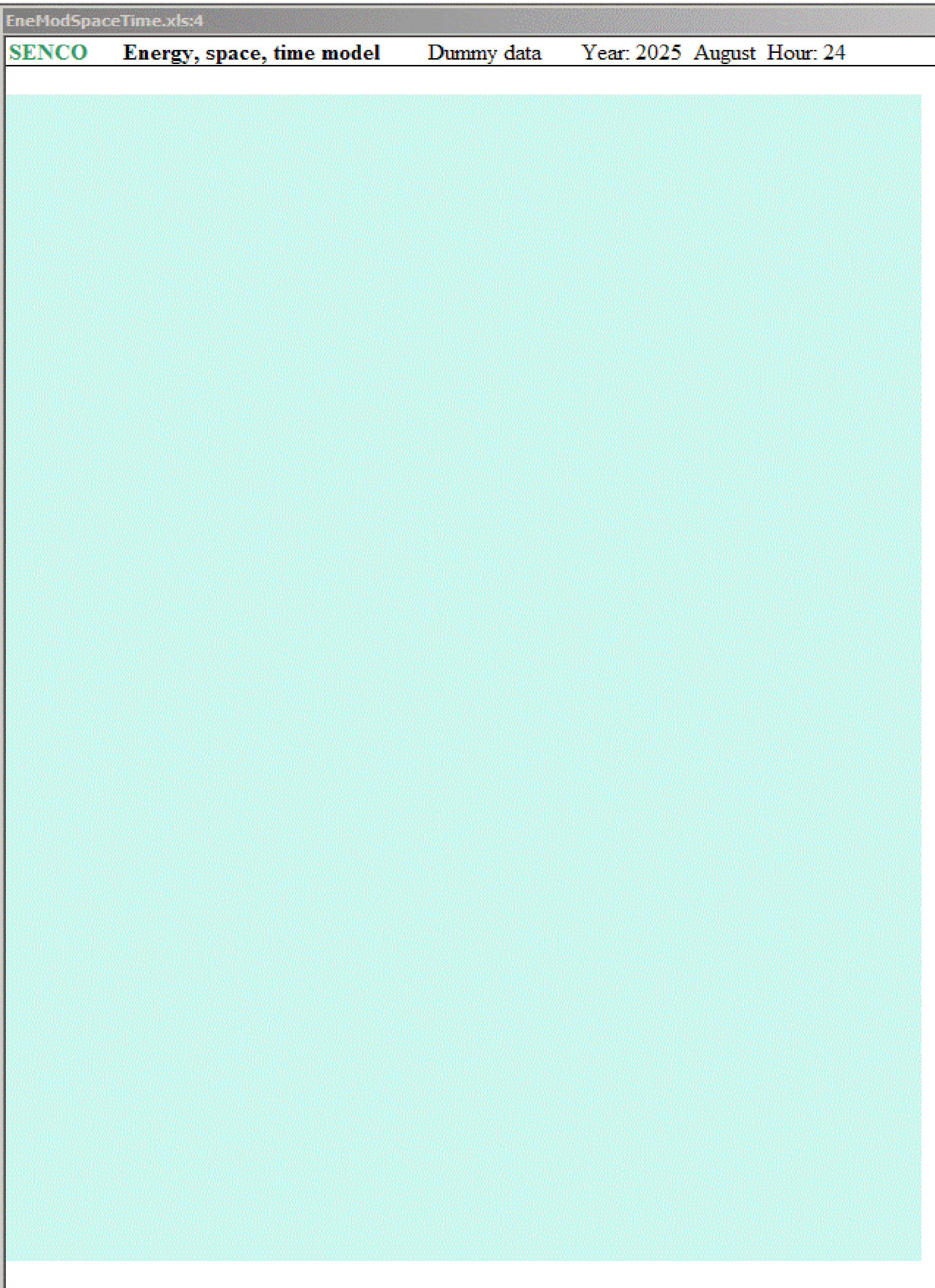
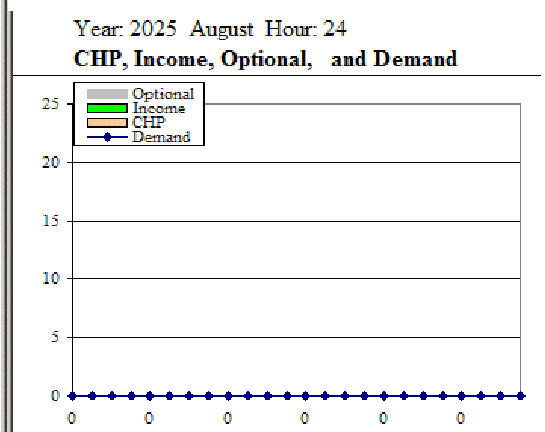


Renewable UK

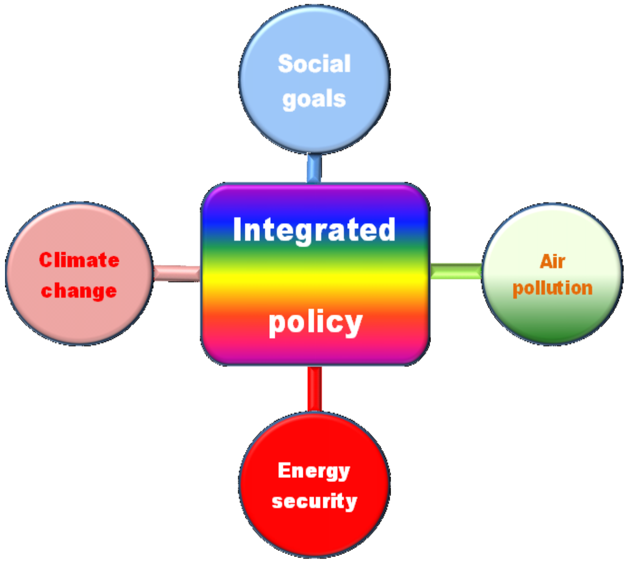
a low regret energy strategy to meet security, climate and air pollution objectives

Mark Barrett
Energy Space Time group

(run presentation to see animations)

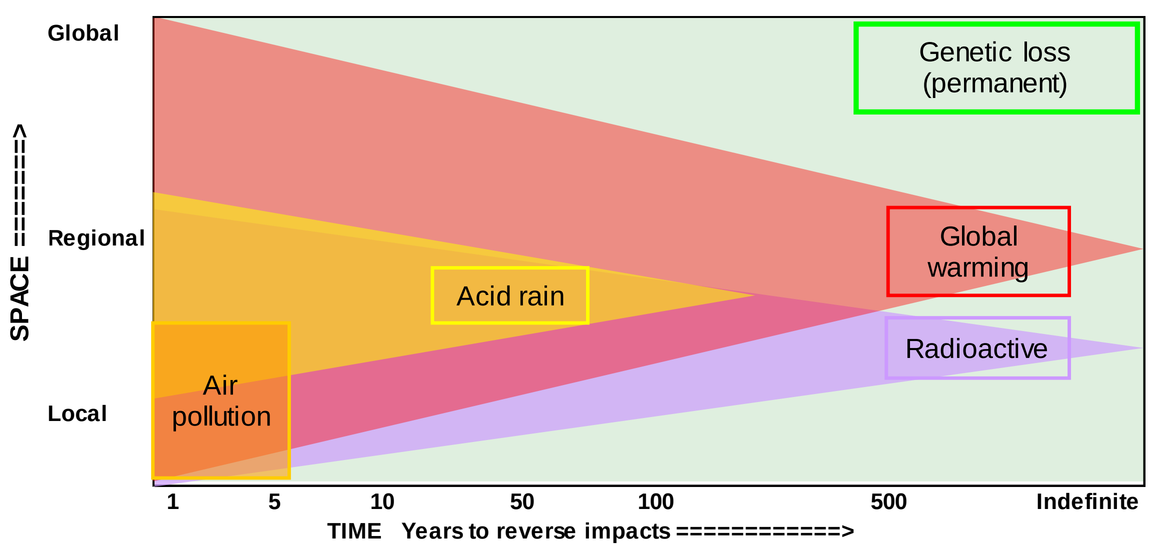


Integrated policy



Integrated, low risk, reversible policy for:

- Social well being
- Energy security
- Climate change
- Air pollution



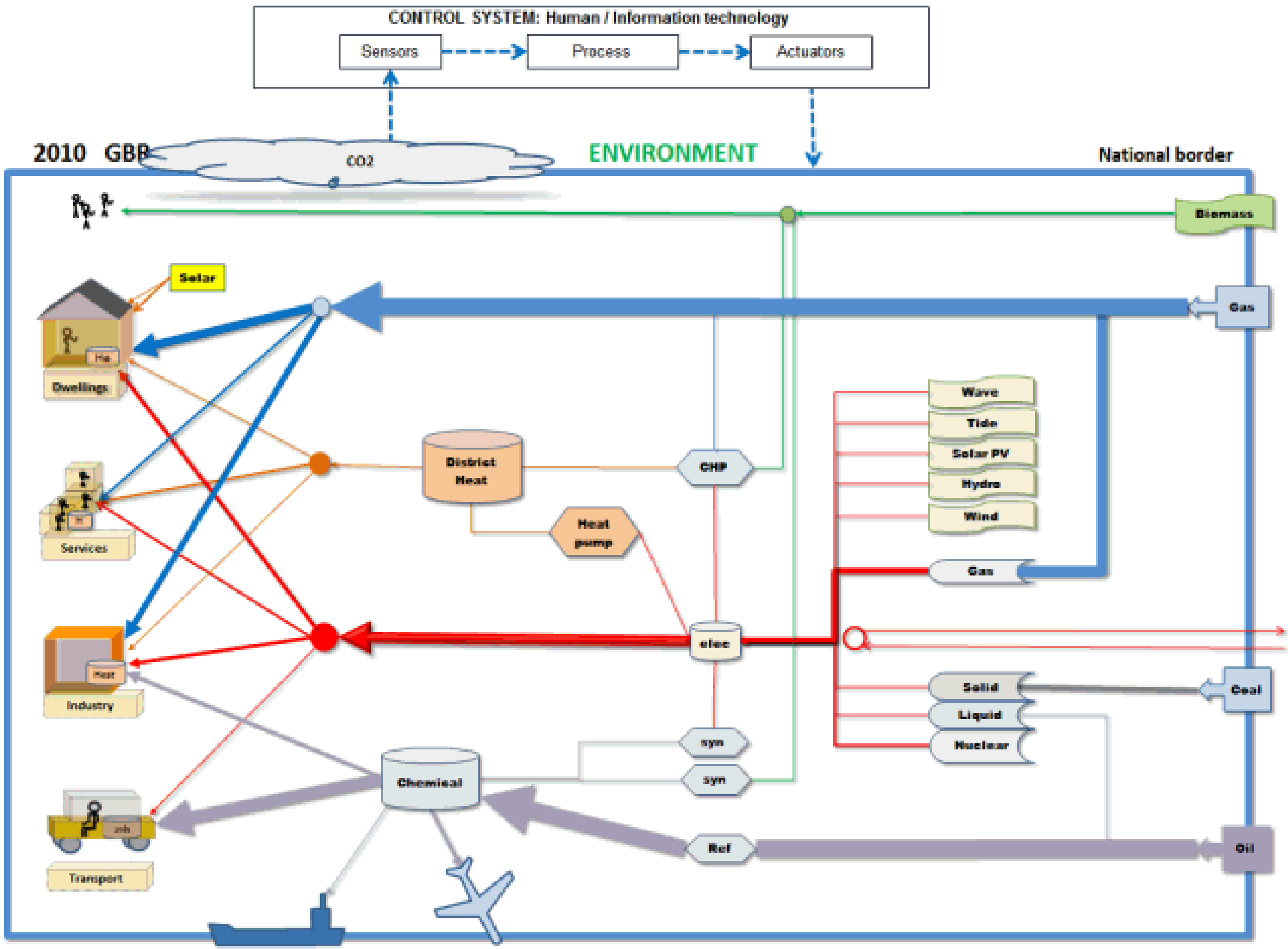
Designing a national energy system

1. Demand

2. Supply

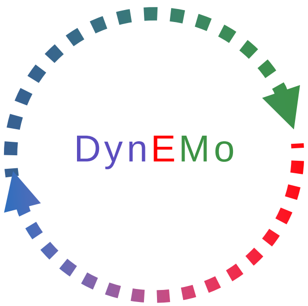
3. Integration

4. Operation



Energy Space Time

DynEMo dynamic energy model

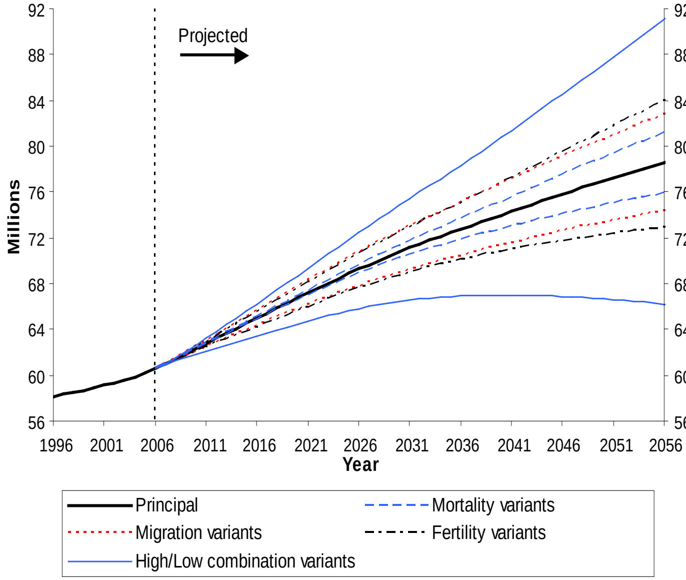


Models whole energy system of principal national consumer and supplies, vectors, storage and a representation of electricity trade

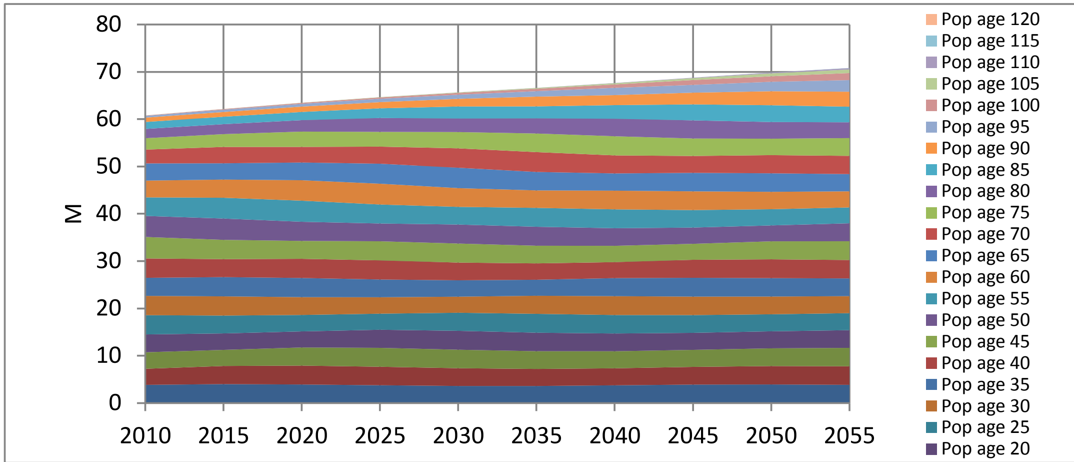
- **Simulates major energy flows over minutes to months and years in scenarios**
- **Has detailed people-dwelling data and modelling**
- **Includes modelling of electricity, heat and chemical stores.**
- **Has operational control (smart) algorithms**
- **Calculates system capital and operational costs with some optimisation**
- **Model run and validated for GBR and FRA**

Drivers - demography, households and dwellings

Population uncertainty

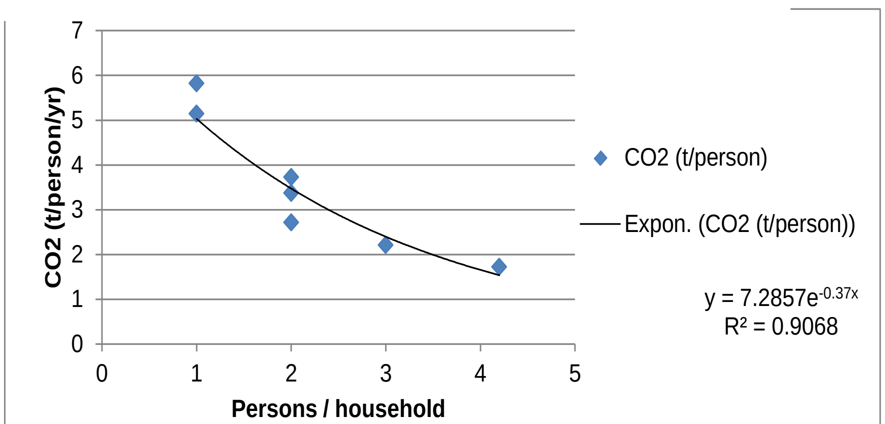


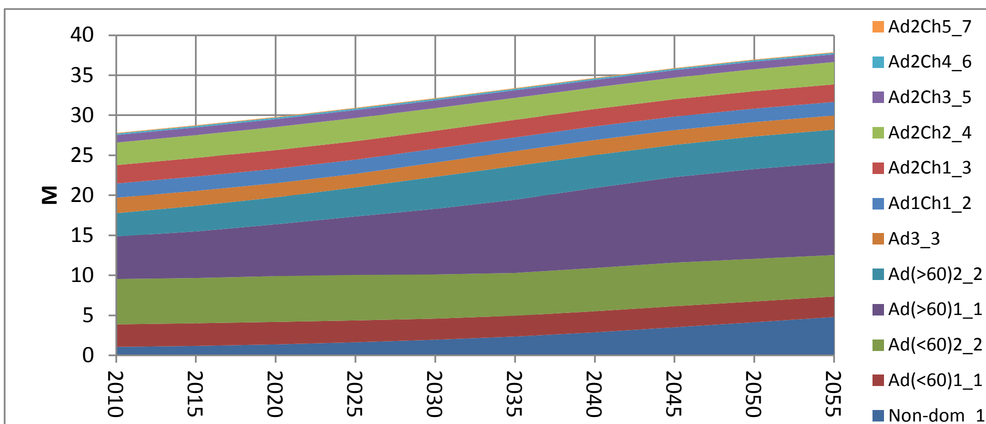
Population: ageing



More energy and carbon per person in small households

Households/dwellings - smaller





Stationary sector strategy

EFFICIENCY

- insulation
- ventilation control/heat recovery
- standards for equipment (appliances, lighting etc.)

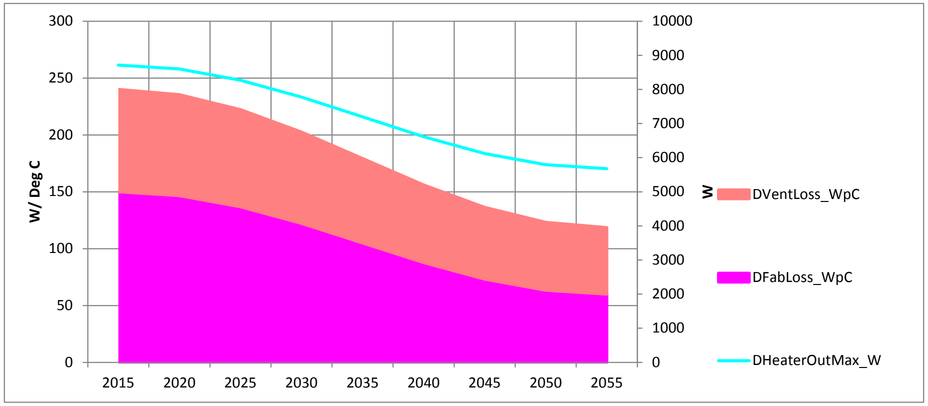
HEATING

Replace gas boilers (keep some for back-up) with:

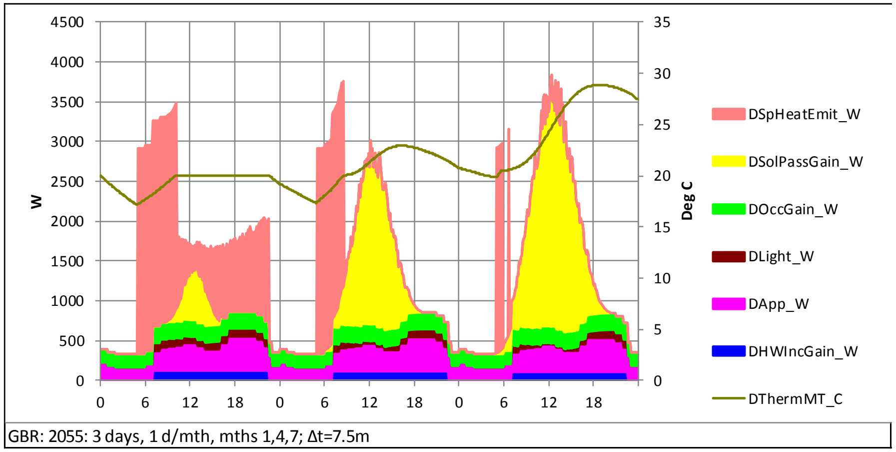
- district heating in high density areas
- CHP and heat pumps with storage in large isolated heat loads – industry, hospitals etc.
- heat pumps – in low density areas where storage space available

Domestic

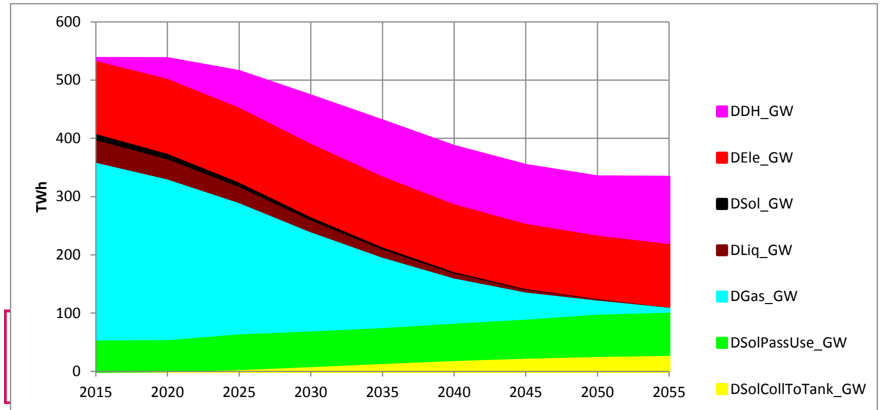
2015-2055 Evolution across years
Dwelling space heat loss (W/oK)



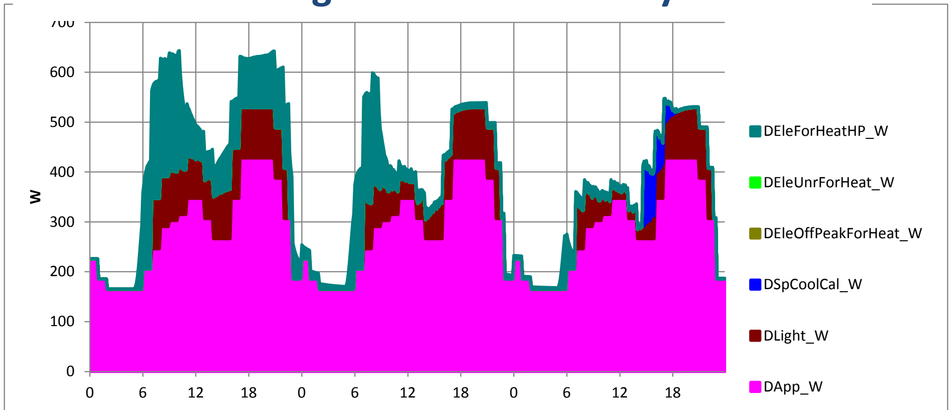
2055 dynamics: winter, spring, summer days
Average house: useful energy



2015-2055 Deliveries



2055 dynamics: winter, spring, summer days
Average house: electricity

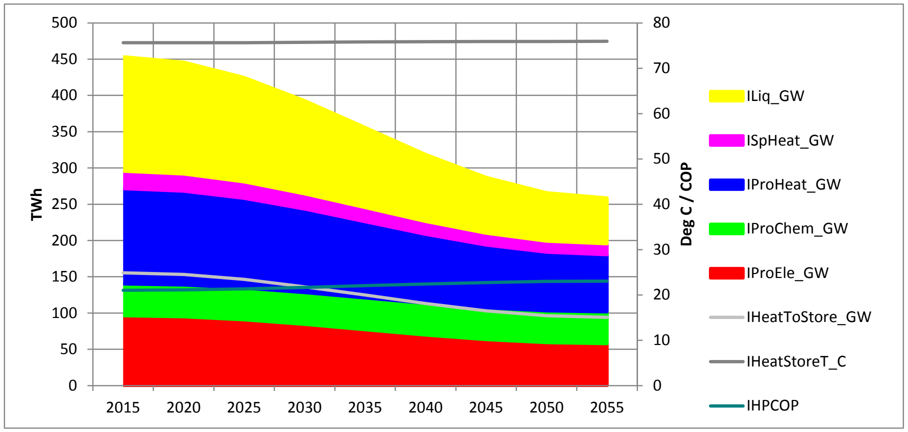


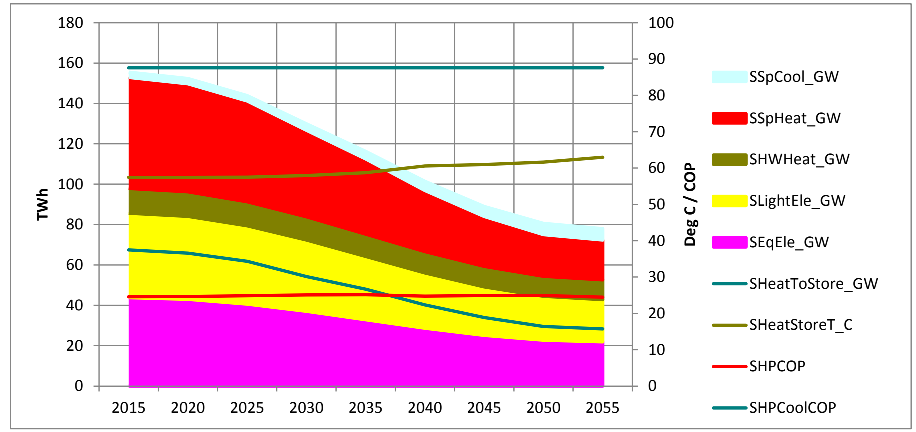
Demand – industry and services

Industry

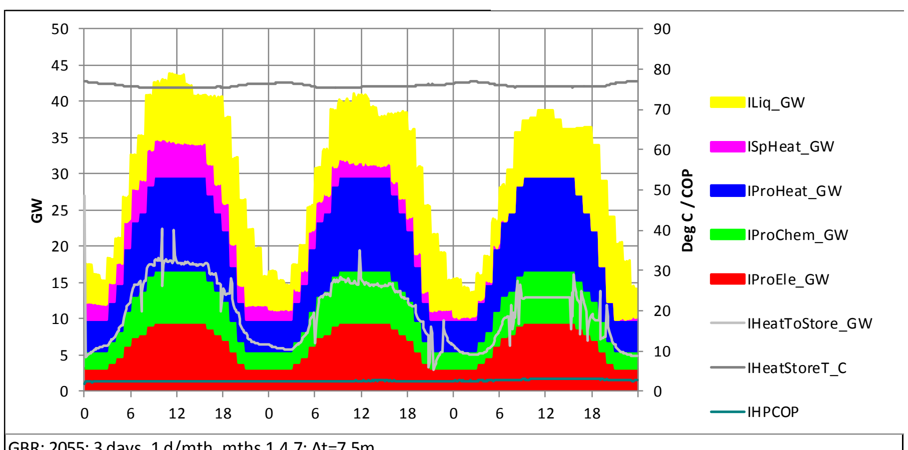
Services

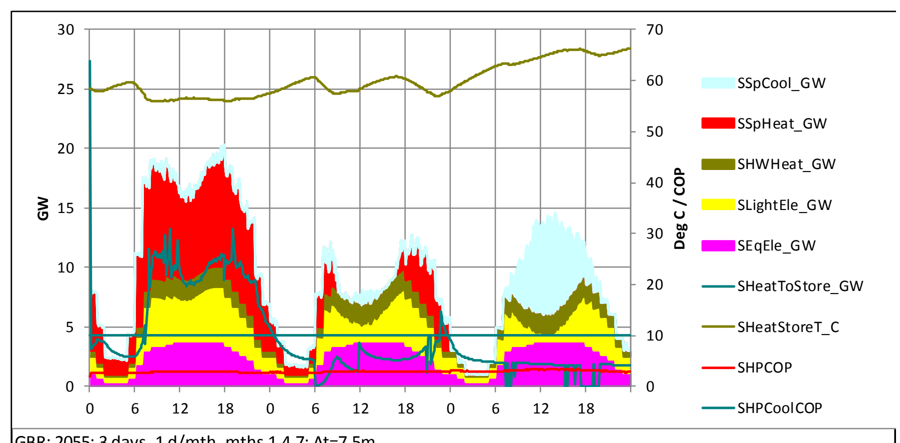
2015-2055 Evolution across years





2055 dynamics: winter, spring, summer days





Transport strategy

UK surface

- Modal shift from road to train, bus, non-mechanised modes
- Light, low drag vehicles
- Switch to electric vehicles and trains. Some hydrogen trucks.

Aviation

- Passenger demand management:
  - Switch to electric rail where possible on shorter journeys
  - Business – more use of internet
  - Leisure –restrain growth !?
- Freight to rail and ship
- Switch to bio - kerosene

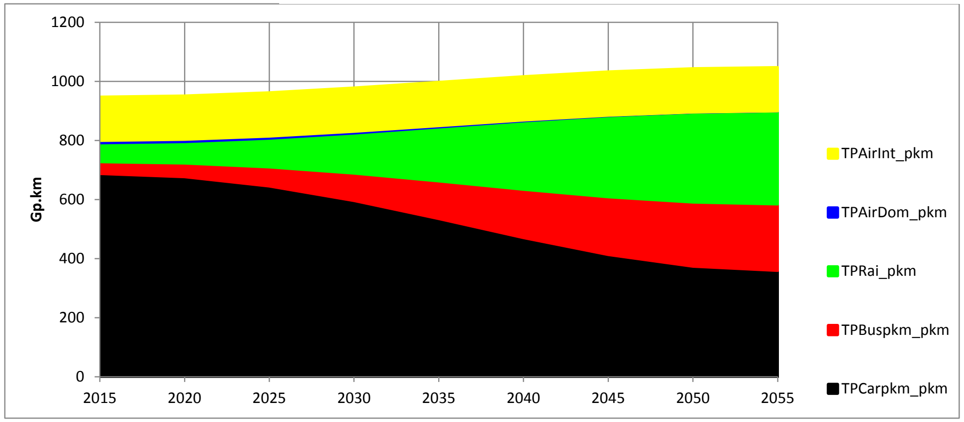
Long distance freight

- Shipping – efficient, lower speed, renewable ammonia fuel
- Electric train – e.g. trans Asian railway

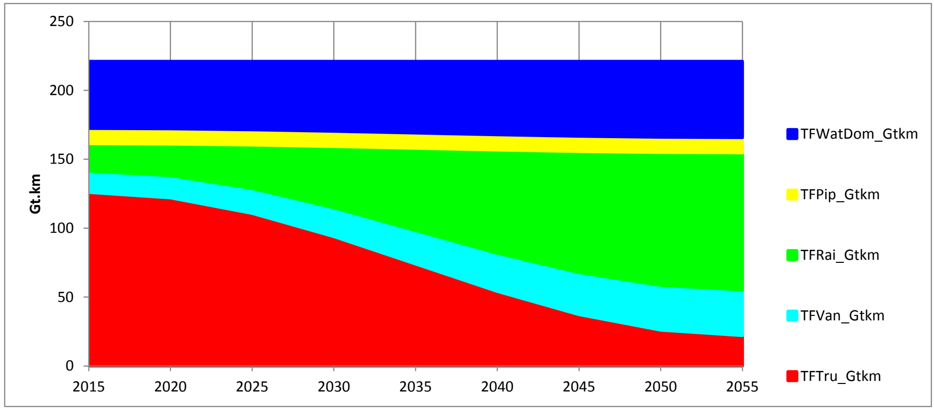
Transport

2015-2055 Demand evolution across years

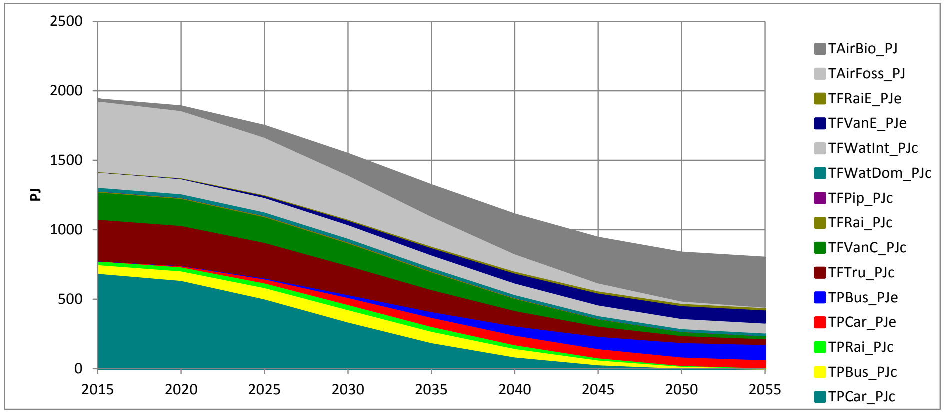
Passenger



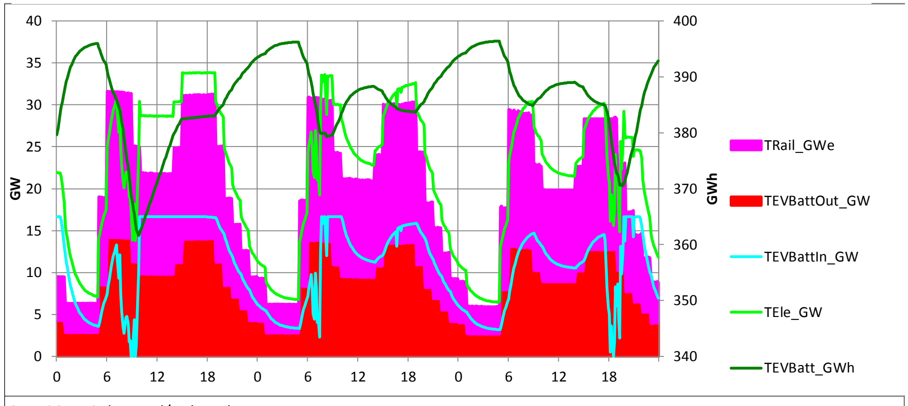
Freight



2015-2055 passenger and freight fuel consumption



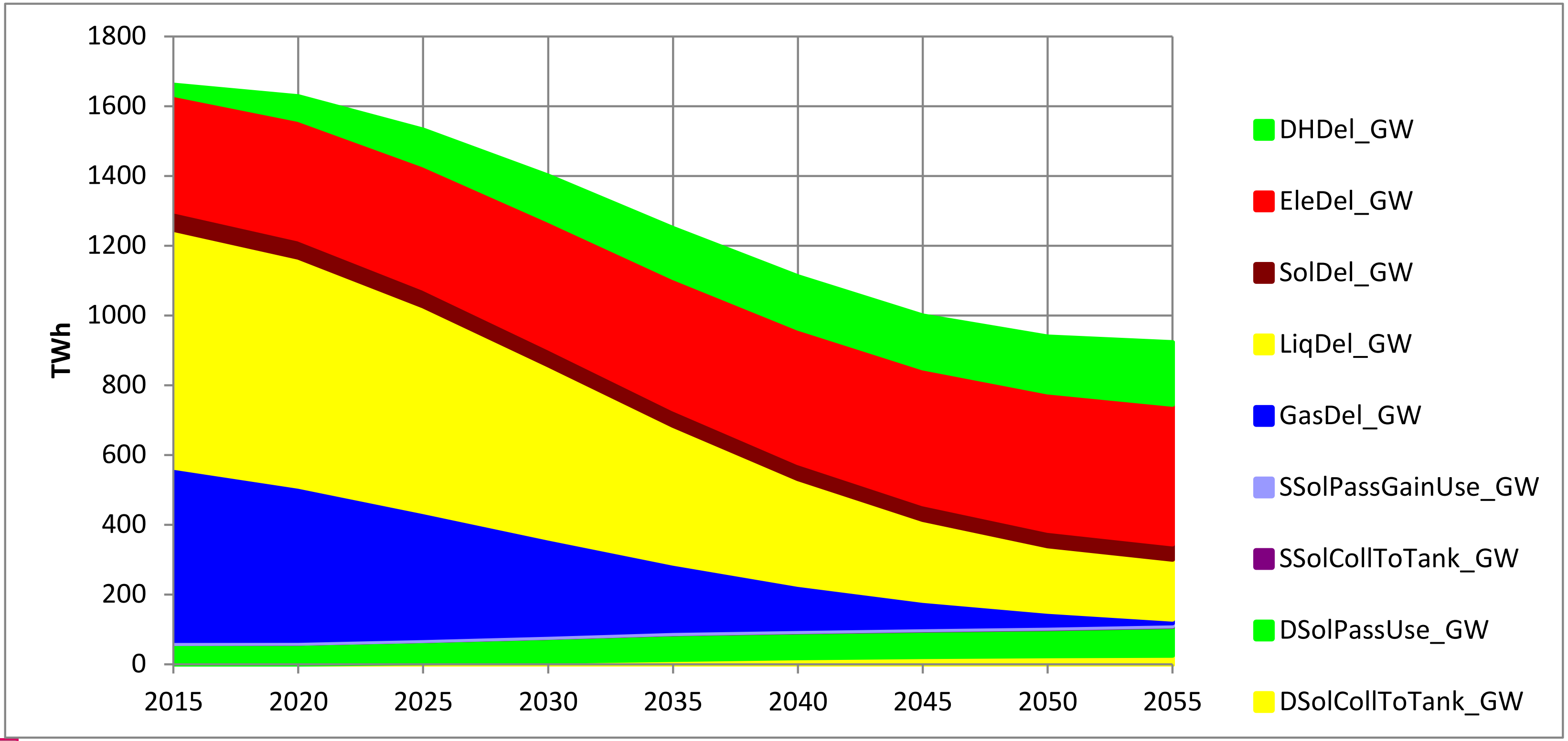
2055 dynamics: winter, spring, summer days



GBR: 2055: 3 days, 1 d/mth, mths 1,4,7; Δt=7.5m

Delivered energy 2015-2055

Including solar water and passive heating.
Large decrease in delivered energy because of demand efficiency and the high efficiency of electric heat pumps and vehicles



SUPPLY: Qualitative selection of lowcarbon options

Mass produced renewables the reversible, low risk option

Relative marks: 10 – good

	Renewables Hydro river Biowaste Solar Wind	Wave Tidal flow	Tidal barrage Hydro reservoir	Biocrop	**Nuclear**	**Fossil Carbon Sequestration**
Reversibility	10	10	5	7	0	0
Risk	10	10	5	5	0	2
Climate change mitigation	10	10	10	5	10	7
Other environment	10	10	8	6	0	8
Potential impact outside UK	10	10	10	10	0	0
Consumption global resources	10	10	10	5	5	7
International political impact	10	10	10	10	0	8
Political security	10	10	10	8	0	9
Transparency	10	10	8	7	0	5
Certainty costs and performance	10	5	6	7	0	2

Renewable electrical energy potential

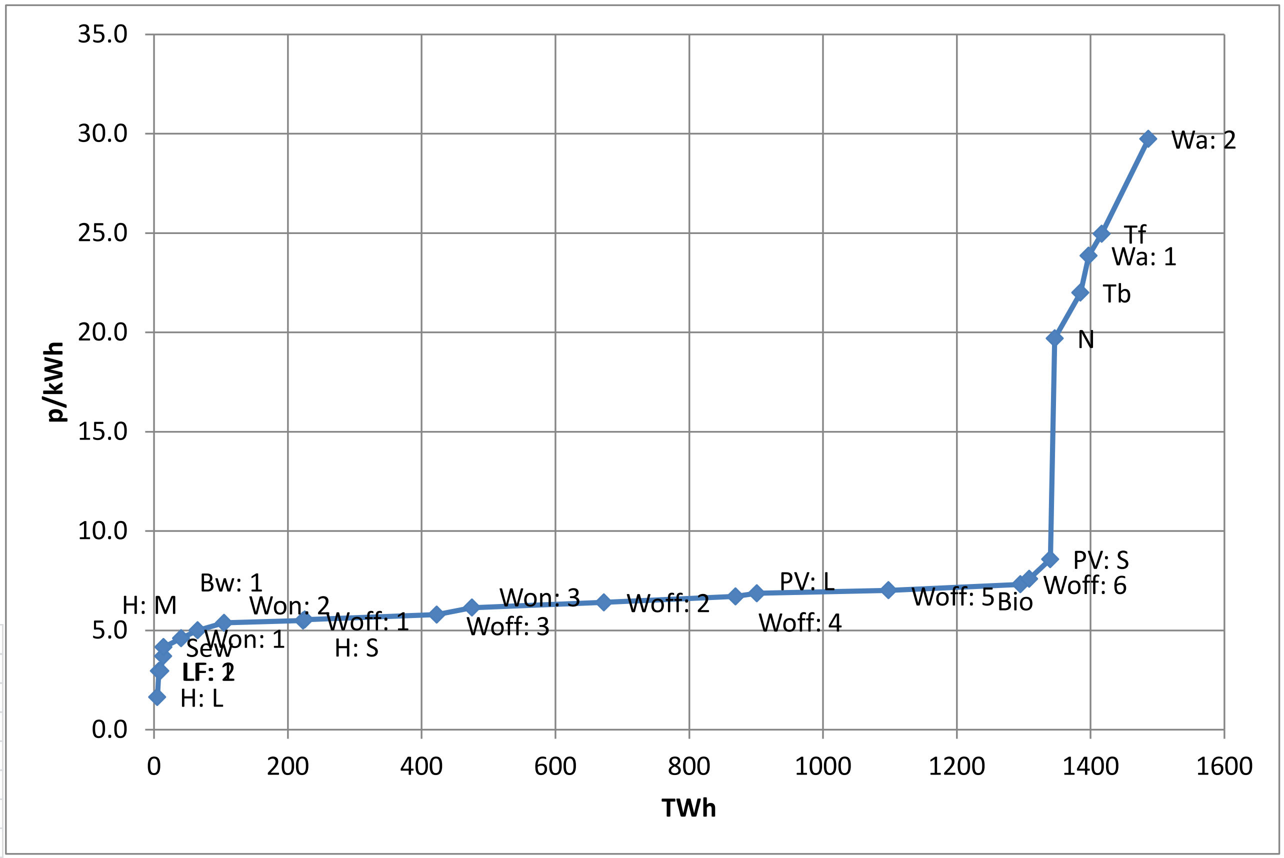
Wind and solar:

- mass produced technologies
- resource vast

Uncertain commercial cost

- Tidal, wave, (nuclear)

An advantage of tidal is that it is predictable, and output can be partially controlled from barrage schemes with storage.



Hydro	H
Biomass	Bio
Biowaste	Bw
Land Fill Gas	LF
Sewage	Sew
Wind-on	Won
Wind-off	Woff
Tidal barrage	Tb
Tidal flow	Tf
Wave	Wa
Solar PV	PV
Nuclear	N

Generation only: excludes system balancing

Discount rate: 5 %/a

Secondary energy production

Electricity
- Renewables
- Biomass/gas CHP
- Biomass/ fossil electricity only plant

District Heat
- CHP, heat pumps and peaking boilers

Synthetic fuels
- Ammonia/hydrogen for ships & trucks
- Biofuels for aircraft

Networks

Electricity

- Low voltage distribution network similar to now
- Higher voltage extensions to connect renewable and CHP generators
- International connectors

Gas

- Retain for back-up and peaking

District heating

- Develop in high heat load density areas

The critical role of district heating

Heat will be a large fraction of service demand.

- Fossil or biogas cannot supply a large fraction of heat because of emission and resource constraints.
- Individual electric heat pump heating with storage is constrained because of space, particularly in dwellings, and may require extensive replacement of low voltage network.

District heating offers a mix of efficient heat inputs (heat pumps, CHP, waste heat, solar, geothermal etc.) and large scale, low cost storage, but high network costs against incumbent gas and electricity networks.

The mix can be varied with no substantial effect on consumers:

- Dynamically across the day and year for system management to absorb or produce electricity.
- Across the years depending on the evolution of renewables etc. In the scenario, CHP is gradually replaced by heat pumps as renewable electricity generation increases.

UCL

Spatial district heat evolution

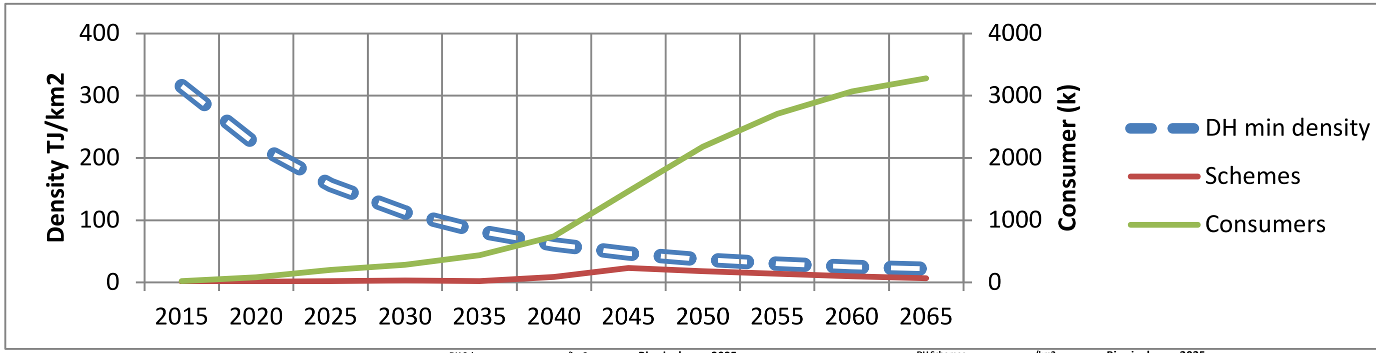
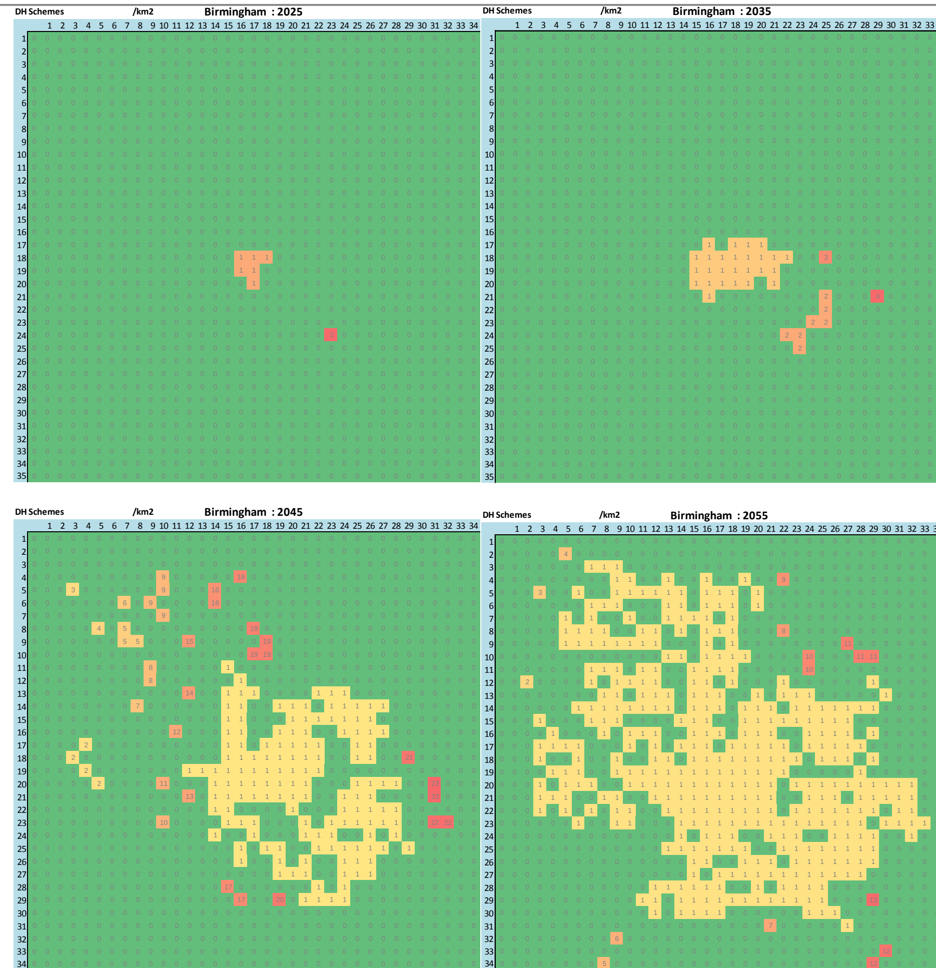
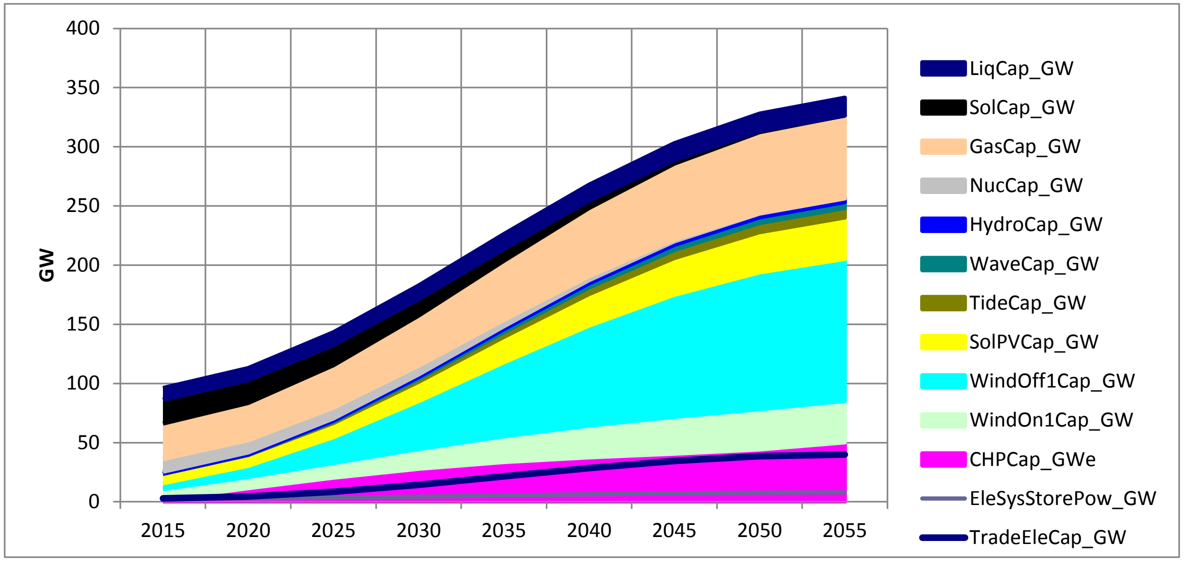


Illustration for the Midlands from the SEECity model



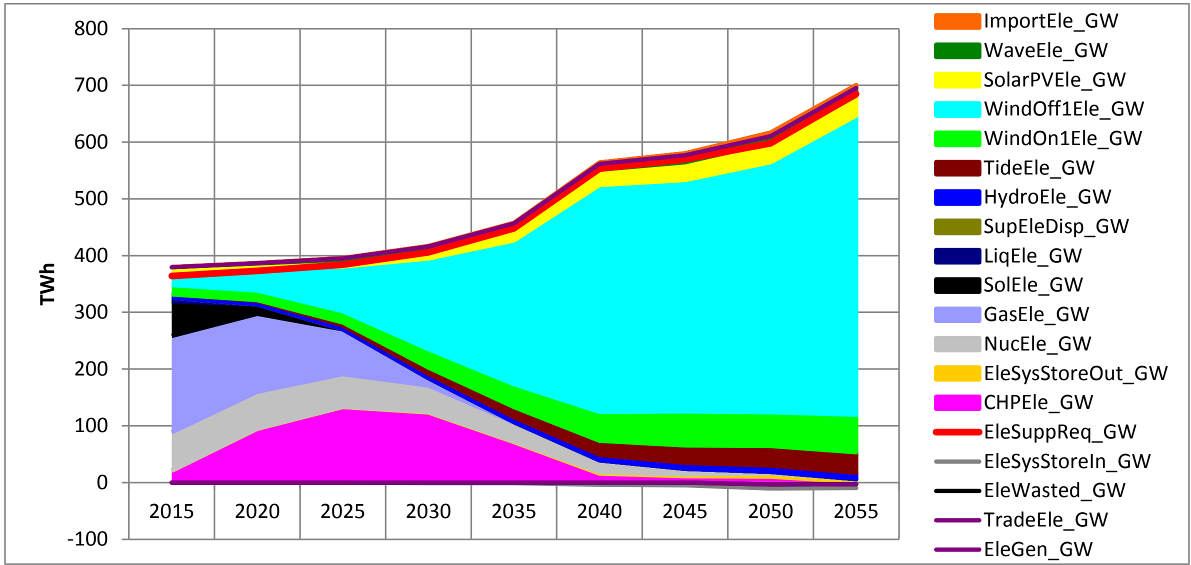
As the minimum heat load density for DH is reduced, the DH systems extend

Electricity capacity and generation



Capacity

- Renewables
- Bio & gas CHP
- Gas/oil back-up
- System storage
- Trade connection



Generation

- Conventional replaced by CHP and renewables
- negligible net annual trade assumed

Energy system dynamics
Simple hourly model

Data: 31 years of hourly meteorology and wind power generation from Dr Ed Sharp
Population weighted
- average ambient temperature (Ta oC) and wind speed (Vwd m/s)
- global horizontal insolation (S W/m2)
- Ed Sharp modelled normalised on (Pnwon) and Pnwoff) off-shore wind generation (GW)

DEMAND MODEL
- Normalised use pattern varying hour to hour: U(h)
- Non heat demand (equipment, lighting, refrigeration etc.)
  - Dnh(h) = k1 U(h)
- Non-space heat demand
  - Dnsh(h) = k2 U(h)
- Space heat demand:
  - Dhsp(h) = k3 U(h) [(Ta(h)-Tinternal) + k4 Vwd(h)]
- Electricity for heat is total heat load divided by the efficiency (COP) of the heat pump assumed to be 45% of Carnot efficiency:
  - Deh(h) = [Dnsh(h) + Dhsp(h)] / HPEff
  - HPEff = 0.45 * [(70 + 273) / (70 – Ta(h))]

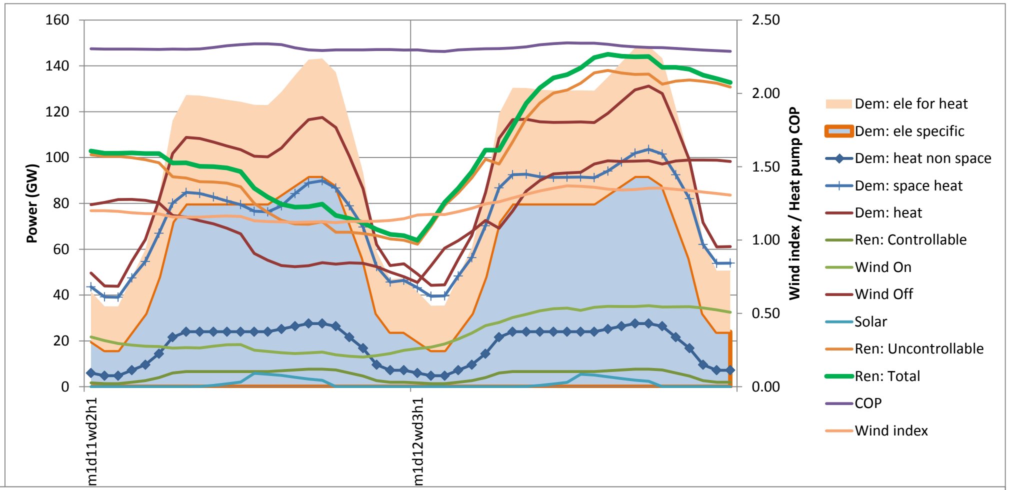
SUPPLY MODEL
- Wind power Pw = Cwon * Pnwon(h) + Cwoff * Pnwoff(h)

Energy system dynamics
System settings

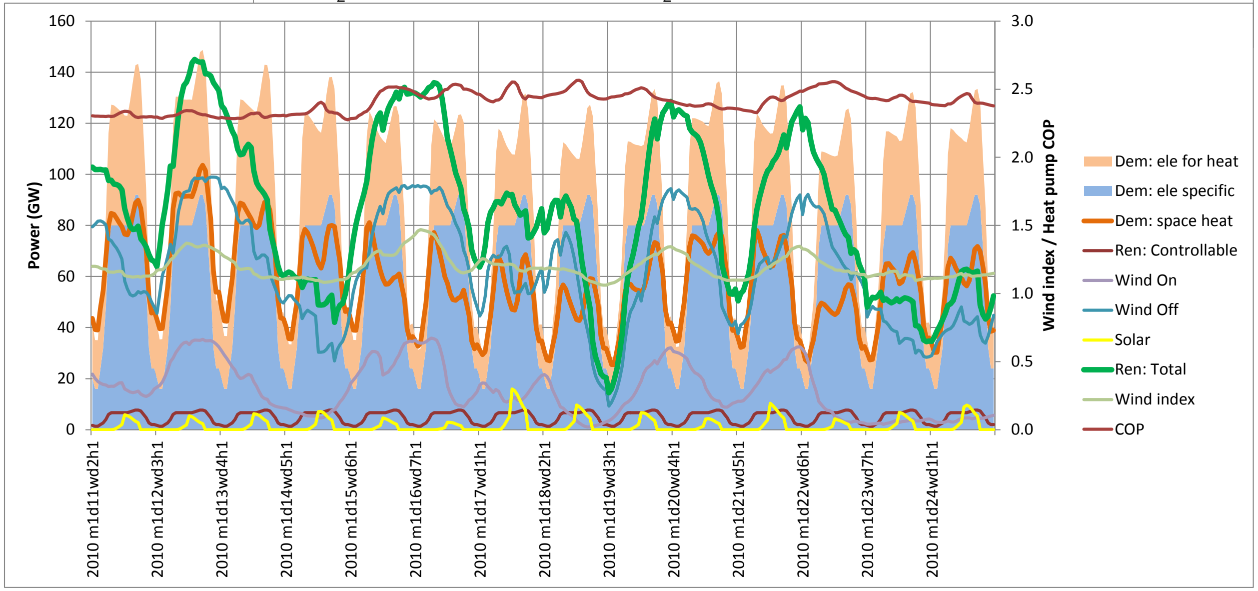
MODEL SETTINGS			
Internal temperature	oC	Tint_oC	17
Space heat loss	GW/oK	SpH_GWpDegC	4.5
Non heat average	GW	DemNonHeatAv_GW	60
Heat: non space average	GW	DemNonSpHeatAv_GW	18
Wind capacity: onshore	GW	WindCapOn_GW	40
Wind capacity: offshore	GW	WindCapOff_GW	100
Solar PV capacity	GW	SolCap_GW	60
Renewable controllable	GW	RenConCap_GW	5
Storage capacity	TWh	Store_TWh	0

Energy system dynamics
Sample 2 days and 2 weeks

2 days



2 weeks

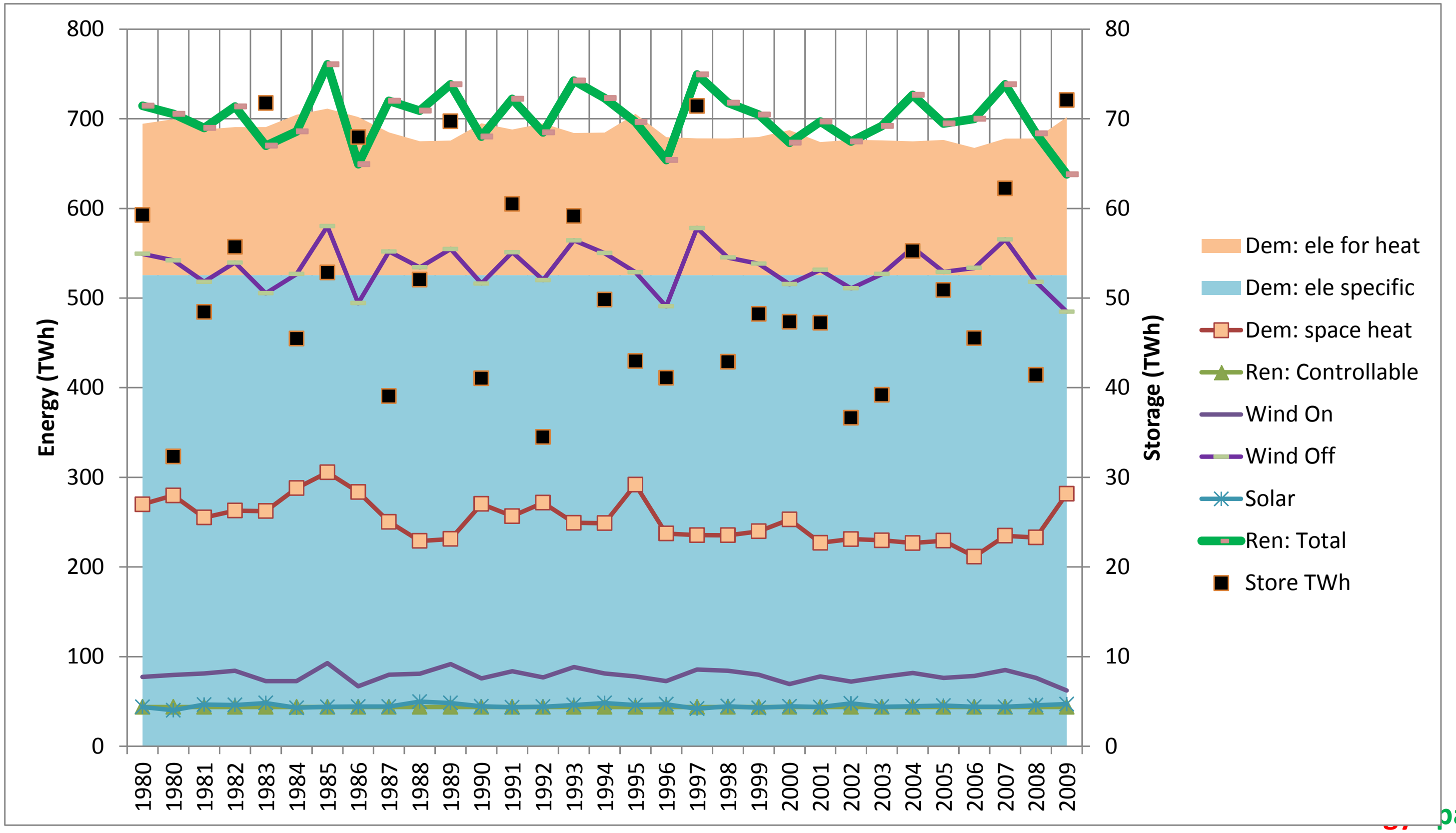


Energy system dynamics

Annual demand and renewable supply variation over 31 years

(Modelling based on 31 years of hourly meteorology and wind power generation from Dr Ed Sharp)

- Considerable inter-annual variation in wind generation (about +/-20% on shore; +/- 10% off-shore)
- Less variation in total demand (about 5%) because the weather driven component of electricity demand is small (in scenario)

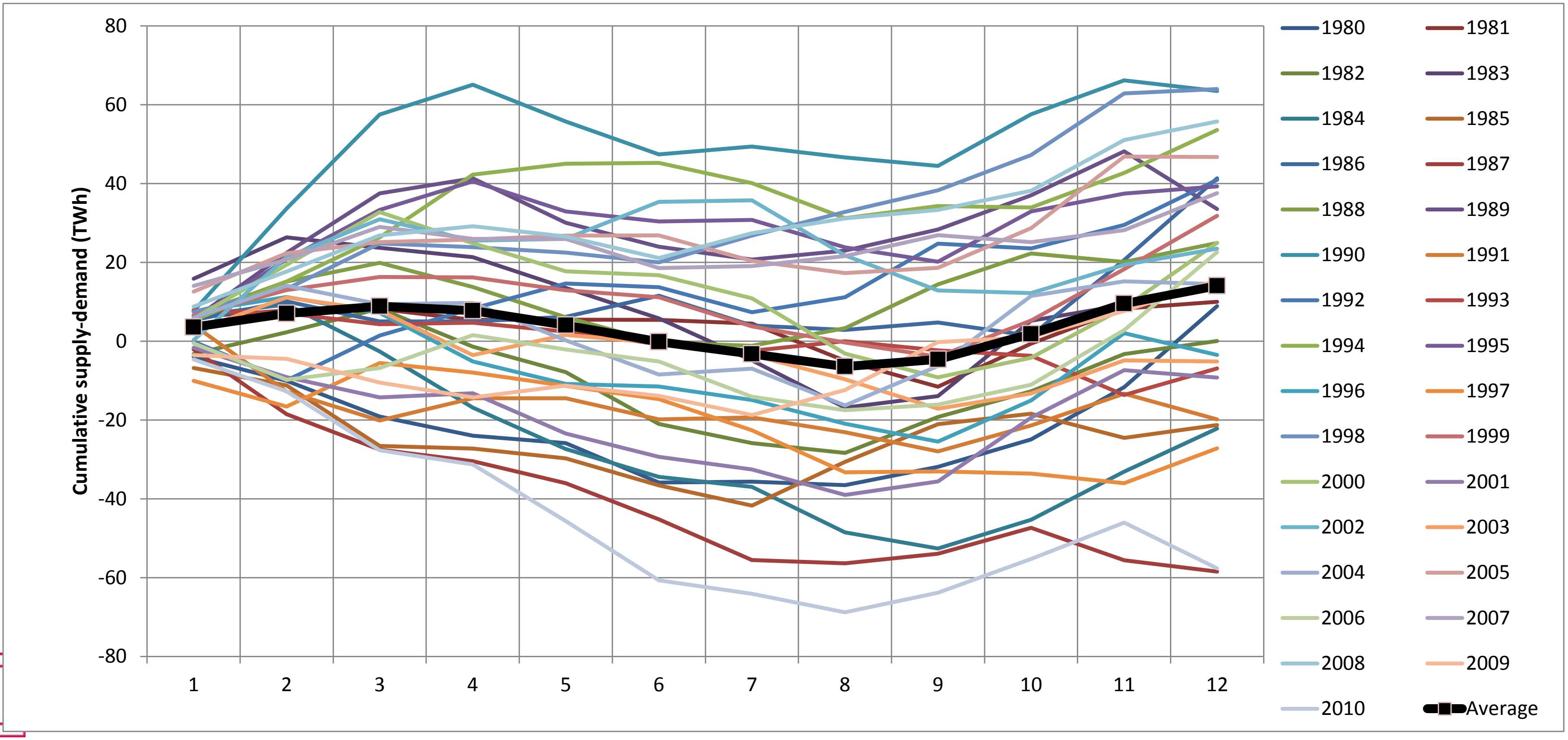


Energy system dynamics

Monthly cumulative supply-demand variation for each of 31 years

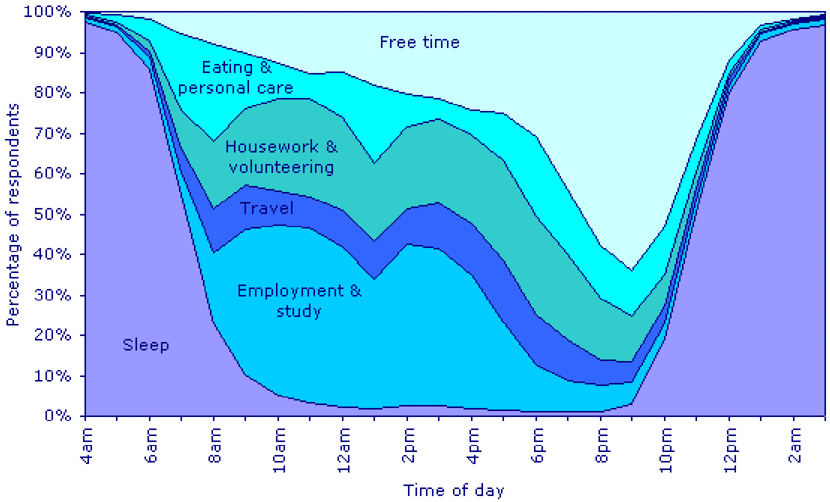
(Modelling based on 31 years of hourly meteorology and wind power generation from Dr Ed Sharp)

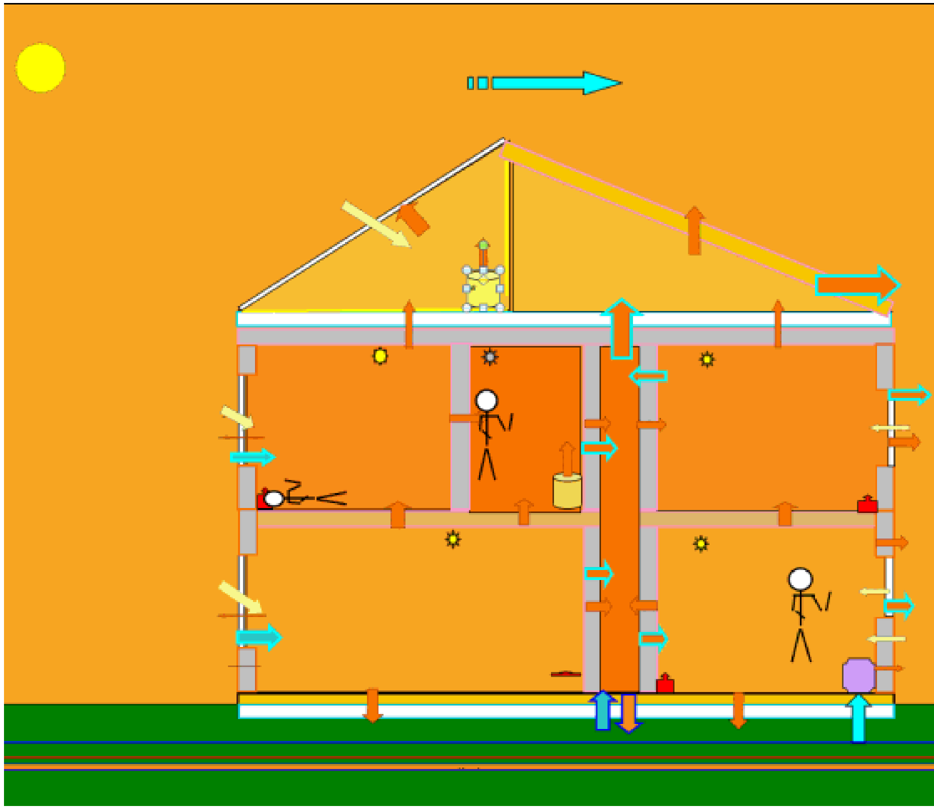
Considerable monthly variation in cumulative supply-demand resulting in minimum and maximum of about -/+ 70 TWh, or 10% of annual demand.



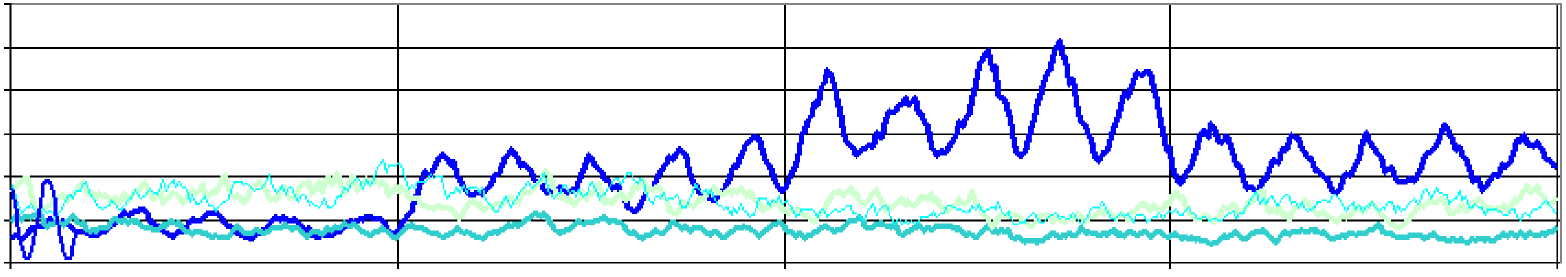
DynEMo Temporal energy drivers

Human use of time – UK
Quite invariable –
a diurnal mammal!



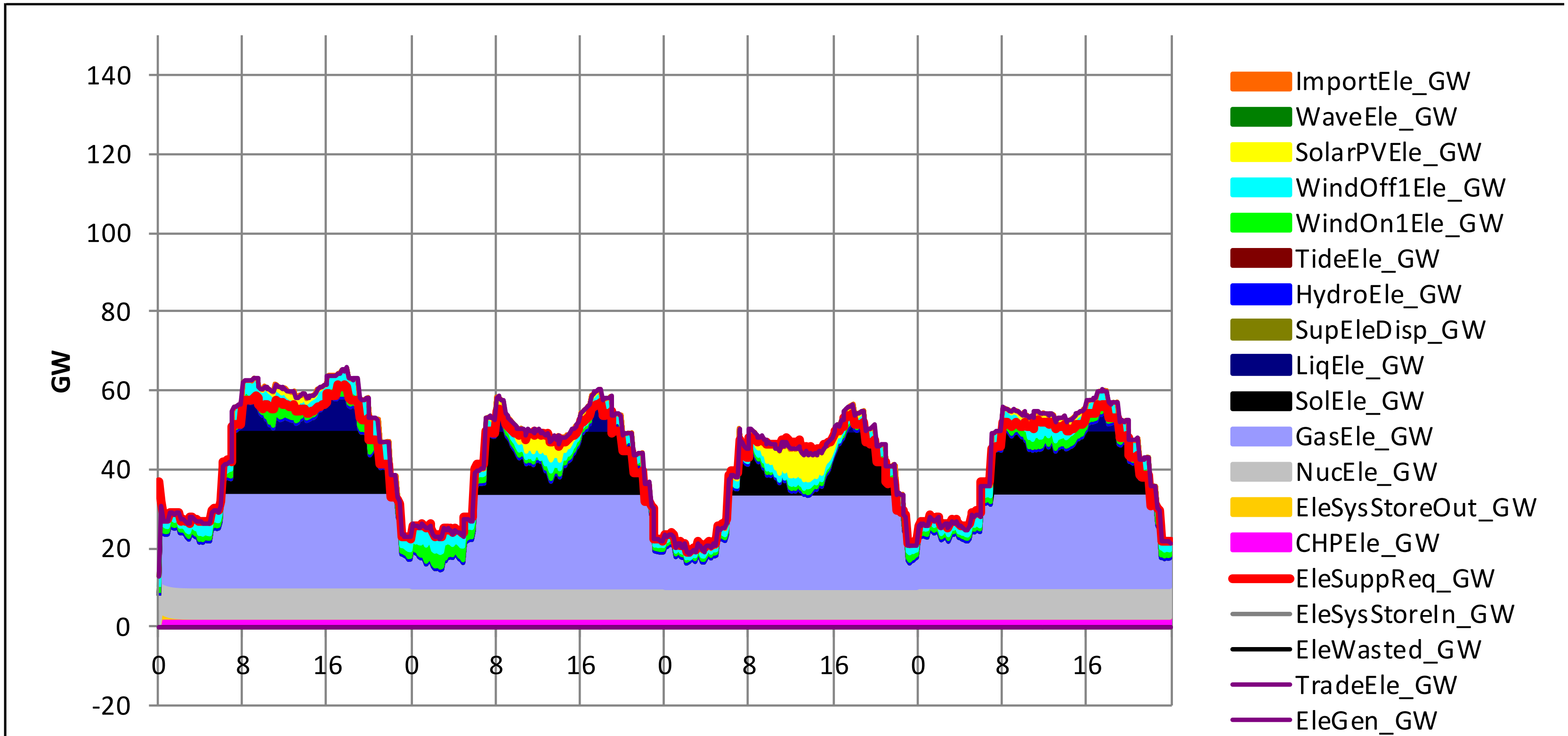


Weather and Renewables



Evolution of electricity system dynamics

2015: most electricity is provided with dispatchable fossil and nuclear generation



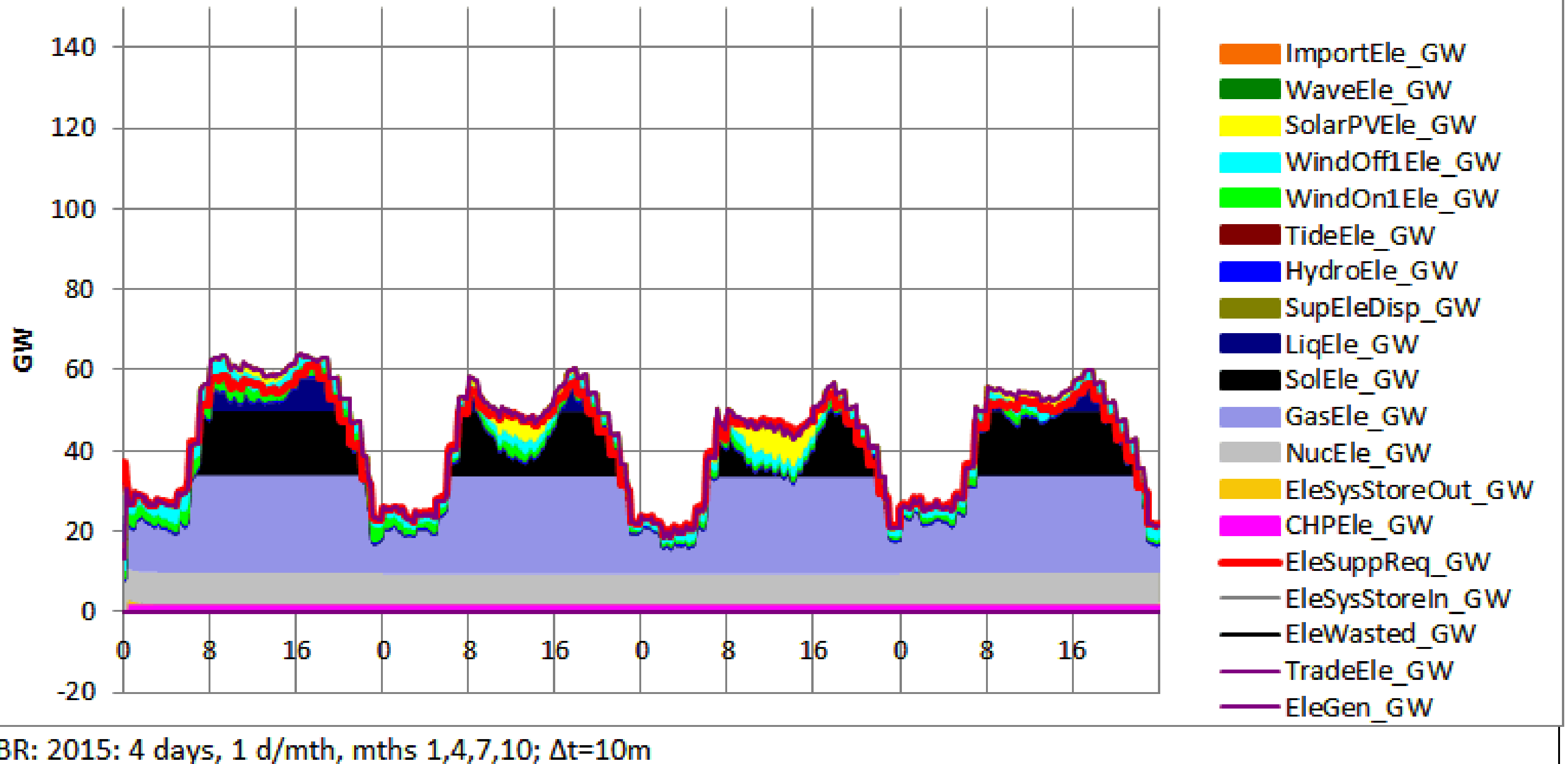
GBR: 2015: 4 days, 1 d/mth, mths 1,4,7,10; Δt=10m

winter spring summer autumn days

Evolution of electricity system dynamics

To 2055, increasing demand and uncontrollable renewables absorbed with storage, dispatchable renewables and trade

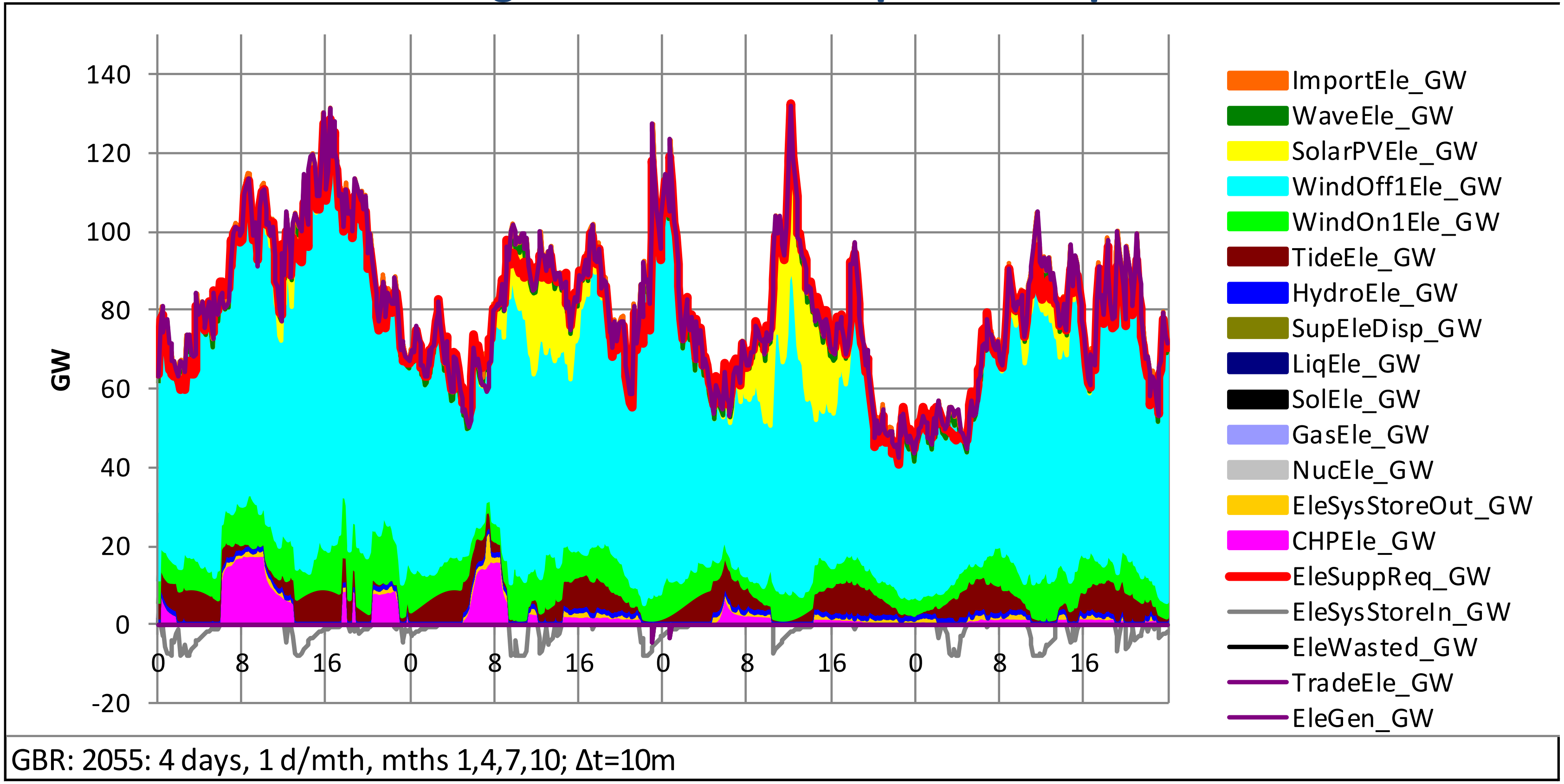
(animation)



winter spring summer autumn days

Evolution of electricity system dynamics

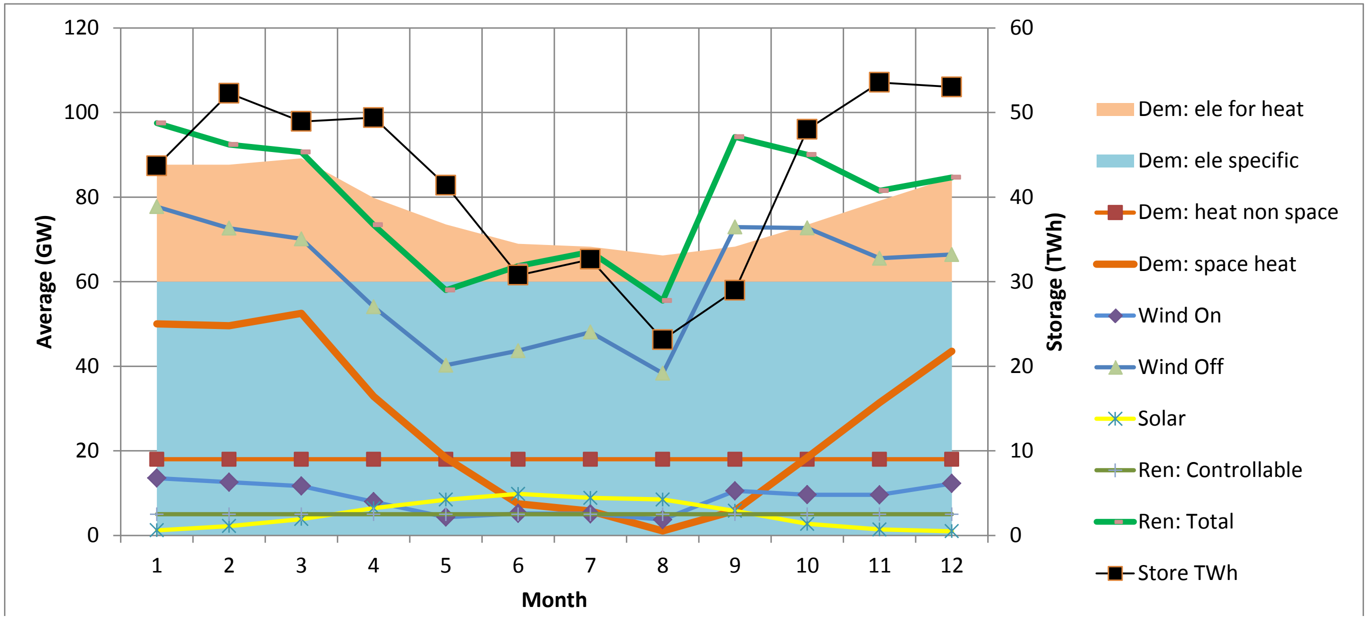
2055: all electricity provided with renewable generation; biomass district heating CHP the main dispatchable plant



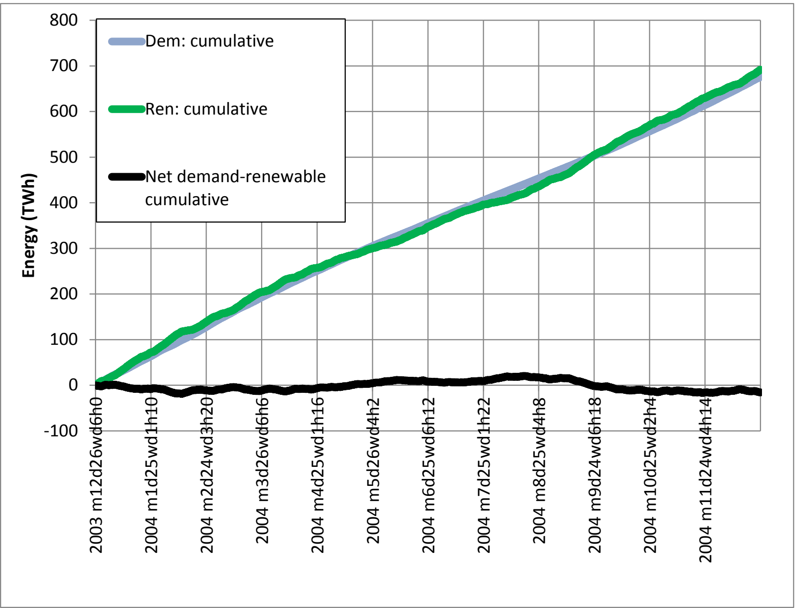
winter spring summer autumn days

How much storage is needed?

(assuming 100% renewables and no trade)



For year 2000, from 31 years of hourly meteorology and wind power generation from Dr Ed Sharp



1. Model hourly demands and renewables across the year

2. The minimum storage is the maximum difference between cumulative demand and supply

For a 700 TWh/a demand/supply system around 70 TWh of storage is required, but will vary depending on demand and renewable patterns.

Storage can be a mix of heat, EV batteries, chemical, biomass, fossil etc.

Storage for system management

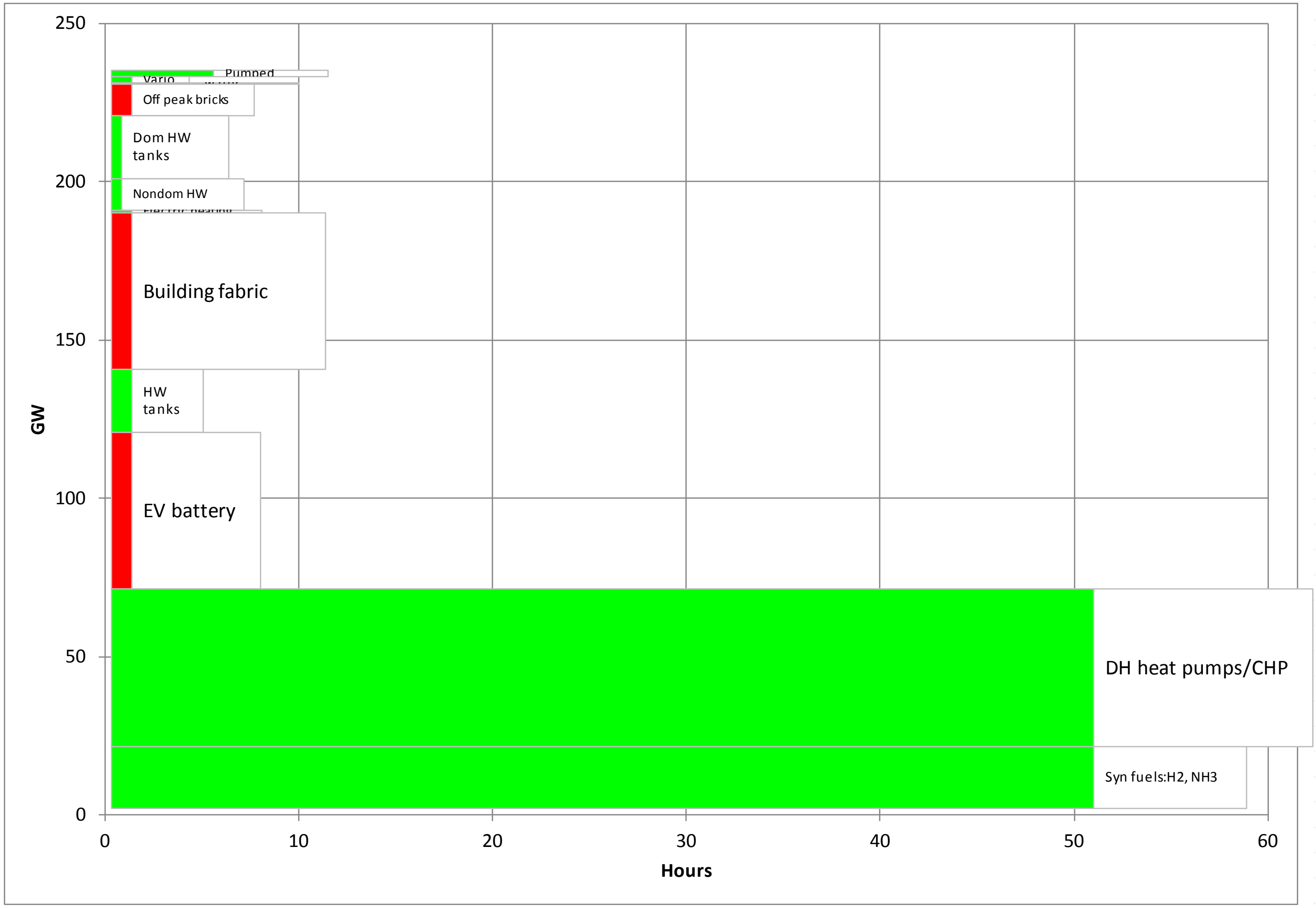
: power and energy potential

(Excluding bioenergy and fossil energy stores)

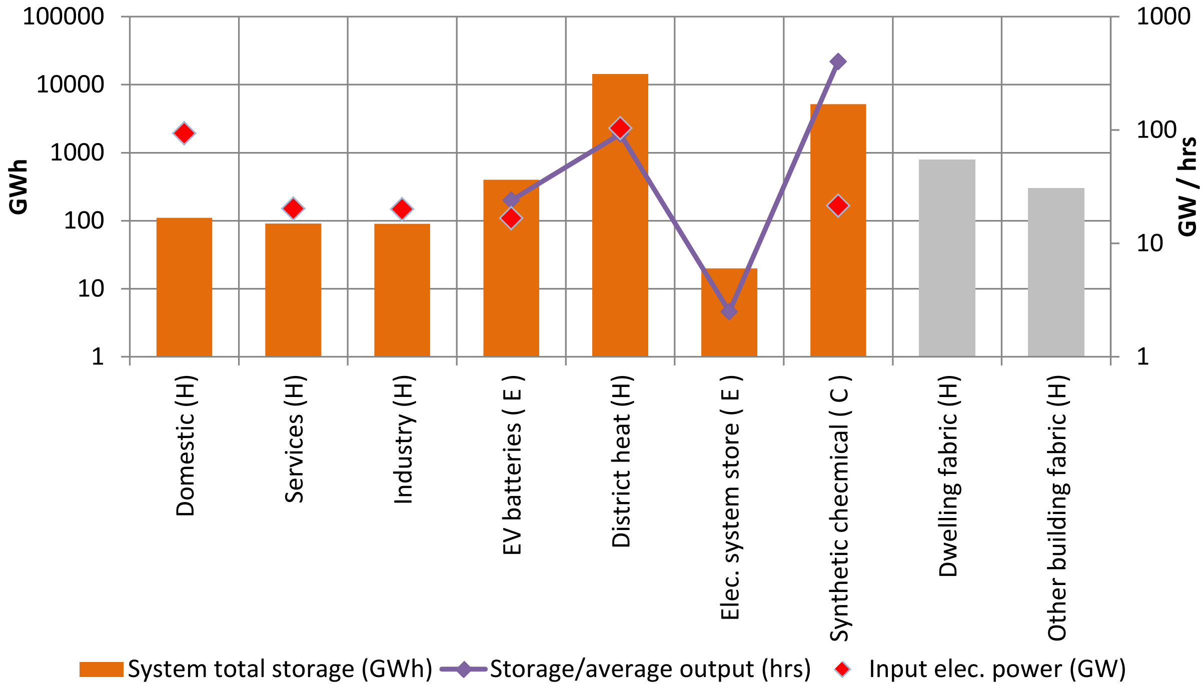
Potential storage with about upwards of 200 GWe power and 5 TWh energy.

Ammonia/hydrogen and district heat stores can be very large

System electricity storage (batteries etc.) relatively costly and inefficient.



Scenario 2055: national – electrically connected storage



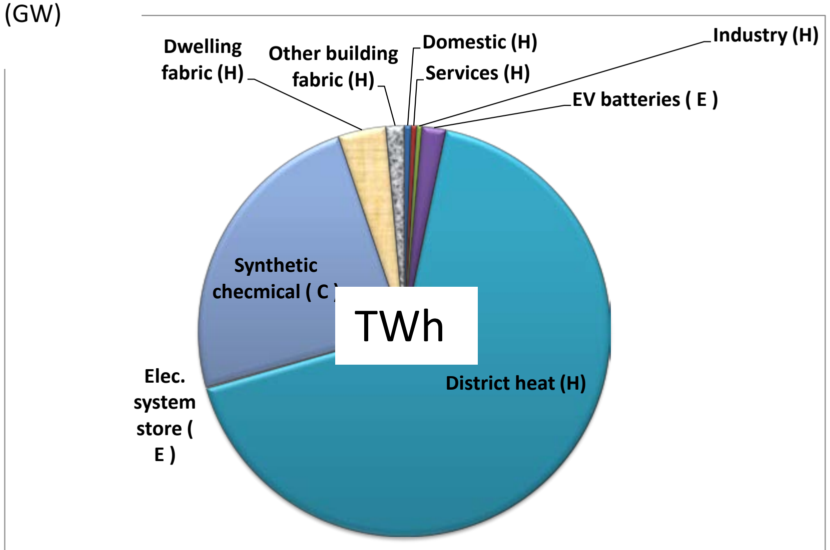
20 TWh and 280 GWe active storage (excluding building passive storage and biomass)

Including:

- **District heat storage 5 days peak heat load**
- **Synthetic chemical (ammonia)**
- **Most other stores constrained**

Will electricity storage with batteries etc. become more competitive in terms of cost and performance?

Would batteries optimally be at consumers' premises, or upstream in the system with economies of scale and diversity advantages?



International trade

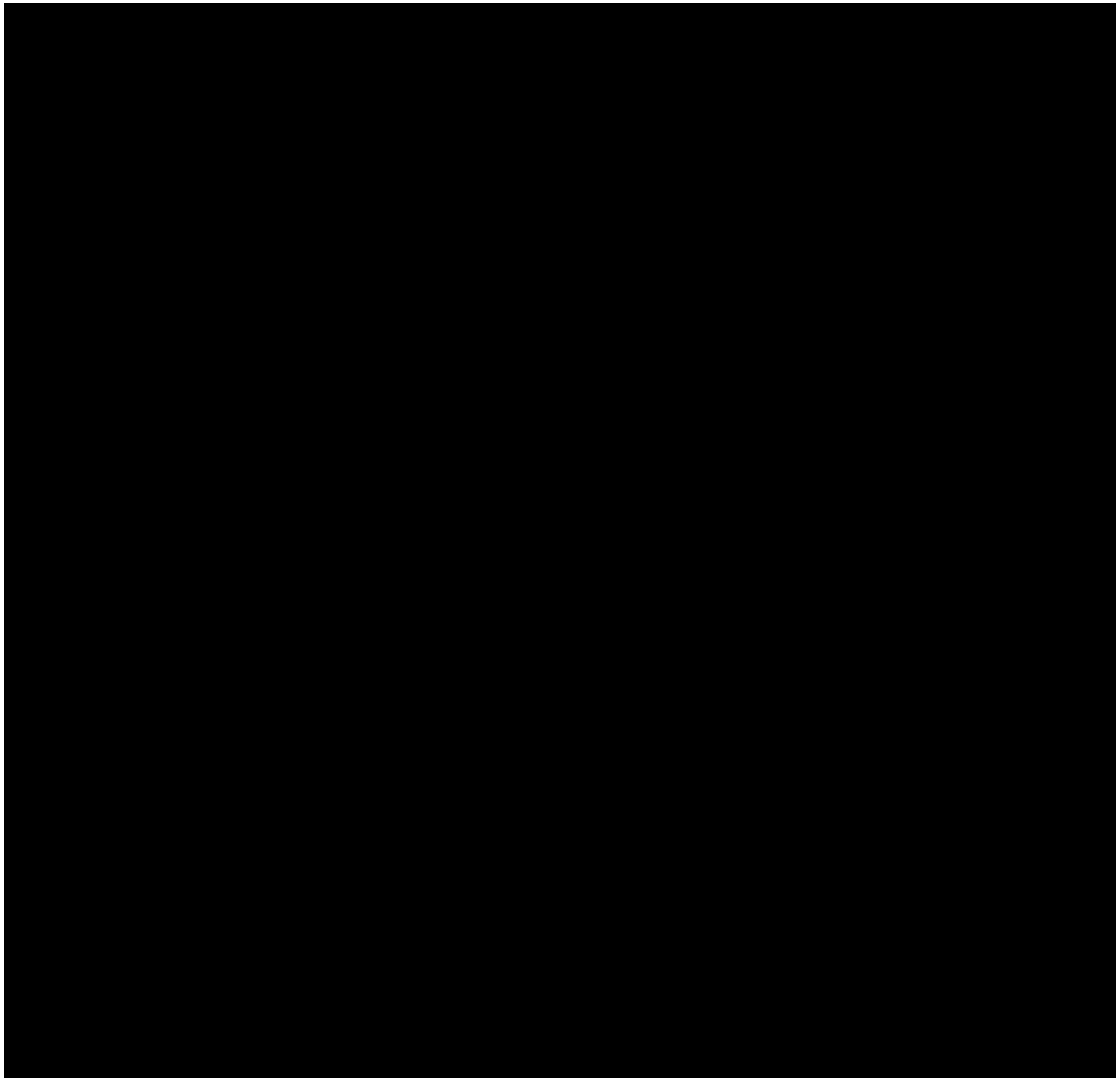
Transmission evens out the variations in demands and renewable supplies so that the demand-supply matching problem is reduced.

The UK now has 4 GW interconnection, another 8 GW is planned, so perhaps 12 GW by 2025.

How will international trade flows vary hour by hour? Need to model all the countries/regions.

Can we rely on importing in time of need?

And exporting in time of surplus?



Dynamic system control

How to manage a system with 40 M consumers, 400 M variable demands, 100 M stores, variable renewables and dispatchable generators, and trade links?

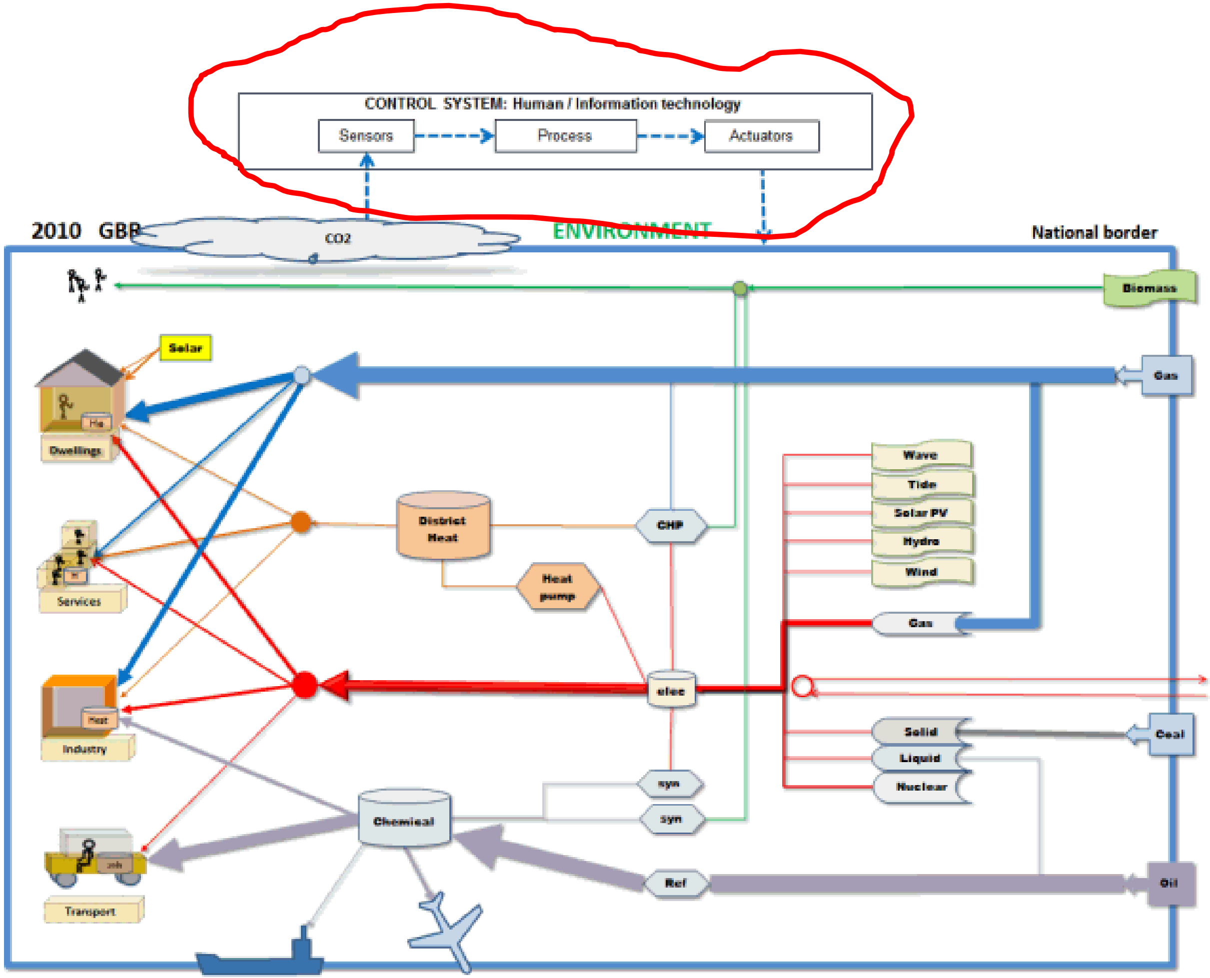
Require:

- Information about current and future projected states of system components
- Strategy formulation
- Control of components

Want:

Global Optimal Dispatcher (GOD) with perfect foreknowledge and power – omniscient, omnipotent.

How close can we get?



Implementing a Global Optimal Dispatcher

How to approach optimal control in a hybrid human and technology system with many contending consumer and supplier agents?

Hardware not a problem – current sensors, actuators, telecomms, computers sufficient

Human and software control algorithms and social structures hard to devise.

Require some mix of centralized/ distributed control as (all?) present systems have.

Purely centralised

- Agents signal centre with information
- Centre devises strategy and controls technologies through orders to agents or directly
- **Stable. Higher cost?**

Purely distributed

- Agents signal centre with information
- Centre does projections of system environment (e.g. prices, demand, wind output) and signals agents
- Agents autonomously use centre's signals to devise strategy and implement control
- **Chaotic. Unequal distribution of cost. Lower cost?**

DynEMo SYSTEM CONTROL ALGORITHMS

Algorithms need to control the whole system, including:

1. Building heating and cooling
2. Active stores
3. Dispatchable generation
4. Multi-fuel switching – e.g. between heat pumps and CHP
5. International trade

Complex non-linear system so use heuristic algorithms

DynEMo SYSTEM CONTROL ALGORITHM OUTLINE

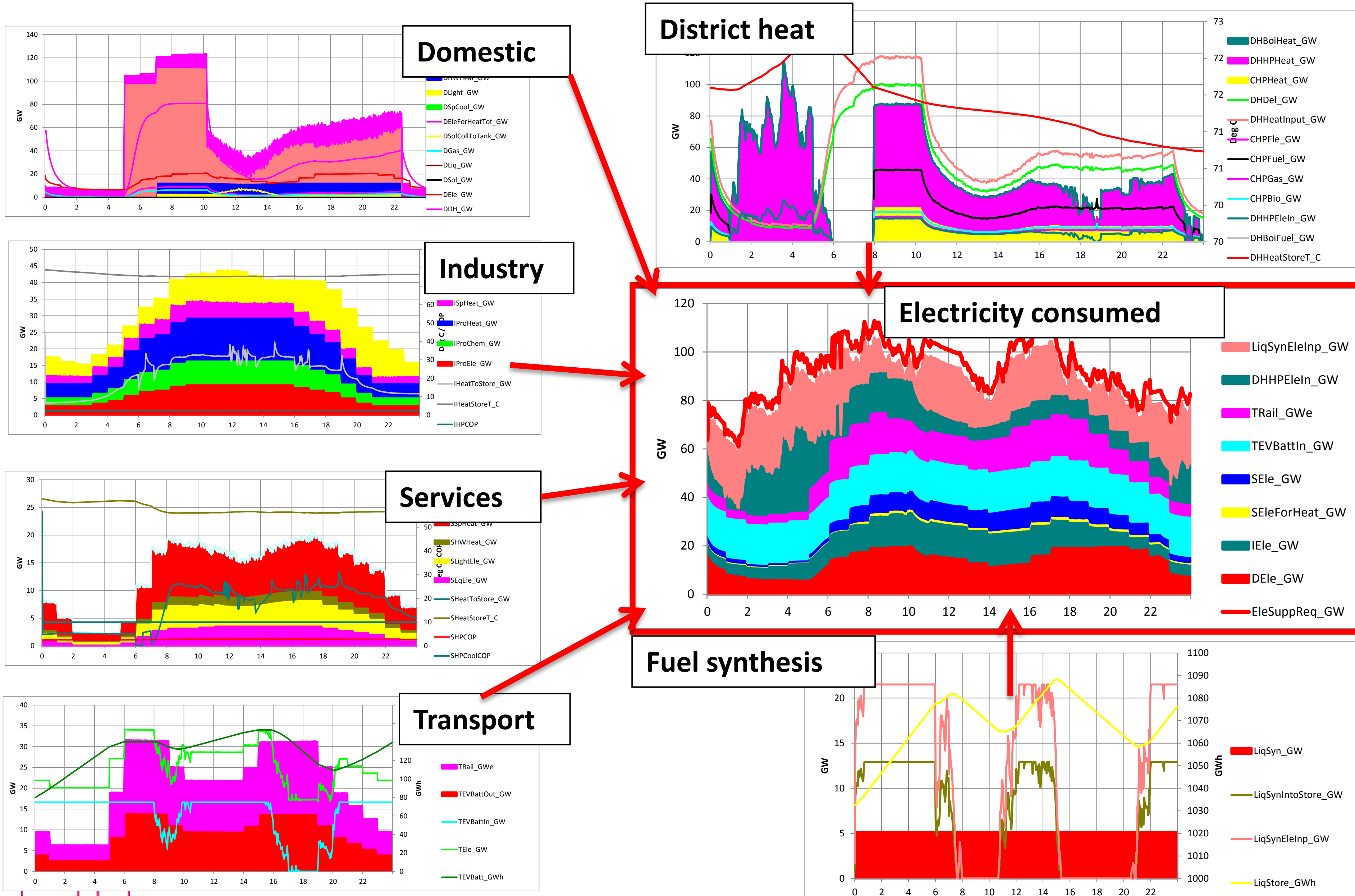
1. **Demand met directly or from stores**
2. **If a renewable surplus**, first put into stores, then export remaining and/or spill energy
3. **If a renewable deficit**, take out of stores
4. **If a deficit and stores empty,** operate DH CHP and then electricity only plant
5. **If DH store low**: operate CHP and use elec in heat pumps; if still insufficient use heat only boilers
6. **(If still a deficit, import if possible)**
7. **Run dispatchable electricity only plant.**

Surplus is sequentially allocated to stores and export according to proximity to service, store size and the availability of multi-fuelling alternatives:

i. domestic (heat stores)
ii. electric vehicle (batteries)
iii. services (heat stores)
iv. industry (heat stores)
v. synthetic fuels (chemical stores)
vi. electricity system storage (e.g. pumped storage)
vii. district heating (heat stores)
viii. export surplus
ix. waste surplus

UCL Energy Institute

Electricity balancing – DynEMo one day for January ; modelled at 5 min intervals



Electricity system stress examples over 3 days

WINTER-5 oC. No wind, no trade.

DH: CHP at maximum. Boiler used when store empty and more heat required.

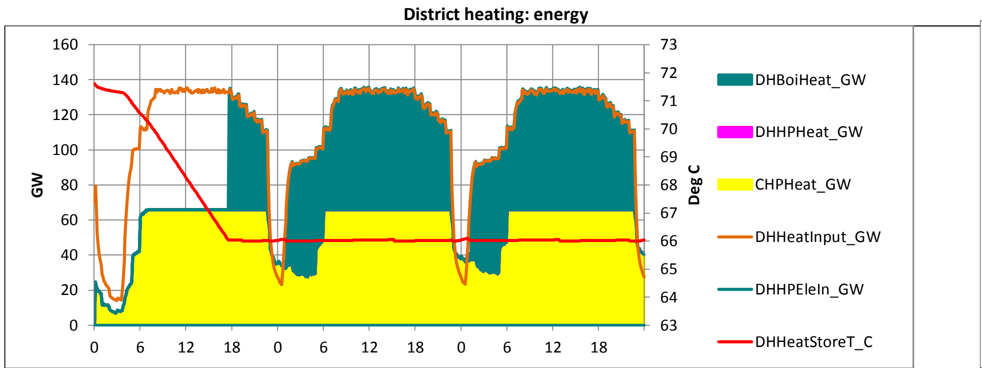
Electricity: bio CHP and fossil gas main supplies.

SUMMER. 35 oC. No wind, no trade.

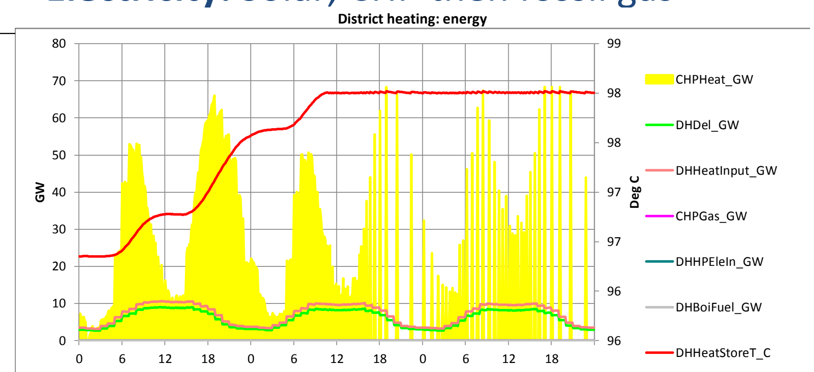
DH: CHP fills store to maximum then just tops up.

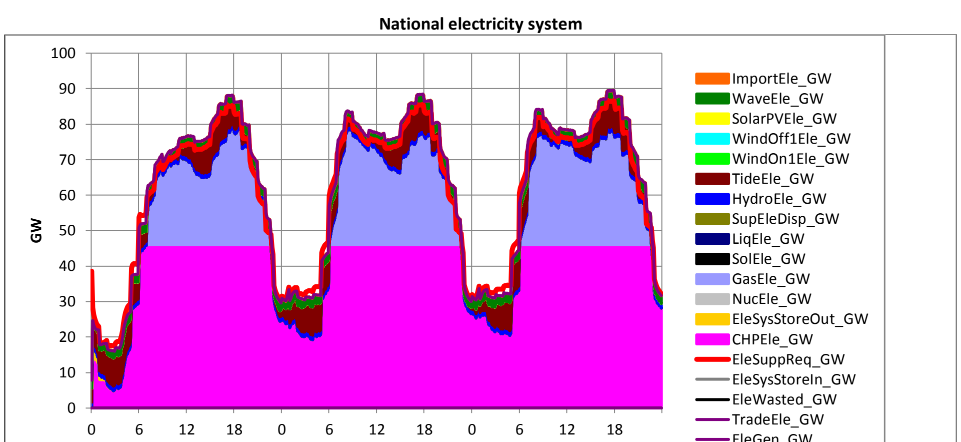
What if DH were used for cooling?

Electricity: Solar, CHP then fossil gas

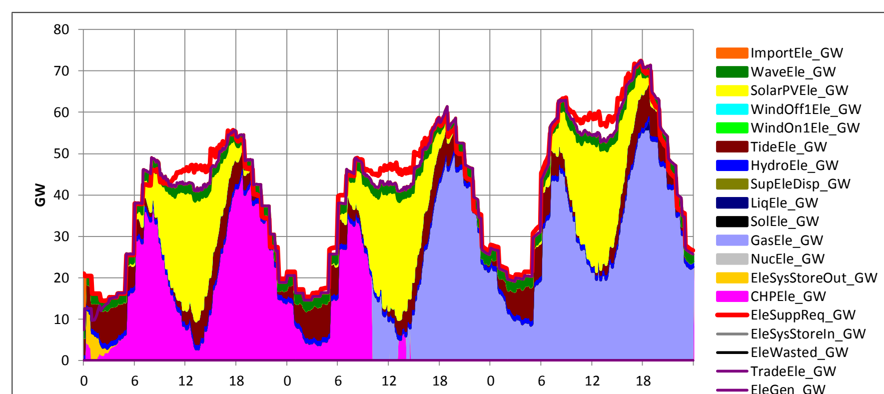


GBR: 2055: 3 days, 3 d/mth, mths 1; Δt=7.5m





GBR: 2055: 3 days, 3 d/mth, mths 1; Δt=7.5m

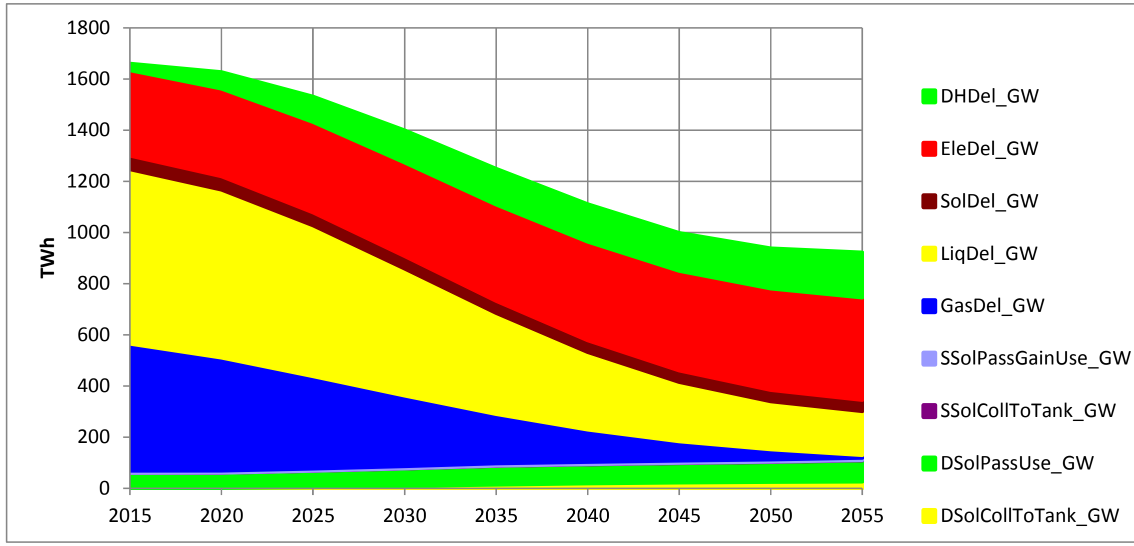


GBR: 2055: 3 days, 3 d/mth, mths 7; Δt=7.5m

Delivered and primary energy

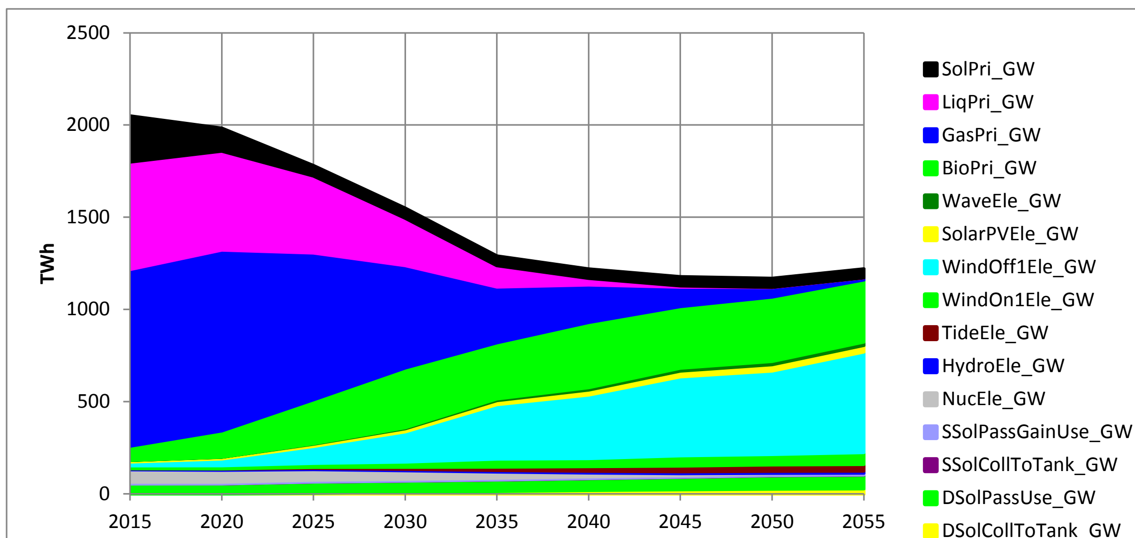
Delivered

Shift from fossil gas and liquid to synthetic liquids, electricity, district heating and some solar heating.



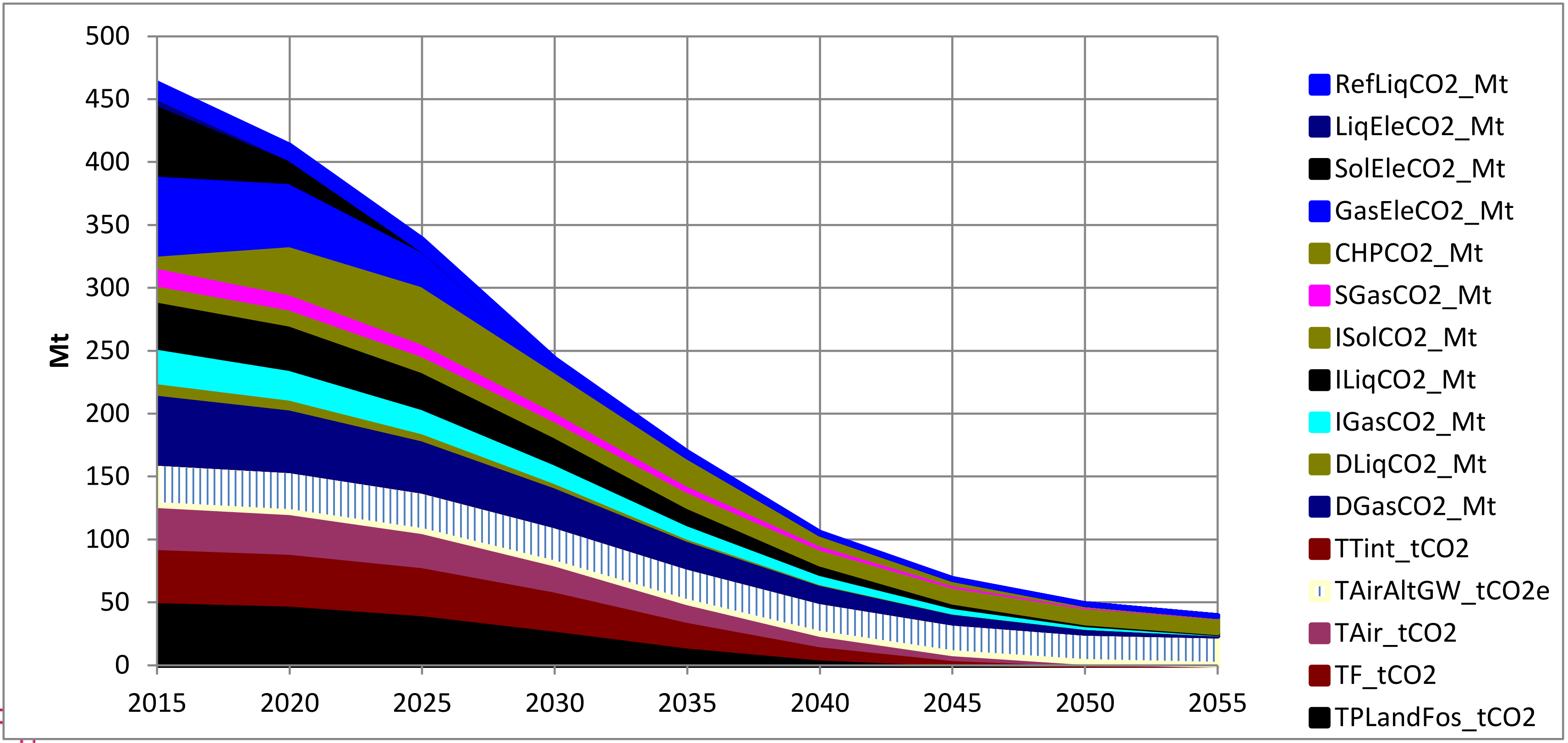
Primary

Shift from fossil and nuclear to renewable electricity, biomass and solar heat.



Energy related CO2 and aviation global warming

- Fossil related emissions of carbon, methane etc. and air pollution fall to near zero
- Much remaining energy related global warming is from high altitude aircraft. Reduce by flying at lower altitude but this would increase energy consumption (unless turboprops used.)

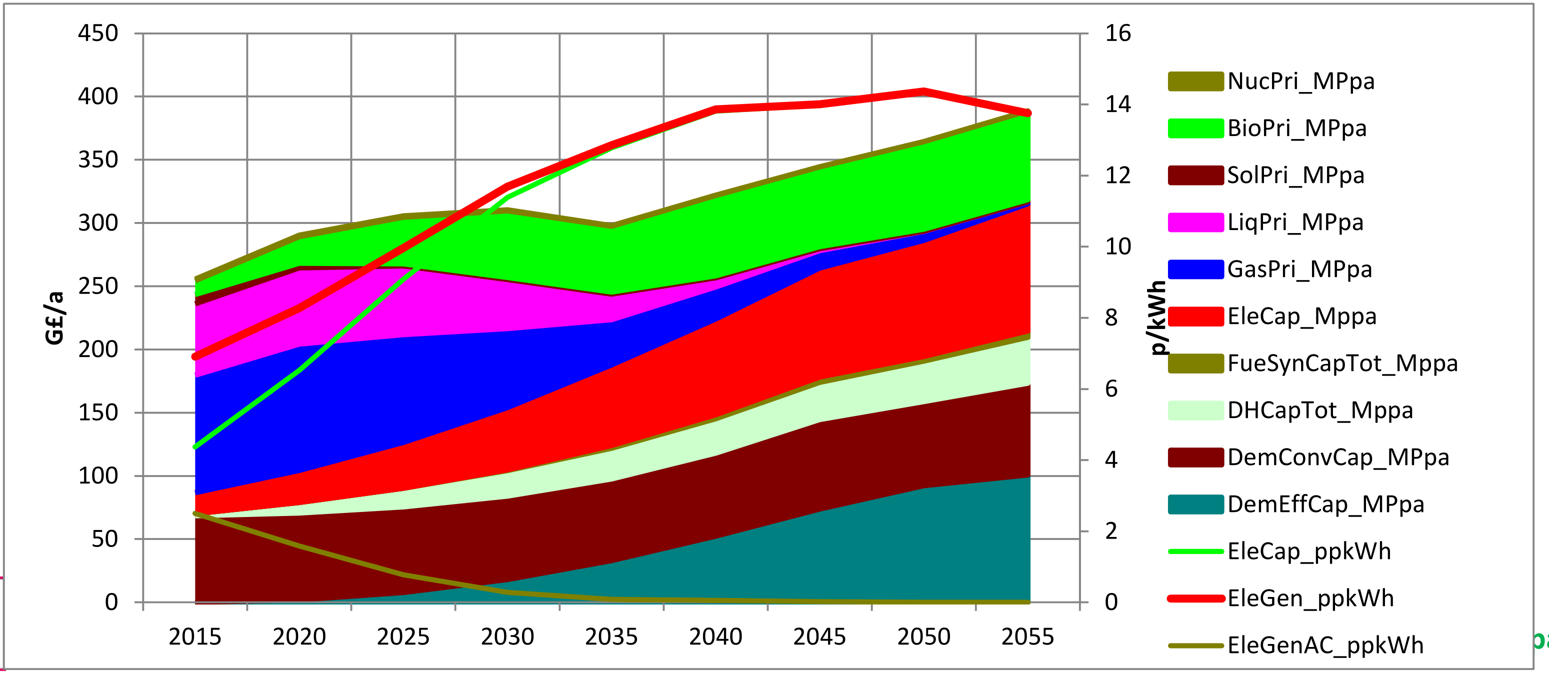


Economics

- Increase of about 60% in total UK energy system cost; 25% increase per capita; little cost change per (smaller) household. [Note: all very low carbon systems will cost more than today.]

- A transition from a fuel cost to a capital cost dominated system. The system is insulated from fluctuating international fuel prices, except for imported biomass.

- Consumer efficiency and end use conversion equipment the major cost
- Electricity unit cost (bulk) increases by about 50%
- Biomass the only substantial fuel cost



Critical design problems

Aviation

- How to reduce global warming due to high altitude water and NOx– fly lower with turboprops? Reduced demand growth probably necessary.

Biomass – the premium renewable resource

- How much will be available at what cost of different types?
- How much available for aviation fuel?

Long distance transmission

- How much to where?

Storage

- How much of what sort?

Starting in the right direction is important. The best design will evolve as the UK and its neighbours, and technologies develop over coming decades.

Difficult implementation problems

Demand behaviour

- Aviation – how to control growth

Energy efficiency

- How to improve the energy efficiency of existing buildings

District heating

- How to secure investment and connection

System control

- How to implement a social structure to dynamically control a variable renewable based energy system

Conclusions

- It is possible to design 100% renewable systems that will function hour by hour in different conditions.
- Detailed spatiotemporal modelling is needed to explore functioning systems.
- There is abundant renewable energy. If demand is higher then renewables, storage etc. can be scaled up.
- Risky, irreversible nuclear is unnecessary and fossil CCS is insufficient for near zero carbon.
- District heating and synthetic fuels have important management roles through storage and multi-fuelling.
- Aviation is the toughest nut.

Thank you for listening. Questions?