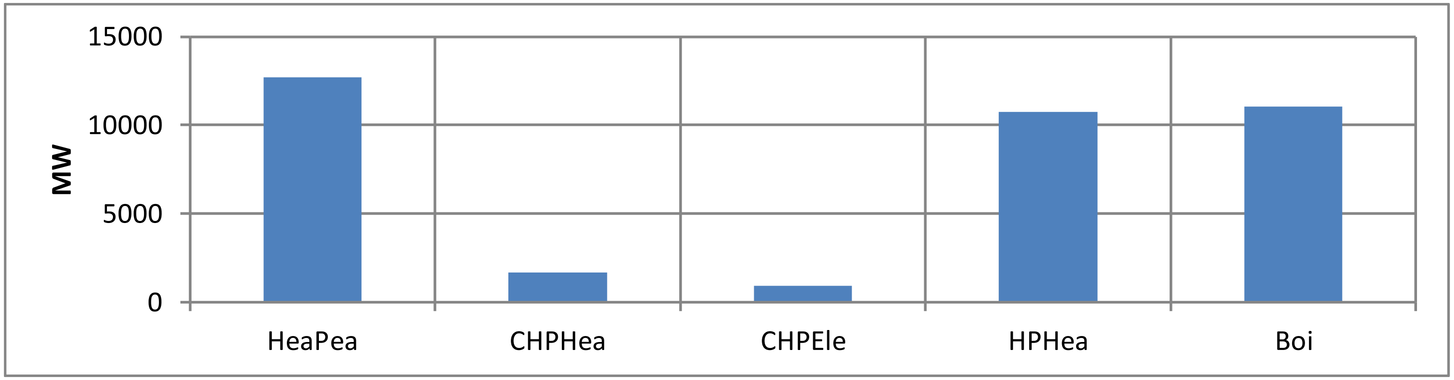
				City	1	2	3	4	5	6	7	8	9	10
		k	People	**2942**	2240	3	3	18	4	5	3	2	5	3
CONSUMPTION		TJ	DHHeaDel	**44793**	34104	46	42	280	58	81	46	38	79	41
		TJ	HeaLos	**6719**	5116	7	6	42	9	12	7	6	12	6
HEAT INPUT		TJ	EleForPump	**-1120**	-853	-1	-1	-7	-1	-2	-1	-1	-2	-1
		TJ	HeaIntoDH	**50392**	38367	51	48	315	65	92	52	43	89	46
		TJ	HeaFromCHP	**6677**	5084	7	6	42	9	12	7	6	12	6
		TJ	HeaFromHP	**42645**	32468	43	40	267	55	77	44	36	75	39
		TJ	HeaFromBoi	**1071**	815	1	1	7	1	2	1	1	2	1
	Generated	TJ	EleGenCHPDH	**5059**	4236	2	2	14	3	4	2	2	4	2
ENERGY	**Input**	TJ	GasForCHP	**-13337**	-10591	-10	-9	-63	-13	-18	-10	-8	-17	-9
		TJ	GasForBoi	**-1235**	-926	-2	-1	-8	-2	-3	-2	-1	-3	-1
		TJ	EleForHP	**-12632**	-9276	-20	-18	-93	-24	-33	-20	-17	-32	-18
CAPACITIES		km	NetDH	**20191**	15373	21	19	126	26	37	21	17	36	18
		MWh	StoHea	**387902**	295101	400	374	2430	505	710	403	335	689	358
		MW	HeaPea	**12722**	9686	13	12	80	16	23	13	11	22	12
		MW	CHPHea	**1686**	1283	2	2	11	2	3	2	1	3	2
		MW	CHPEle	**919**	700	1	1	6	1	2	1	1	2	1
		MW	HPHea	**10766**	8197	11	10	67	14	20	11	9	19	10
		MW	Boi	**11037**	8403	11	10	69	14	20	11	9	19	10
EFFICIENCIES		pc	CHPHeaEff	**0%**	48%	68%	68%	66%	68%	68%	68%	68%	68%	68%
		pc	CHPEleEff	**0%**	40%	20%	20%	22%	20%	20%	20%	20%	20%	20%
		pc	HPHeaEff	**0%**	350%	220%	219%	287%	225%	234%	220%	217%	233%	218%
		pc	BoiEff	**0%**	88%	71%	71%	81%	72%	73%	71%	71%	73%	71%
EMISSIONS		kt	NOx	**0**	0	0	0	0	0	0	0	0%	0%	0%
		kt	PM25	**0**	0	0	0	0	0	0	0	0%	0%	0%
COST	**Unit capital costs**	Cpm	Pipe	**0**	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
		CpkWh	Sto	**0**	5	9	10	5	6	5	9	13	5	11
		CpkWe	CHP	**0**	715	1198	1198	1186	1197	1196	1198	1198	1196	1198
		CpkW	HP	**0**	200	925	930	636	906	871	924	937	874	933
		CpkW	Boi	**0**	70	493	497	248	474	440	492	505	443	500
		CpkW	EneHub	**0**	70	493	497	248	474	440	492	505	443	500
	Capital cost	MC	Pipe	**20191**	15373	21	19	126	26	37	21	17	36	18
		MC	Sto	**2002**	1476	3	4	12	3	4	3	4	4	4
		MC	CHP	**739**	501	1	1	7	1	2	1	1	2	1
		MC	HP	**2734**	1639	10	9	43	13	17	10	9	17	9
		MC	Boi	**1072**	588	6	5	17	7	9	6	5	9	5
		MC	EneHub	**686**	484	1	1	7	2	2	1	1	2	1
		MC	TotCap	**27424**	20061	42	40	212	51	70	42	37	68	38
	Annuitised capital	MCpa	TotCap	**1598**	1169	2	2	12	3	4	2	2	4	2
	Energy costs	MCpa	ElePum	**30**	23	0	0	0	0	0	0	0	0	0
		MCpa	EleHP	**341**	251	1	0	3	1	1	1	0	1	0
		MCpa	Gas	**136**	108	0	0	1	0	0	0	0	0	0
		MCpa	CostOM	**470**	358	0	0	3	1	1	0	0	1	0
		MCpa	EleGenCHPDH	**-118**	-99	0	0	0	0	0	0	0	0	0
	Total cost	MCpa	TotCost	**2457**	1809	4	3	18	4	6	4	3	6	3
	Cost delivered	CpGJ	HeaCost	**54.86**	53.04	78.01	78.86	65.42	75.89	73.89	77.91	80.53	74.04	79.45
		ppkWh	HeaCost	**19.8**	19.1	28.1	28.4	23.6	27.3	26.6	28.0	29.0	26.7	28.6

Scenario (London) District heating: technical summary

Energy flows

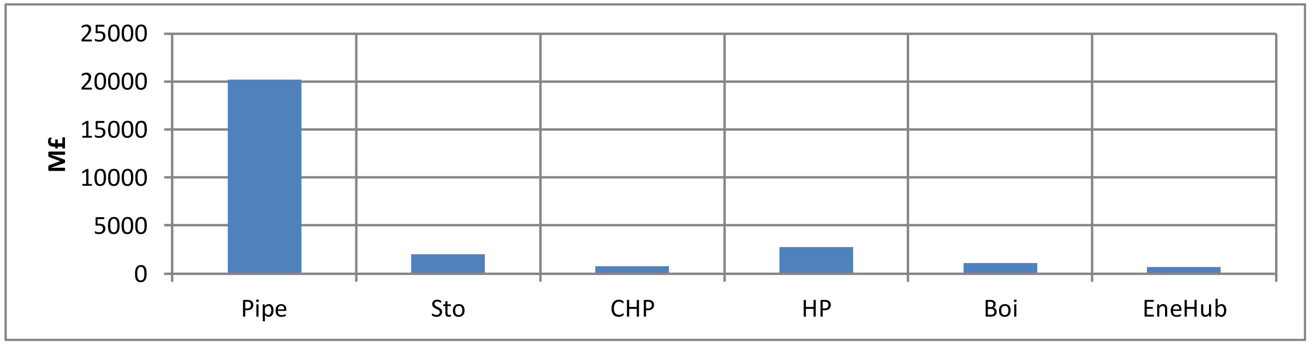


Capacities



Scenario (London) District heating: economic summary

Capacity capital value



Annuitised costs

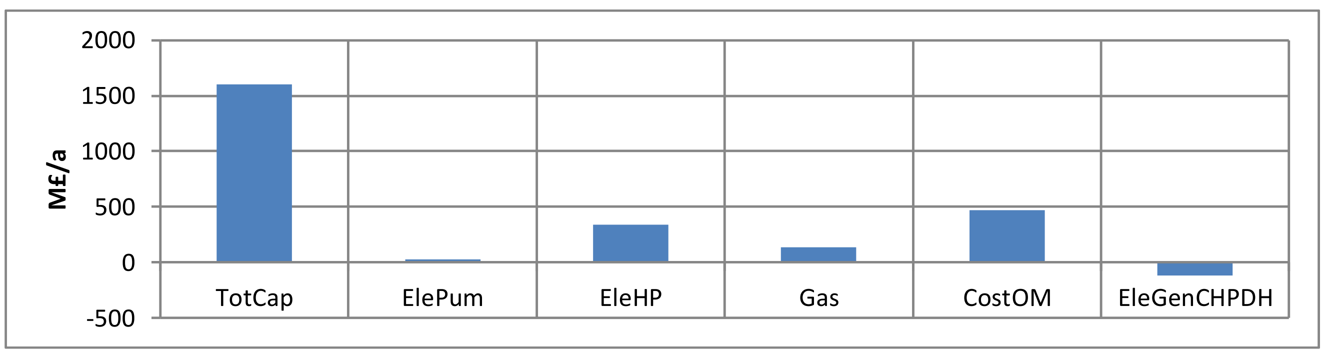
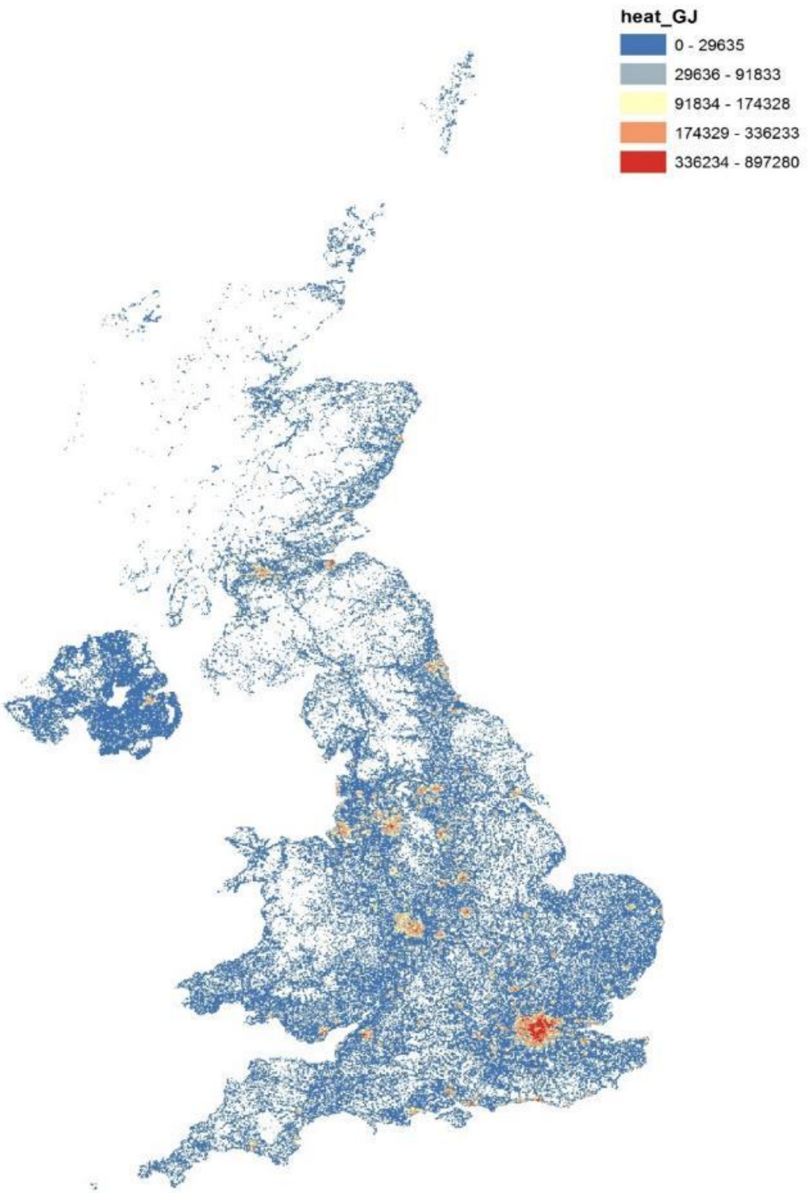


Illustration: UK heat load density

Density GJ/km^2

Total UK heat load 2500 PJ



Heat Load (total 2.5 bn GJ)

Time

Consumer comfort costs

Total cost of insulation (3 levels), heating system (6 types) and energy by built form (6) = 108 combinations

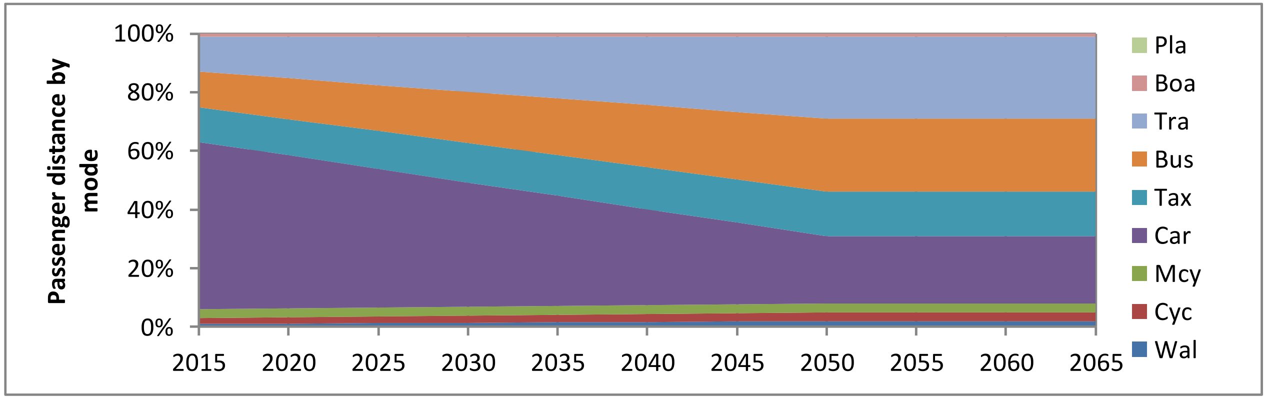
Sector		k	Energy services GJ/a						Deliveries GJ/a				Energy costs £/a						£/a	Capital k£		£/a			Comfort cost p/kWh				
Acronym	Efficiency	Number	EleNonHea	Space heat	Heat other	Heat total	System	Efficiency	Gas	Ele	Ele Gen CHP	Heat DH	Gas	Ele	Ele Gen CHP	Heat	TOTAL	For heat	O&M	Efficiency	Heat system	Efficiency	Heat system	TOTAL	Energy	Efficiency	Heat system	O&M	Total
D Det	1	90	24	33	8	41	BoiGas	71%	116	24			1254	691			1945	627	90		5.7		379	2414	5.5		3.3	0.8	9.5
D Det	1	90	24	33	8	41	EleRes	91%		70				2004			2004	1312	65		2.2		147	2216	11.4		1.3	0.6	13.3
D Det	1	90	24	33	8	41	EleOff	86%		72				2080			2080	1389	74		3.4		224	2378	12.1		2.0	0.6	14.7
D Det	1	90	24	33	8	41	HPEle	221%		43				1230			1230	539	125		10.7		712	2067	4.7		6.2	1.1	12.0
D Det	1	90	24	33	8	41	CHPgas	62%	134	-7	31		1445	-202	893		1242	722	145		13.6		906	2294	6.3		7.9	1.3	15.4
D Det	1	90	24	33	8	41	DisHea	100%		24		41		691		1093	1784	1093	82		4.6		309	2176	9.5		2.7	0.7	12.9
D Det	2	87	22	25	7	32	BoiGas	71%	91	22			985	622			1607	492	83	13.3	4.8	444	317	2452	5.5	5.0	3.5	0.9	15.0
D Det	2	87	22	25	7	32	EleRes	91%		57				1646			1646	1024	63	13.3	1.8	444	121	2274	11.4	5.0	1.3	0.7	18.5
D Det	2	87	22	25	7	32	EleOff	86%		59				1706			1706	1084	69	13.3	2.8	444	184	2403	12.1	5.0	2.1	0.8	19.9
D Det	2	87	22	25	7	32	HPEle	217%		36				1049			1049	427	112	13.3	8.8	444	588	2193	4.8	5.0	6.6	1.2	17.6
D Det	2	87	22	25	7	32	CHPgas	62%	103	-2	23		1115	-51	673		1064	558	128	13.3	11.1	444	741	2377	6.2	5.0	8.3	1.4	20.9
D Det	2	87	22	25	7	32	DisHea	100%		22		32		622		851	1473	851	76	13.3	3.8	444	252	2246	9.5	5.0	2.8	0.9	18.2
D Det	3	4	17	13	6	18	BoiGas	69%	53	17			568	498			1065	284	69	37.5	2.7	1250	183	2567	5.6	24.6	3.6	1.4	35.2
D Det	3	4	17	13	6	18	EleRes	90%		37				1080			1080	582	57	37.5	1.0	1250	67	2454	11.5	24.6	1.3	1.1	38.6
D Det	3	4	17	13	6	18	EleOff	85%		39				1114			1114	616	61	37.5	1.5	1250	101	2526	12.2	24.6	2.0	1.2	40.0
D Det	3	4	17	13	6	18	HPEle	210%		26				748			748	251	85	37.5	5.0	1250	331	2414	4.9	24.6	6.5	1.7	37.8
D Det	3	4	17	13	6	18	CHPgas	64%	58	5	12		621	142	356		763	311	93	37.5	6.1	1250	408	2513	6.1	24.6	8.0	1.8	40.6
D Det	3	4	17	13	6	18	DisHea	100%		17		18		498		483	980	483	64	37.5	2.1	1250	137	2432	9.5	24.6	2.7	1.3	38.1
D Sem	1	290	15	25	5	30	BoiGas	70%	85	15			921	432			1353	460	80		4.3		289	1722	5.5		3.5	1.0	10.0
D Sem	1	290	15	25	5	30	EleRes	91%		48				1386			1386	954	61		1.6		109	1557	11.5		1.3	0.7	13.5
D Sem	1	290	15	25	5	30	EleOff	86%		50				1442			1442	1010	67		2.5		166	1675	12.1		2.0	0.8	14.9
D Sem	1	290	15	25	5	30	HPEle	216%		29				833			833	401	106		8.0		533	1472	4.8		6.4	1.3	12.5
D Sem	1	290	15	25	5	30	CHPgas	63%	96	-6	21		1035	-186	618		849	518	120		10.0		668	1637	6.2		8.0	1.4	15.7

Transport

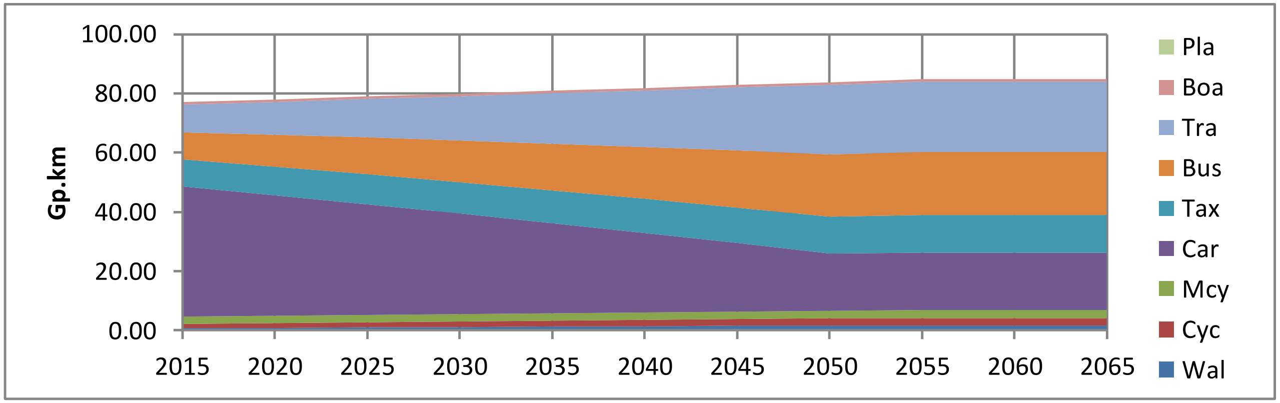
Scenario: transport passenger

Demand by mode

Shift from car to non-mechanised, bus, train

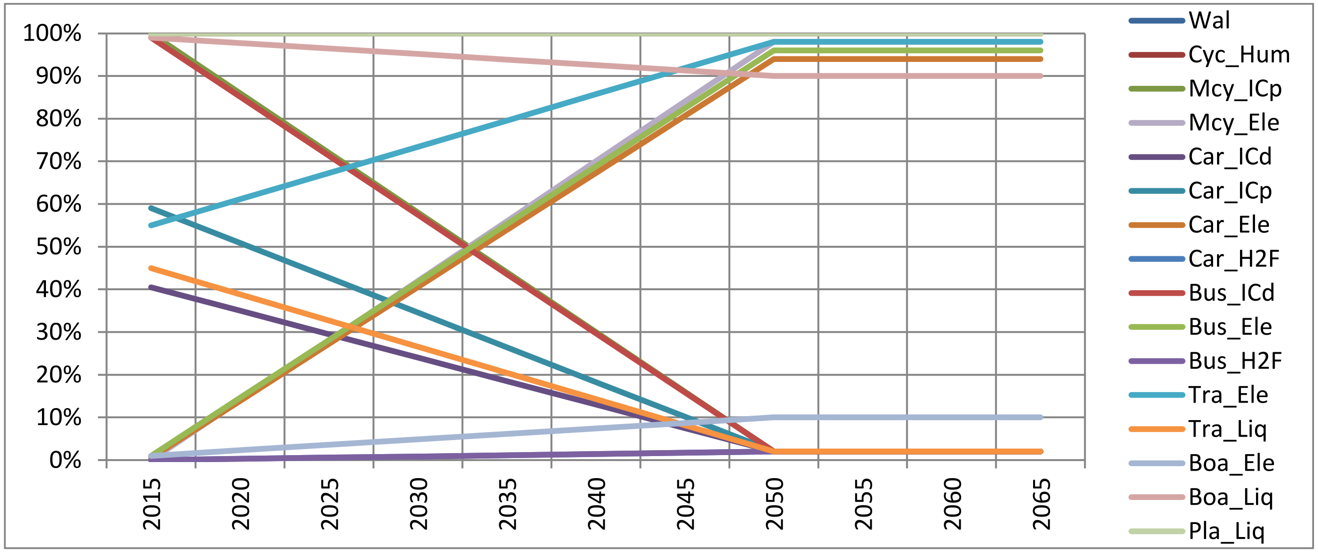


Passenger distance by mode

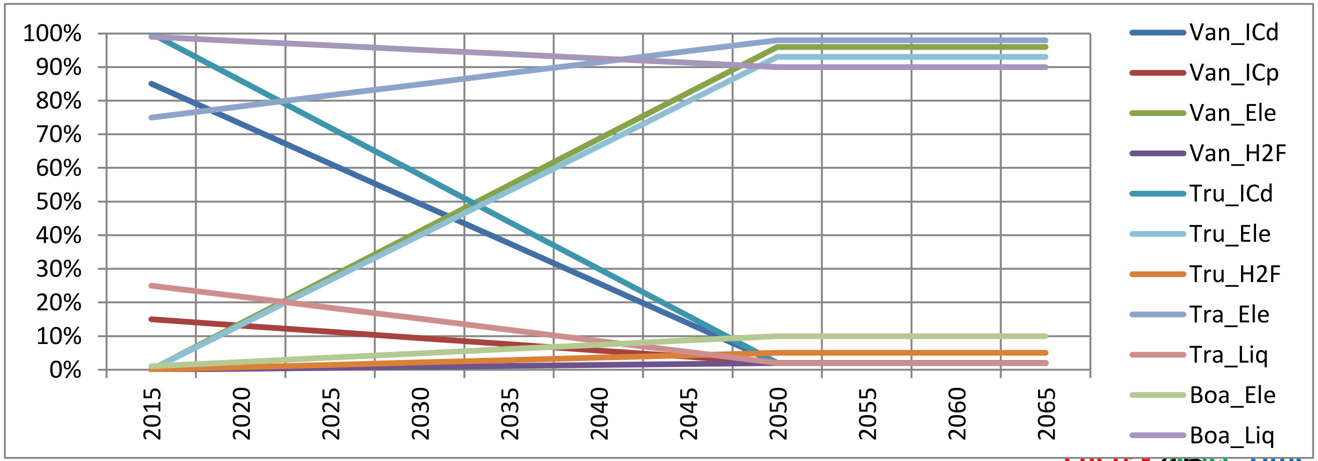


Scenario: transport technology share - shift to electricity

Passenger

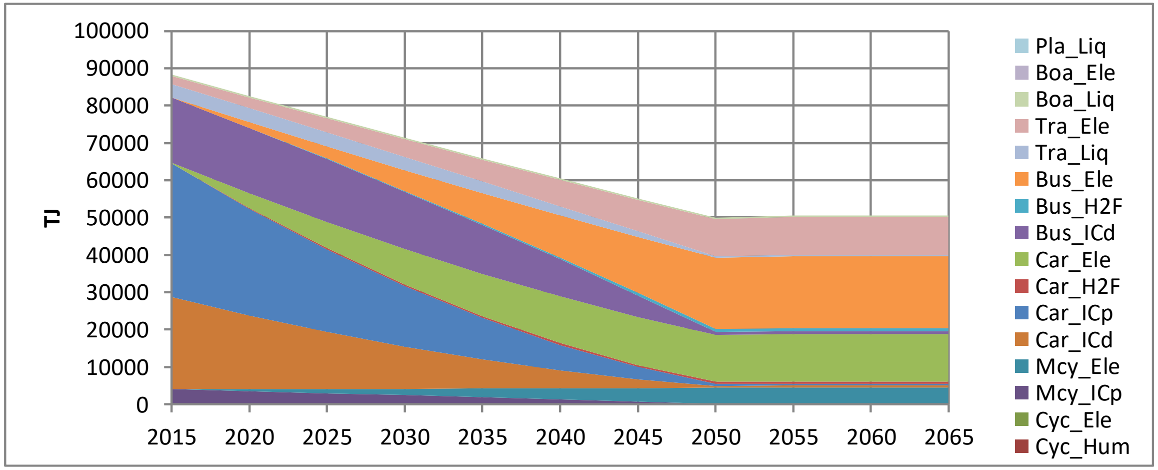


Freight

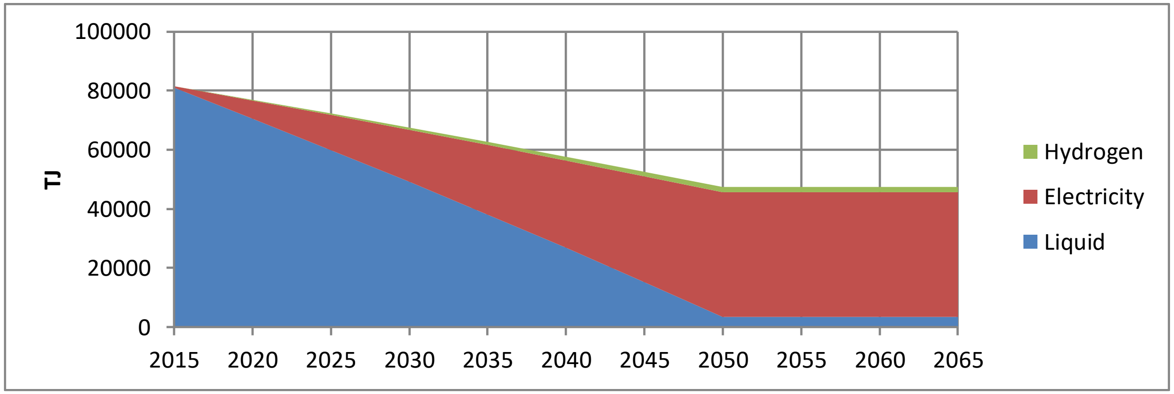


Scenario (London): transport energy

Passenger energy by technology



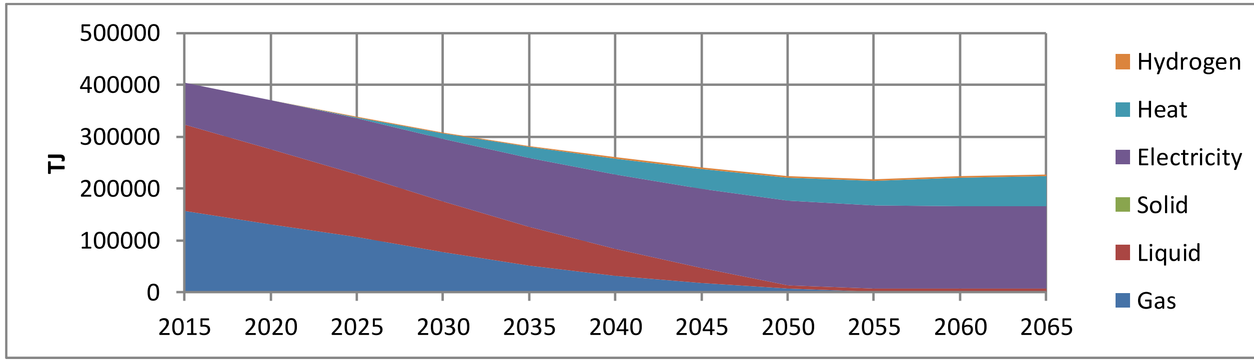
Energy for passenger and freight



Scenario (London)– demand and supply

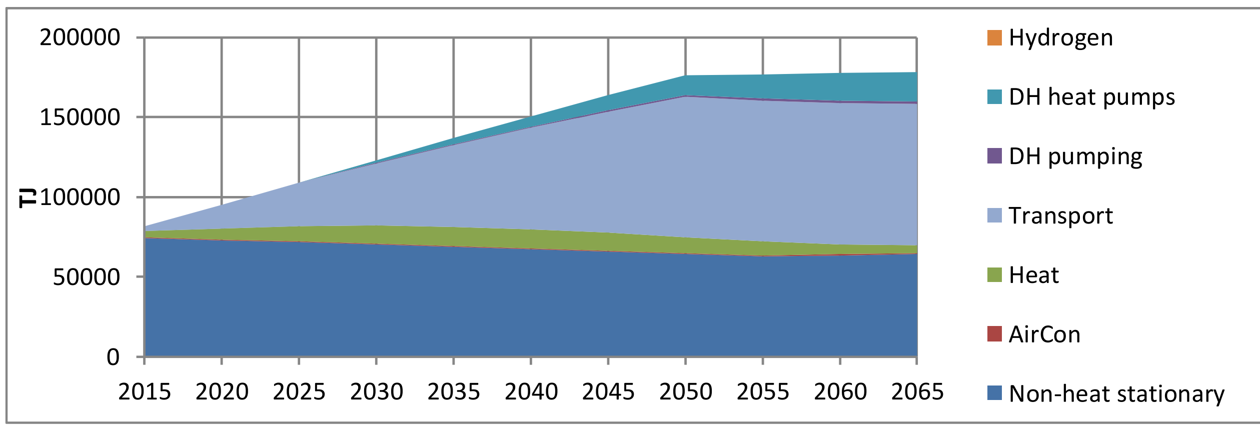
Deliveries

Shift from fossil gas and oil to electricity and DH



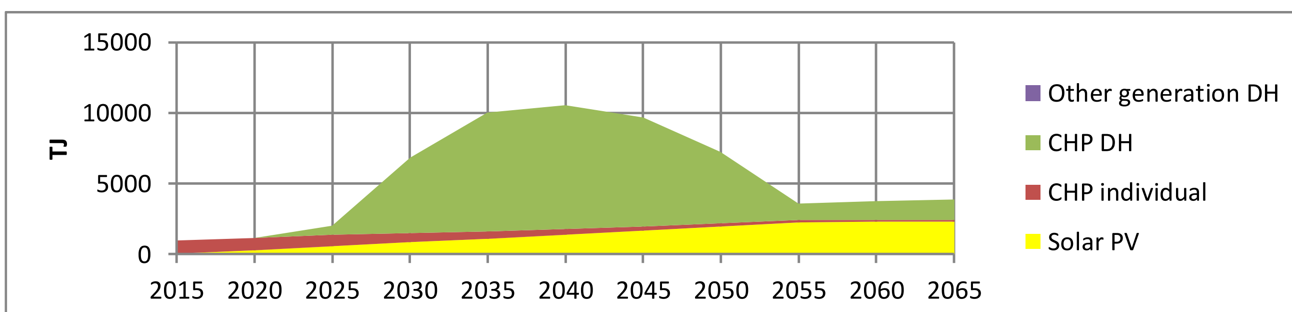
Electricity consumption

Increase for heating and transport



Electricity generation

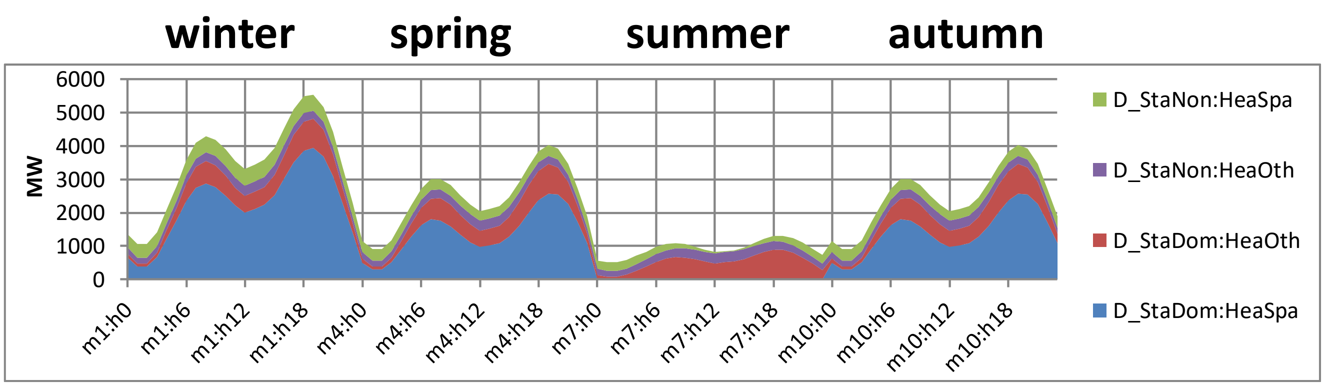
Steady increase in solar PV and increase then decline in CHP



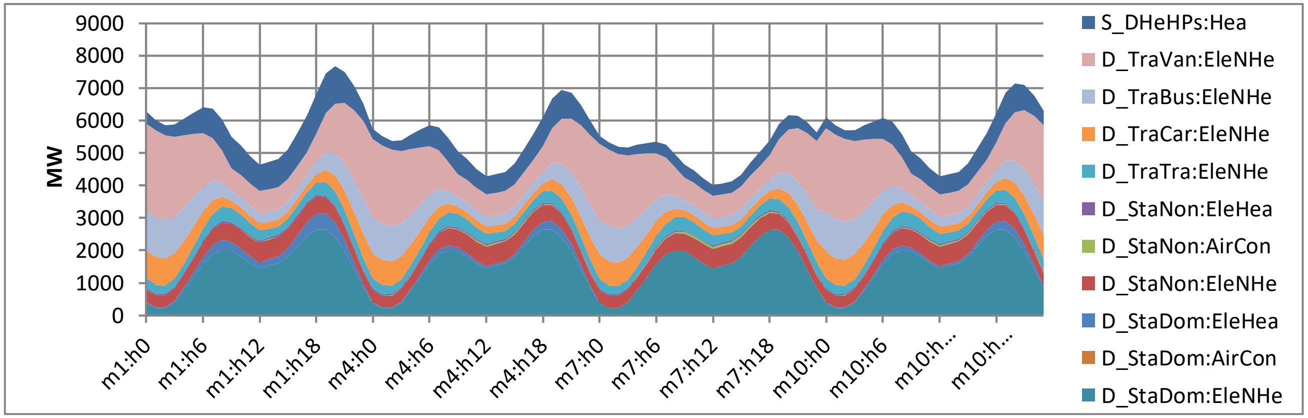
Scenario 2050 (London) heat and electricity dynamics

NB. dynamics crudely modelled

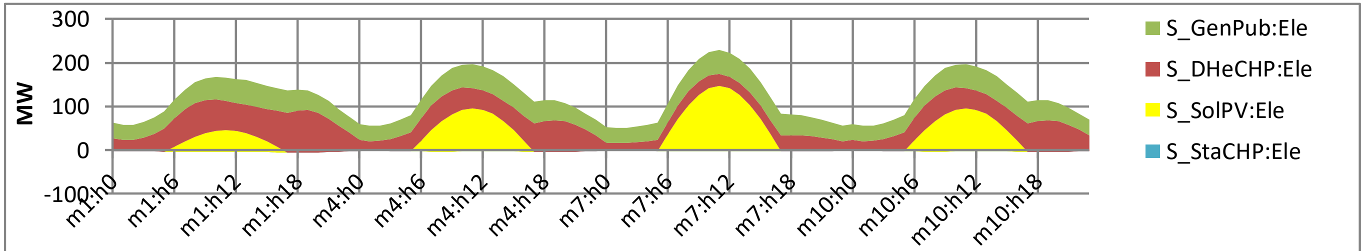
Heat



Electricity demand
Load manipulation with EV batteries



Electricity generation



Economics

Economics

INPUT UNIT COSTS (taxes and subsidies not included)

National energy

- Scenarios for energy costs and carbon contents

Technology

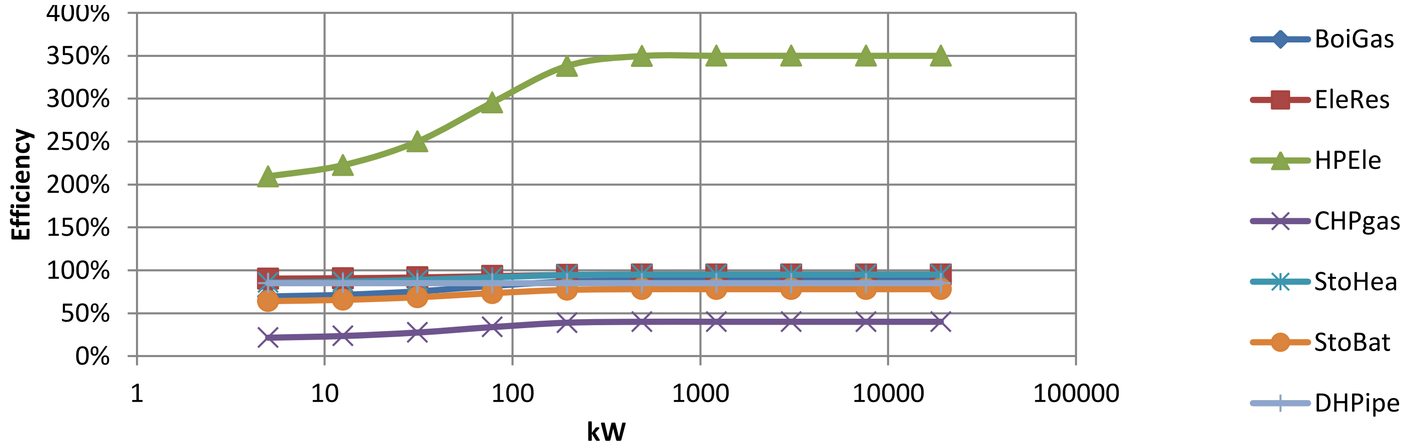
- Scale dependent unit capital and operational costs of technologies - energy efficiency, vehicles, energy converters, storage and networks

CALCULATION OF ANNUAL COSTS

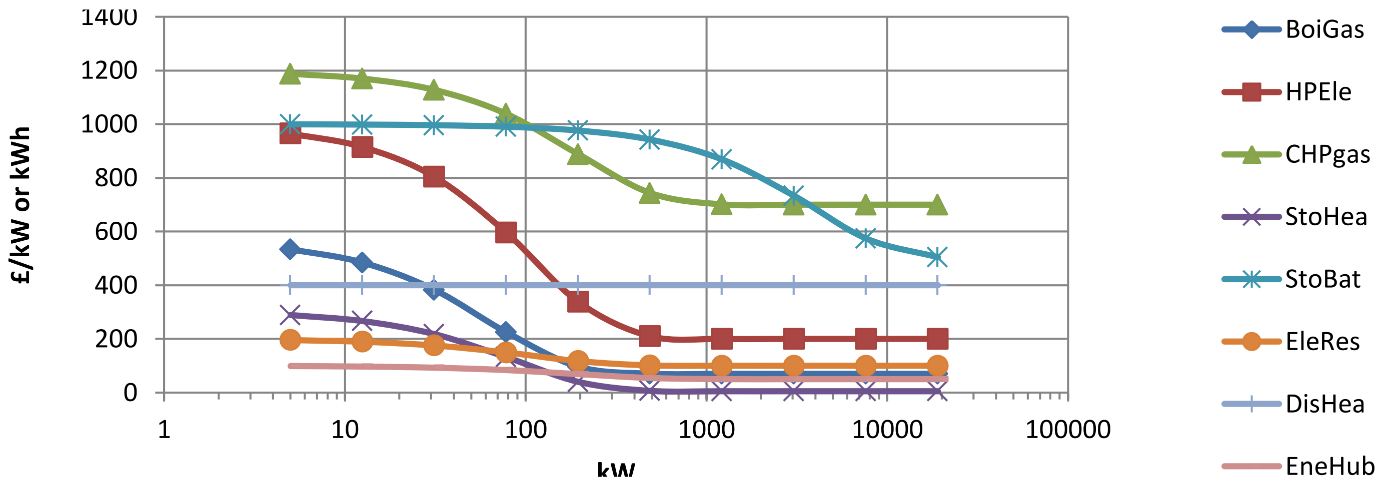
- Calculate annual costs and revenues of energy related services and technologies for consumers, suppliers and whole city.
- Capital costs of installed technology annuitised over technology lifetimes with a single discount rate
- Operation and maintenance costs of installed technology .
- Energy costs and revenues calculated with national energy costs
- Could calculate cost of air pollution health damage from premature deaths or years of lost life?

Technology scale economies

Efficiency



Capital costs



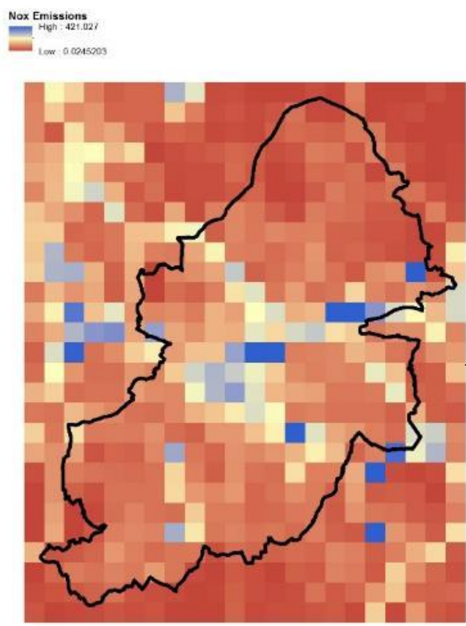
Air pollution

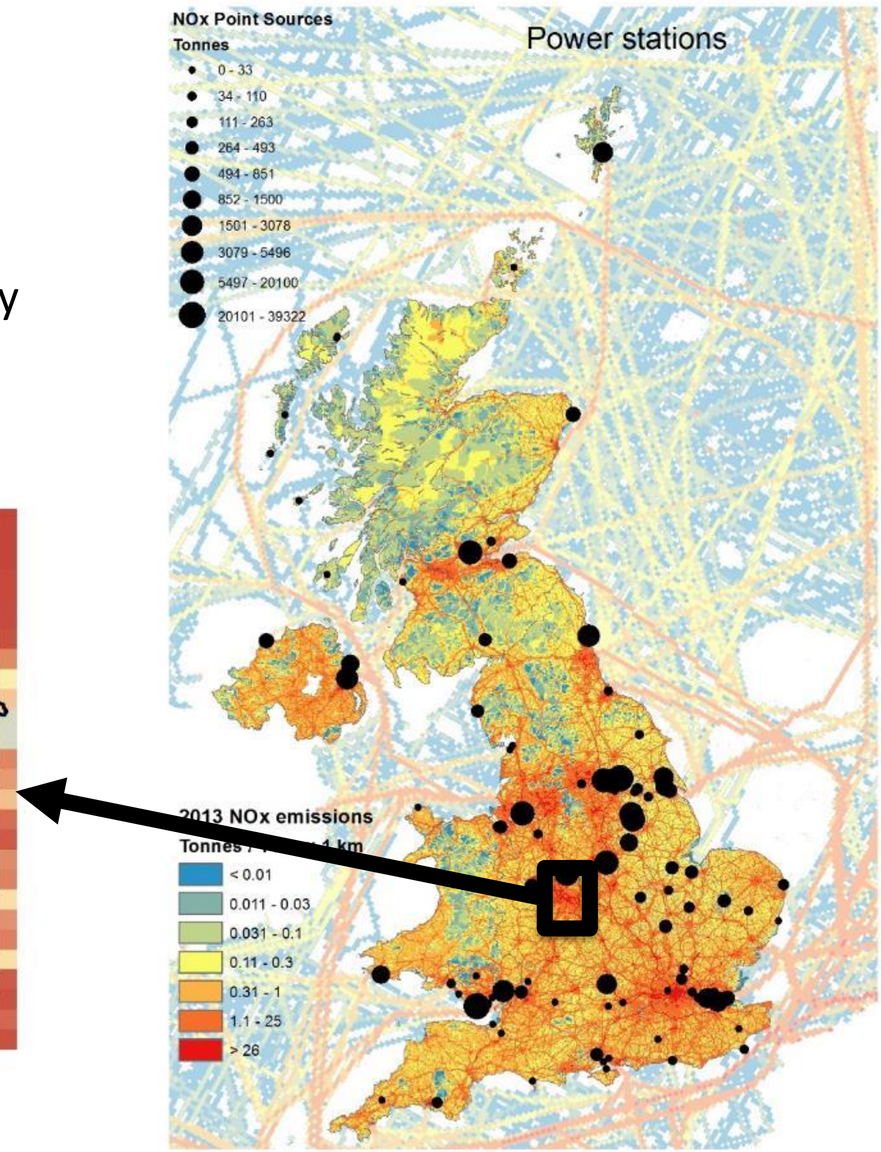
Air pollution calculation

1. Collate base year concentrations by source for city
2. Project city and national emissions
3. Project concentrations using:
    a. changes in emissions from sources
    b. NOx oxidation
    c. Secondary PM formation
4. Calculate premature deaths and years of lost life

Air pollution data:

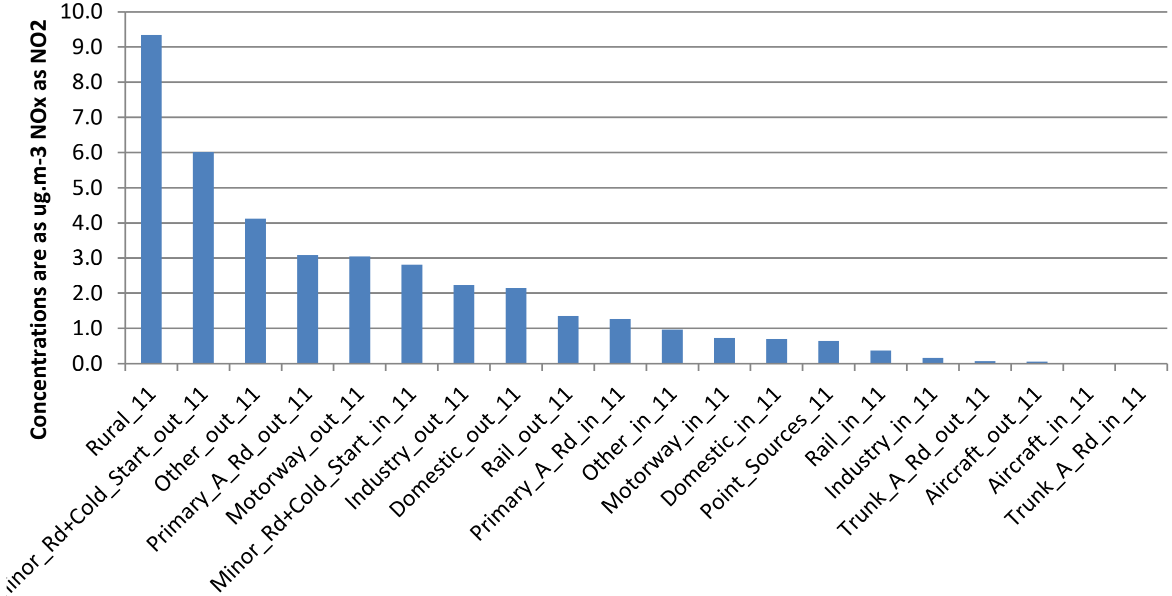
- Emissions available by source
- Contribution to concentration as per algorithm below
- Concentration isolated by Local authority
- External sources contribute



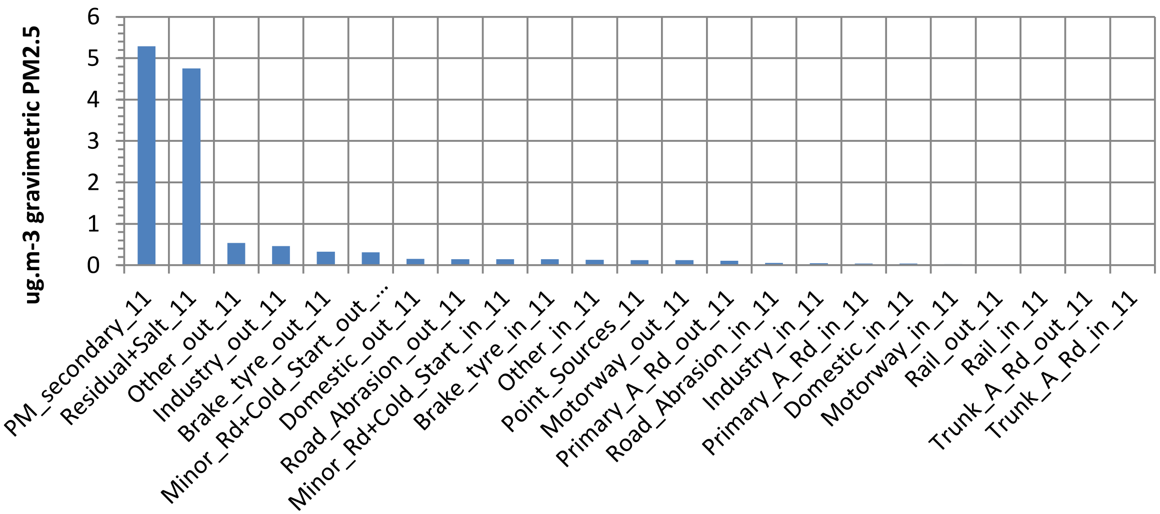


Air pollution base year concentration by source - Birmingham

NOx as NO2



PM2.5



Emission to concentration model

Multiply base year concentrations Cb for each source by the ratio of future emission/formation index (Icf) which is the calculated future year NO2 (primary and 'rural') and PM2.5 (primary and secondary) divided by the calculated base year index (Icb) to obtain future concentrations Cf.

For each source:

Cf = Cb Icf / Icb µg/m3

The proposed methods for calculating the NOx and PM2.5 indices are on the next 2 slides.

NOx to NO2

For base and future year:

1. Estimate city and national (and European?) NOx emissions (kt) from different sectors – transport, electricity etc.

2. Estimate fraction f(NO2) of city and national NOx from these sources that is emitted as nitrogen dioxide (NO2), with the rest being nitric oxide (NO)

3. Estimate oxidation of city and national NO to NO2 using oxidation equation with NO2 and ozone oxidants

4. Normalise calculated NO2 to Defra base year value.

5. Result is city and rural (or background) concentration indices; $Ic_{NO2(c)}$ and $Ic_{NO2(r)}$ (µg/m3)

Secondary PM2.5

For base and future year:

1. Assume UK (and Europe) emissions of:
   - Primary PM2.5
   - PM2.5 precursors: nitrate, sulphate and ammonium

2. Estimate formation of secondary PM2.5 to obtain background concentration index for each city with a linear equation:
   $Ic_{PM2.5}$ = k1 NOx + k2 SO2 + *(k3 NH3 assumed constant)*

3. Add national primary and secondary PM2.5 to give PM2.5 (rural/background) concentration index for city; $Ic_{PM2.5(r)}$

Air pollution: conclusions, solutions and questions

Conclusions

- Large variation in internal/external contributions to concentrations city to city
- For individual city policy, assumptions about what happens outside city critical

Solutions (technical)

- Renewable electricity (except biomass) and electrification are **a general solution to NO2 on city and larger scales, and reduce GHG emission, requiring city and (inter)national policy**
- **PM** heterogeneous and primary PM from natural sources and non-exhaust vehicle and secondary PM from ammonia hard to control.

Some questions

- Are natural PM sources important in terms of health – dust, salt, etc.?
- How robust are the health response:concentration relationships, including the synergy between PM2.5 and NO2?
- What about exposure in confined spaces – buildings & transport - where people spend ~90% of their time? Could air cleaning (removal of NO2, PM etc.) be used here?
- Will switching from diesel to gasoline reduce NOx but increase CO2?

Model algorithm

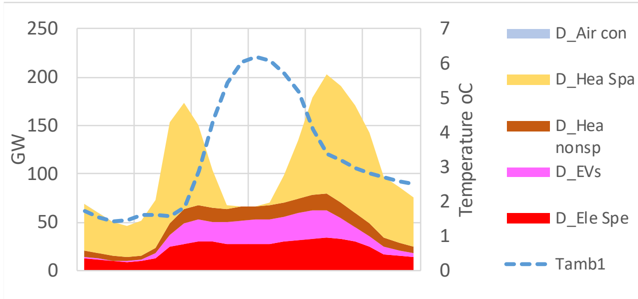
x

Demands	Weather independent	(Use pattern) x (average demand)
	Weather dependent	(Use pattern) x (Tint_oC - Tamb_oC) (Specific heat loss) - (IncGain)
	Elec: general	(Use pattern) x (average demand)
	Elec: BEVs	(vehicle use pattern) x (average demand) x (weather sensitivity)
	Hydrogen demand	Variable demand for heat + average demand for industry/NH3
	Ammonia demand	Average demand
Generation	Hydro	follows general use pattern
	Sol PV	hourly varying resources
	Win_on	hourly varying resources
	Win_off	hourly varying resources
	Nuclear	base load
	Flexible	dispatched if shortage
BEV	Charge	if battery nearly empty
Heat supply	**Consumer HP**	(Heat demand) (HP heat share)
	Elec use - cons HP	Consumer HP / COP(Tdemand, Tamb)
	District heating	(Heat demand) (DH heat share)
		1 Heat from store
		2 Heat from heat pumps to demand if store empty
		3 Heat and elec from CHP if more heat needed
Surplus	If surplus electricity	1 To EV battery
	and store not full	2 To electricity store
		3 Put heat into DH store using DH heat pumps
		4 To H2 electrolyser
		5 To DACCCS
Deficit	If deficit electricity	1 From electricity store
		2 From flexible generator

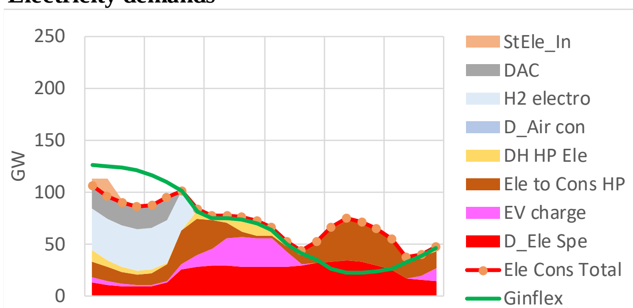
Winter day

Day of year 51 February | **2010 met year** | **Dbas2CDH30%**

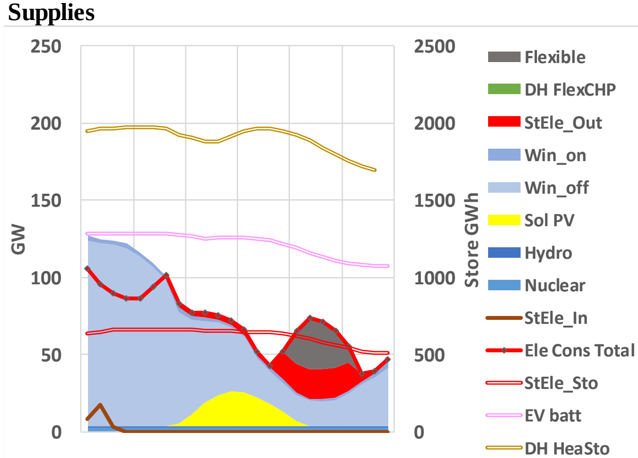
Demands



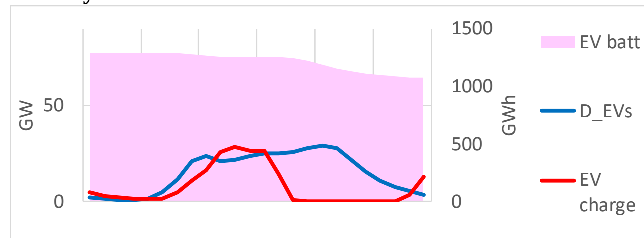
Electricity demands



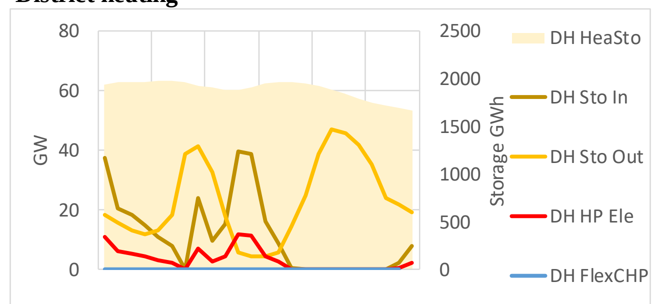
Supplies



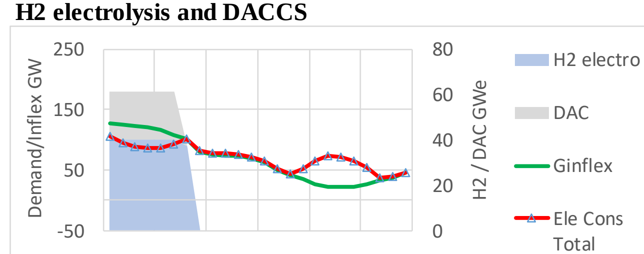
Battery vehicles BEV



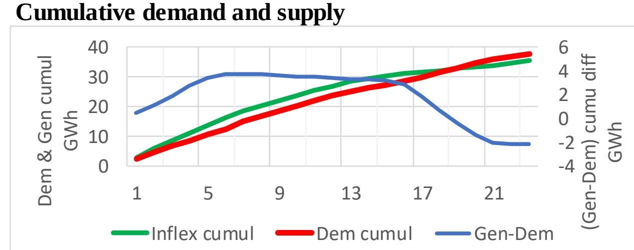
District heating



H2 electrolysis and DACCS



Cumulative demand and supply



Energy Space Time

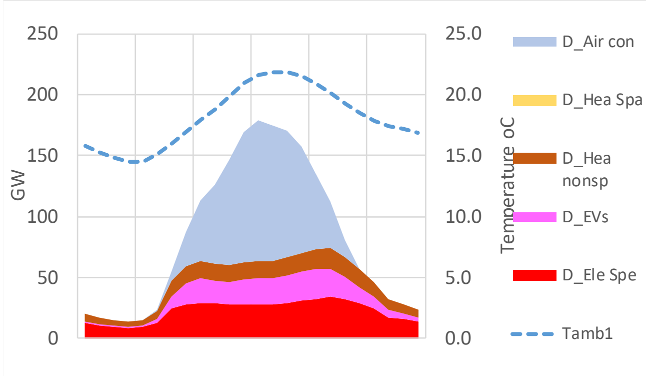
Summer day

Day of year 194 July

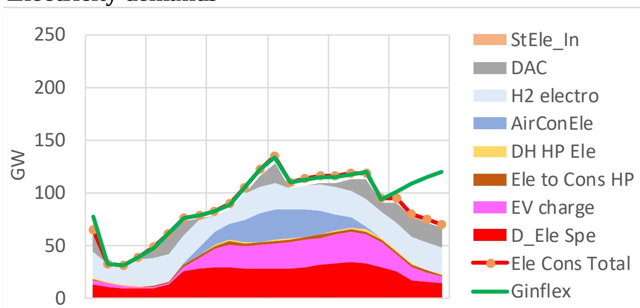
2010 met year

Dbas2CDH30%

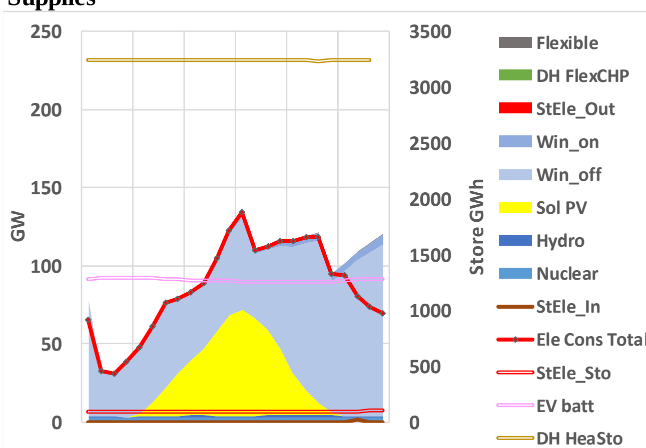
Demands



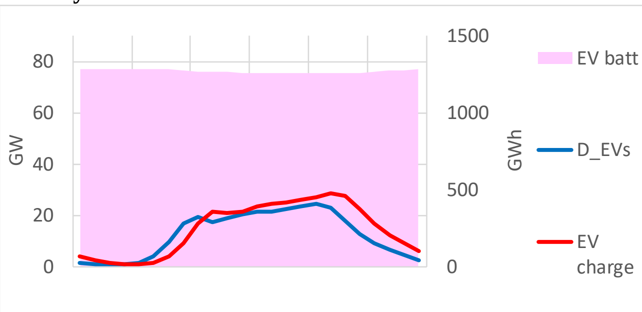
Electricity demands



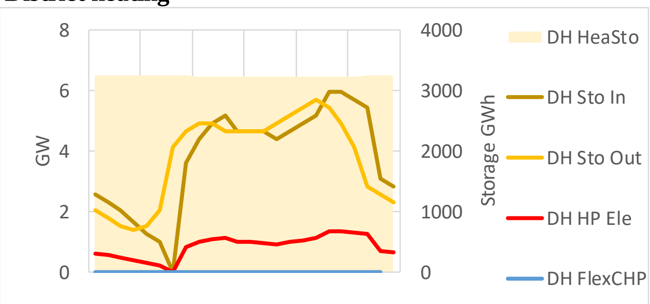
Supplies



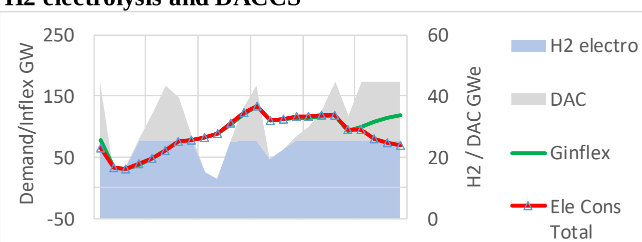
Battery vehicles BEV



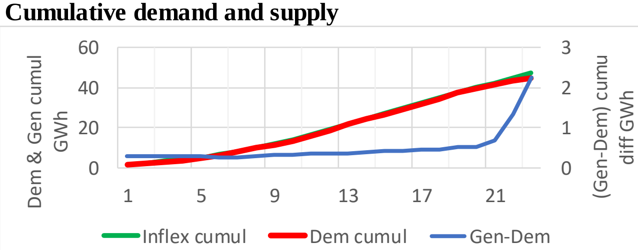
District heating



H2 electrolysis and DACCS



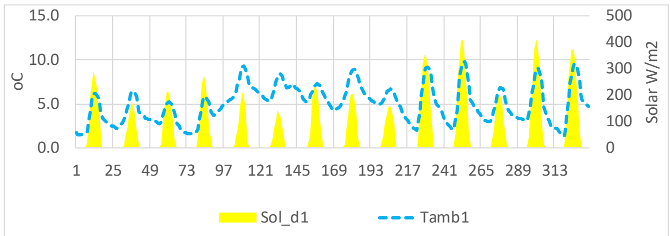
Cumulative demand and supply



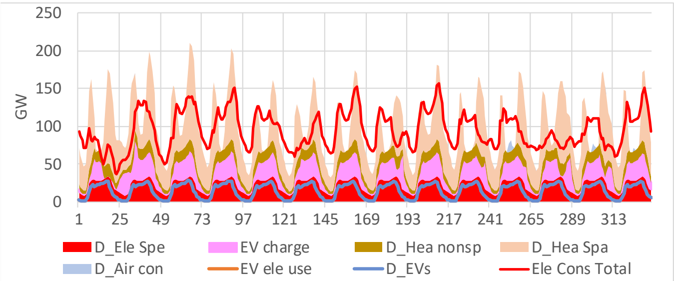
Winter fortnight

Fortnight from day	51	February	2010 met year

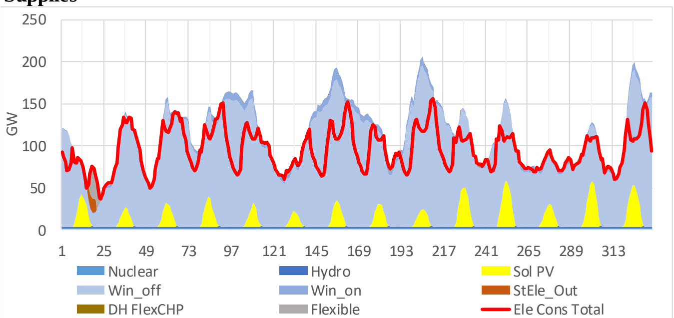
Meteorology



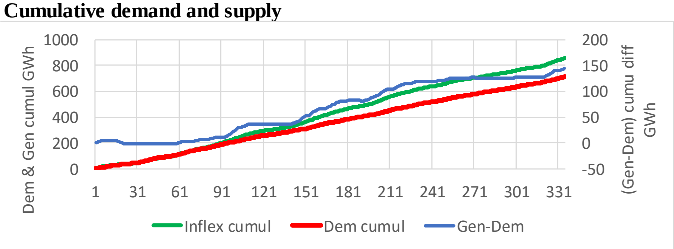
Demands



Supplies

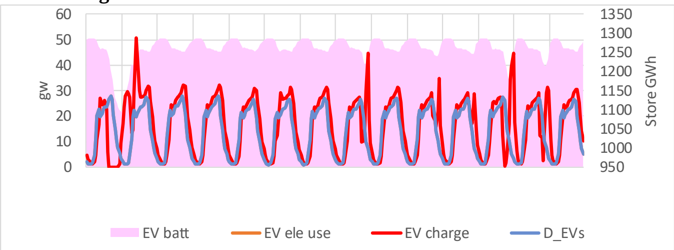


Cumulative demand and supply

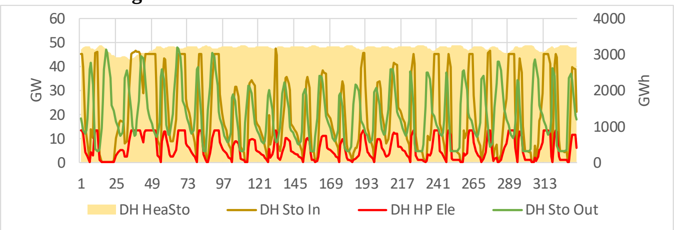


Fortnight from day	51	February	2010 met year

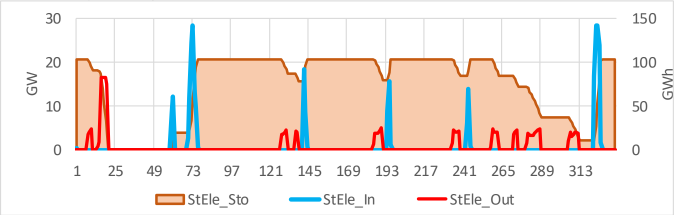
BEV storage



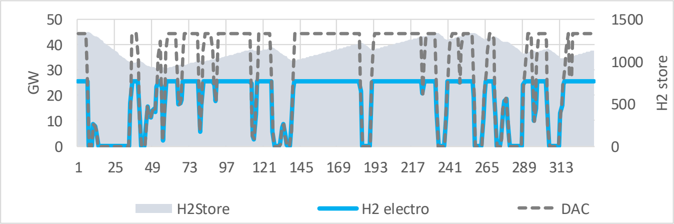
District heating



Electricity storage



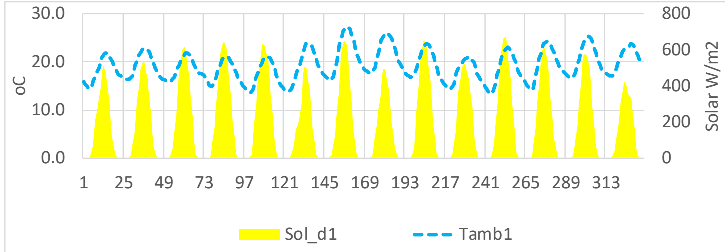
H2 electrolysis and DACCS



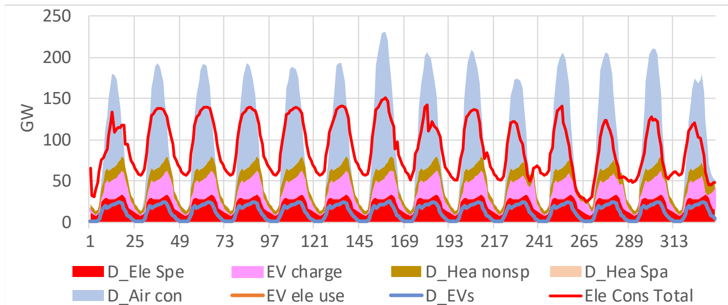
Summer fortnight

Fortnight from day	194	July	2010 met year

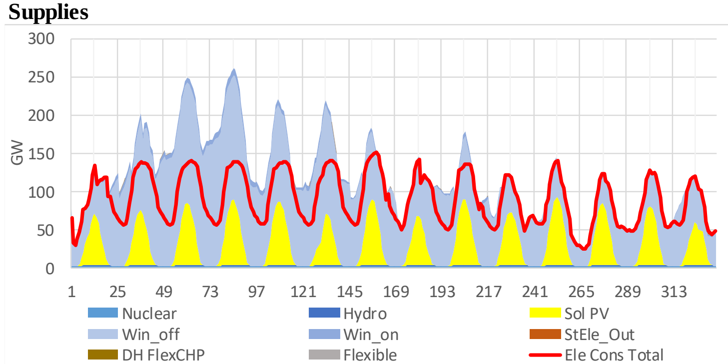
Meteorology



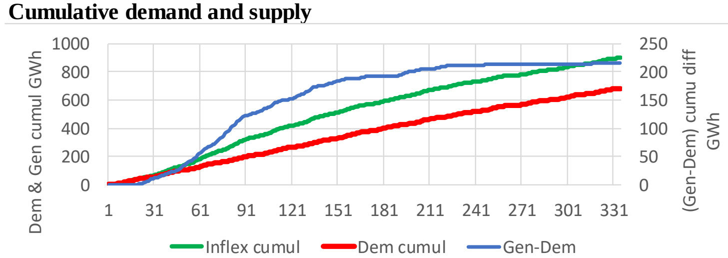
Demands



Supplies

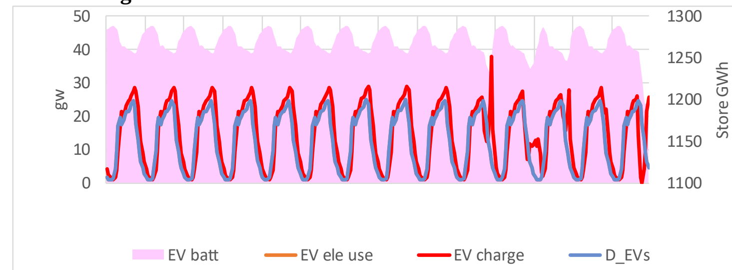


Cumulative demand and supply

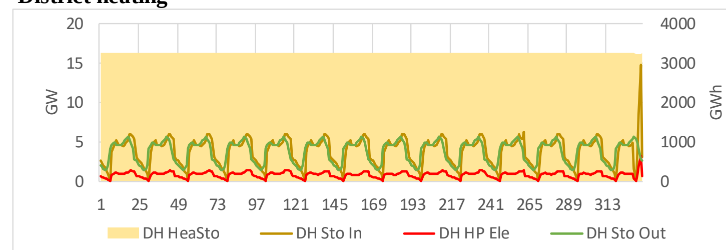


Fortnight from day	194	July	2010 met year

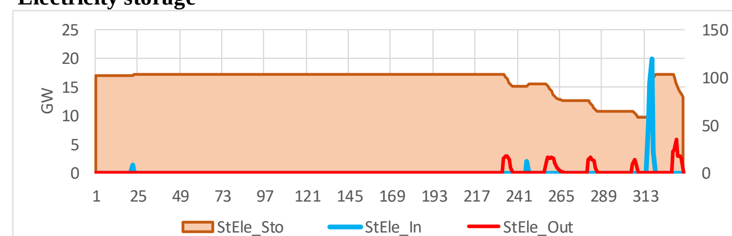
BEV storage



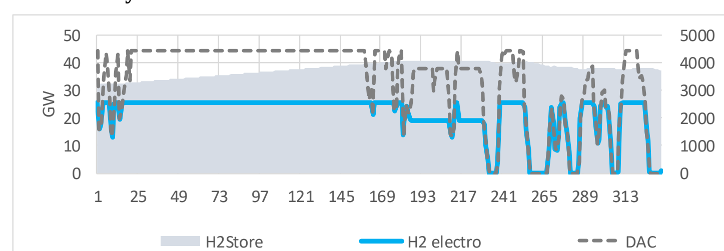
District heating



Electricity storage



H2 electrolysis and DACCS



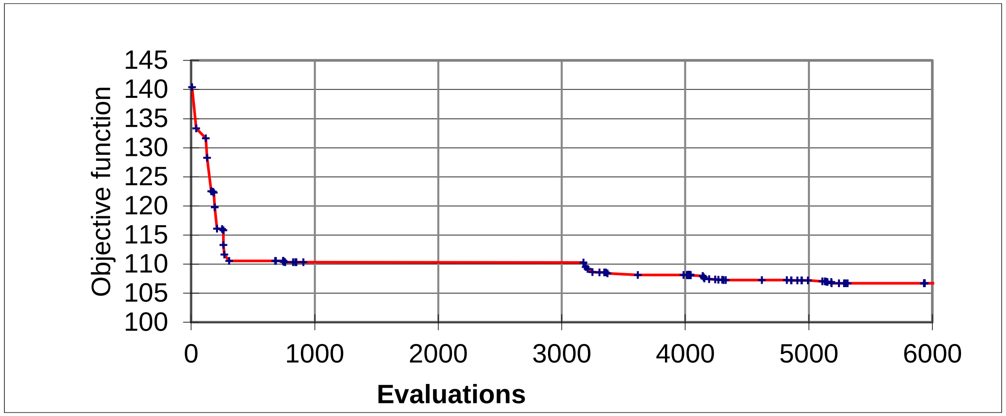
Optimisation – main decision variables

The main decision variables are heating shares, and the capacities of generators, stores, electrolysers and DACS.

Heat Share	SUPPLY					INTERMEDIATE							
	Renewable			Other		Electricity storage					H2		DAC
DH share	Sol PV	Win_on	Win_off	Nuclear	Flexible	StEle_In	StEle_Sto	StEle_Out	DH HP	DH HeaSto	H2 electro	H2 store	DAC
%	GWe	GWe	GWe	GWe	GWe	GWe	GWh	GWe	GWe	GWh	GWe	GWh	GWe
30%	**120.0**	**16.6**	**178.2**	**3.3**	**40.0**	**28.5**	**103.7**	**17.9**	**13.4**	**3252.6**	**25.5**	**4081.7**	**19.0**
70%	120	200	400	3.30	100	100	300	100	50	10000	150	20000	30
70%	15	15	15	3.30	0	3	30	3	0	0	0	0	0
MaxGW	99.9	16.4	178.0	2.8	39.8	28.5	103.7	16.6	13.4	3250	26	4067	19
MinGW	0.0	0.1	4.9	2.8	0.0	0.0	0	0.0	0.0	671	0.0	566	0.0
Eff	*20%*			*40%*	40%	93%	86%	93%			75%		
TWh	**136**	**43**	**873**	**25**	**3**	**4**	**104**	**3**	**31**	**3253**	**166**		**113**
CapFac	13%	**30%**	**56%**	85%	0.7%	1.4%	11%	2.0%	7%	11%	74%		68%
£/kW	400	1100	1300	8500	350	25	100	25	2000	5	500	5	*7000*
Yrs	30	25	30	50	35	25	25	25	25	40	20	30	*20*
G£	48	18	232	28	14	1	10	0	27	16	13	20	*133*
G£/a	2.6	1.1	12.6	1.2	0.7	0.0	0.6	0.0	1.6	0.8	0.9	1.1	*9.4*
OM%cap	1.0%	2.1%	1.7%	2.0%	1.0%	2.0%	2.0%	2.0%	2.0%	1.0%	1.0%	1.0%	*2.0%*
G£/a	0.5	0.4	3.9	0.6	0.1	0.0	0.2	0.0	0.5	0.2	0.1	0.2	*2.7*
G£/a				0.2	0.3								
G£/a	3.1	1.5	16.5	2.0	1.2	0.1	0.8	0.0	2.2	0.9	1.0	1.3	*12.0*
p/kWh	**2.3**	**3.4**	**1.9**	**8.1**	**44.5**	**1.6**	**0.8**	**1.2**	7.1	0.0	*0.6*	0.0	*10.6*
O&M%	18%	34%	31%	47%	20%	33%	33%	33%	33%	21%	14%	18%	28%
% Cost	4%	2%	23%	3%	2%	0%	1%	0%	3%	1%	1%	2%	17%

Optimisation – approaching a minimum

Marginal improvements in optimum gradually reduce



Even near the optimum large changes in decision variables (design) possible