UCL BARTLETT SCHOOL OF GRADUATE STUDIES
COMPLEX BUILT ENVIRONMENT SYSTEMS GROUP

A RENEWABLE ELECTRICITY SYSTEM FOR THE UK

A RESPONSE TO THE 2006 ENERGY REVIEW

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Cover image: wind turbines at Royd Moor, South Yorkshire. © R.L. Lowe

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EXECUTIVE SUMMARY

This submission summarises the results of a study based on an hourly dynamic physical energy model of a future UK electricity supply system based almost entirely on renewable sources of electricity. This report represents work in progress, and is a condensed version of a longer paper currently in preparation. It nevertheless demonstrates the technical feasibility of a 95% renewable electricity system, a finding which is of strategic importance to the energy review. This submission is unusually long and detailed, qualities which are unavoidable if the reader is to get a sense of the level of the modelling and the plausibility of the scenario presented but not previously published.

Key findings of the study to date are:

- A system in which 95%of the energy is renewable can supply electricity reliably hour by hour over the whole year
- The emissions of greenhouse gases and air pollutants from electricity generation can be virtually eliminated
- The unit electricity costs of the system are not excessive as compared to future finite fuelled generation, and are not subject to the uncertain availability and price of imported finite fuels
- The system is secure in the long term because it is based on indigenous energy sources, and does not employ irreversible technologies that pose substantial risks
- The renewable electricity can be used to substitute for some gas and liquid transport fuels

Introduction

The goal is to design a sustainable electricity service system that meets environmental objectives for global warming and air pollution, and that also reduces or eliminates several categories of risk associated with other electricity supply mixes. The electricity system proposed would reduce the problems posed by the Energy Review concerning the control of carbon dioxide emission and the securing of energy supplies in a context of declining UK fossil fuel production and nuclear generation.

This document describes an electricity service system for the UK in which 95% of electricity demand is met by renewable energy sources sited in the UK. The options exercised in the scenario include energy efficiency, the large scale introduction of renewable electricity only sources and biomass fuelled CHP. It is also assumed that fossil fuelled generation is used for firm capacity, the trade link with France is reinforced and existing nuclear stations are not replaced. The systems modelled result in very low emissions of greenhouse gases and other atmospheric pollutants because fossil fuel use is small. This system is one which might be put in place over the next 10 to 40 years as nuclear and fossil generation decline.

It is argued that the system proposed here is technically and economically feasible and would meet environmental and energy security objectives. *Prima facie*, the system is more desirable than one based on finite energy sources such as coal or nuclear power. It is therefore argued that such sustainable systems be further developed and assessed before strategic decisions involving irreversible technologies are taken.

The remainder of the paper has these parts:

i. Description of the overall energy scenario context including sectors other than electricity.

ii. Description of the components of the electricity system: demand, storage and generation.

iii. Description of an optimised integrated system.

iv. Conclusions and discussion.

This paper is a condensation of material on energy and electricity scenarios, some of which may be found at: www.CBES.ucl.ac.uk/projects/EnergyReview.htm

Scenario context

The provision of electricity services cannot be planned in isolation from the overall UK, and indeed, European energy systems. Energy planning should be integrated across all segments of demand and supply. If this is not done, the system may be technically dysfunctional or economically suboptimal. Energy supply requirements are dependent on the sizes and variations in demands over timescales from minutes to years, and these depend on future social patterns and technologies. Some examples of integrated planning issues are:

- CHP electricity generation depends on heat load, and this depends on insulation in buildings and how much heat is provided from other sources such as solar.

- Electric vehicles will add to electricity demand, but reduce fossil liquid fuel consumption and add to electricity storage capacity which aids renewable integration.
- Is it better to burn biomass in CHP plants and produce electricity for electric vehicles, or inefficiently convert it to biofuels for use in conventional engines?

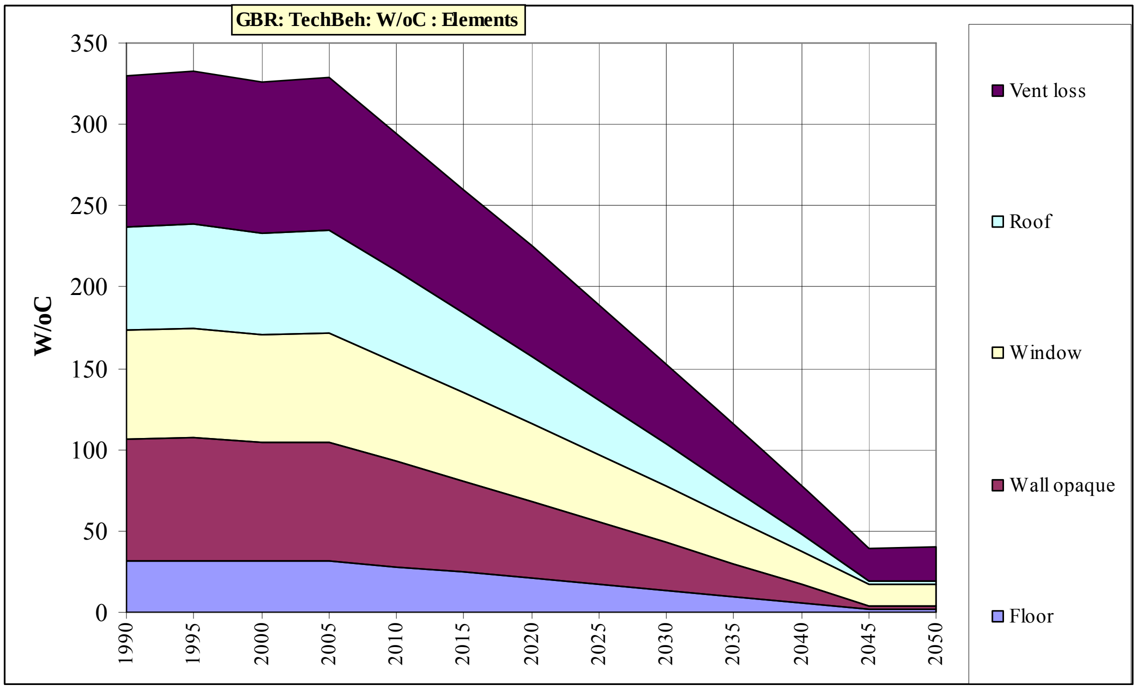
Some materials on the scenario context are presented here. More detail may be found at www.CBES.ucl.ac.uk/projects/EnergyReview.htm

Scenario context: dwelling space heating

As an example of context, the interaction between dwellings and energy supply is briefly explored. This is only to illustrate and emphasise that determining optimum supply mixes can only be done with detailed analysis extending across all segments of demand.

The implementation of space heat demand management (insulation, ventilation control) will change the amount and time variation of heat demand in the domestic sector. Figure 2 shows a profile over the coming decades for demand management as building regulations and refurbishment takes effect.

Figure 1 : Scenario context: dwelling heat loss factors



Figures 2 and 3 illustrate how increased energy efficiency will change heat loads in a typical building now and a future insulated dwelling maintained at low temperatures. Increased energy efficiency will reduce the seasonal variation in heat demand. However, air conditioning needs will increase if house design is poor. These heat load variations are shown to illustrate how the supply requirements for heating fuels — gas, electricity, CHP heat — depend on many demand factors.

Note that in Figure 3 the thermostat setting refers to the temperature below which space heating is activated. (There is a different upper limit above which air conditioning is activated.) The particular space heat setting of 15 C is one where is assumed that warmer clothing has reduced the comfort temperature. (This is part of an analysis of the effects of occupant behaviour.)

Figure 2 : Scenario context: current dwelling monthly heat demands

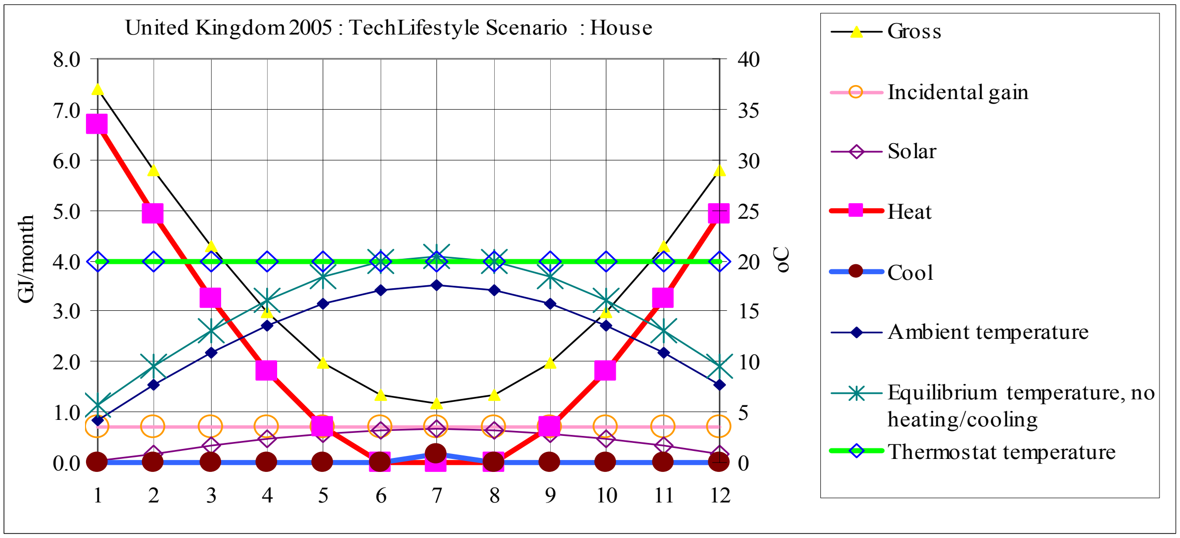
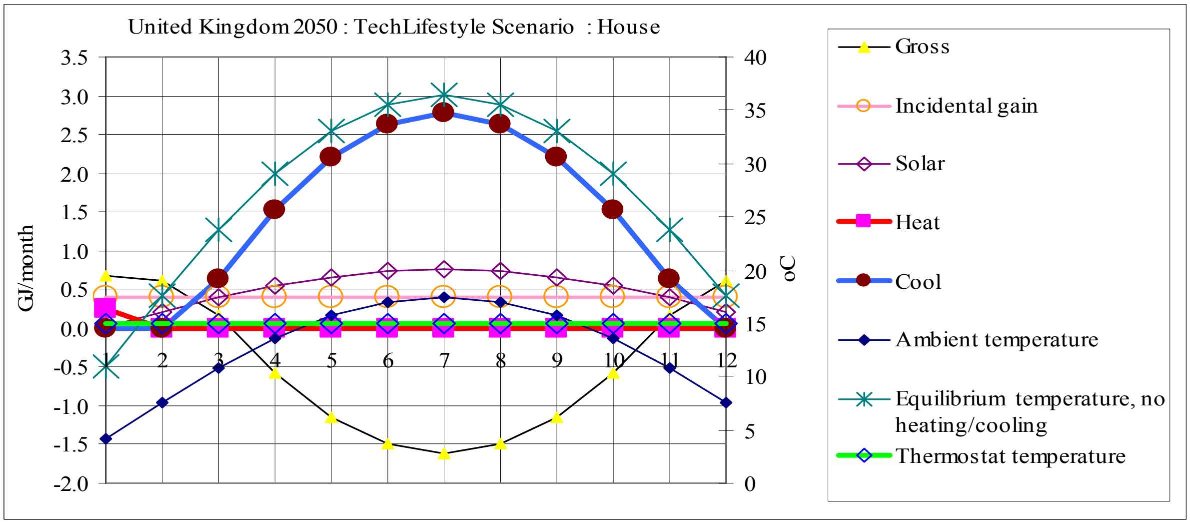


Figure 3 : Scenario context: insulated dwelling monthly heat demands



A sustainable electricity system

The bulk of the remainder of this paper describe the construction of a scenario for a sustainable integrated electricity system for the whole of the UK. The development profile over the years of the system is not described here; if the ‘end state’ system appears feasible based on current technology and incremental extensions thereof, there seems to be no reason to doubt that the system could be constructed over the coming decades.

The components of the system are described: demands, generators, stores and trade links. These are then assembled into an optimised system such that demands are met securely at least cost. This involves modelling the hourly variation in demand and supplies, and adjusting the capacities of the different sources until the minimum cost is found.

In this study, spatial issues are not addressed. Increasing the geographical range of electricity systems increases the temporal diversity of demand and supply, but also imposes requirements for transmission and distribution networks. These requirements and their associated costs are not analysed.

Electricity demands

Future electricity service demands in terms of type, temperature, quantity, time, weather dependency depend on the scenario context. In this scenario, it is assumed that the demands for electricity -specific services that can use no other fuel (computers, communications, lighting, some motive power...) will generally stabilise because efficiency gains will offset growth factors such as population.

The usage of electricity for heating depends on the relative availability and prices of other fuels that can perform this function. Energy efficiency will reduce the heat demand in dwellings, but gas will eventually have to be replaced, perhaps with electric heat pumps. The balance of these effects on electricity demand requires analysis.

The replacement of liquid fossil fuels is perhaps the most difficult energy supply problem. Electric vehicles are assumed to make large inroads into the car and light haulage markets. Vehicles are mostly in use during times of high electricity demand, and so their batteries would be predominantly charged at off-peak times thus reducing the diurnal variation in total electricity demand. The use of electricity for making hydrogen to be used in fuel cells is excluded because this route is less efficient than the combination of batteries and electric motors. If hydrogen technologies were to improve, hydrogen fuel cells would replace batteries where appropriate. This substitution would not change the rest of the electricity system significantly because the electricity requirements for charging batteries or producing hydrogen would be similar in quantity.

Other characteristics of demand can also be important:

- end use technologies; the capacity for control, storage, interruptibility
- multi-fuelled energy services; electric/ solar / gas heating; electric / liquid fuelled hybrid cars. Fuels can be switched according to which energy supply is available.

Electricity service demands are divided into six categories, each with different weather dependencies, use patterns and service storability. A long term forecast of 282 TWh is used, as shown in the Table. This varies from year to year because of weather.

Table 1 : Annual UK electricity demand

Service	Service storable	Weather dependent	TWh	
Lighting	No	Yes	22	8%
Non-space heating	Yes	Slightly	70	25%
Space heating	Yes	Yes	34	12%
Air conditioning	Yes	Yes	4	2%
Electric vehicle charging	No	Slightly	37	13%
Electricity specific	No	Slightly	114	40%
Total			**282**	100%

Energy storage

Energy storage is used to improve the match between demand and supply. Since 1950, energy storage has been extensively used in electricity systems. Storage has been used to reduce the capacity requirements for transmission, distribution and generation.

- System storage, currently in the form of pumped storage, is used to even out the load on generators and provide fast response in case a large generator fails. Presently, pumped storage has a capacity of some 2 GW power, and 10 GWh energy.
- To increase base load demand and thereby improve the economics of large coal and nuclear generators, off-peak heating was introduced in the form of hot water tanks and off-peak storage heaters. Currently some 10% of dwellings have electric space heating, and a large fraction have electric water heaters (immersion heaters) although most water heating is done with gas. These existing systems incorporate stores which have an electrical input power of perhaps 40-60 GWe and a maximum energy storage capacity of some 200 GWh.
- Further storage can be implemented, such as: embedded in end use technologies (building thermal mass, refrigerators); batteries/electrolyte recharging for refuelling electric vehicles.

Generation

Renewable electricity sources

Cost and performance figures for the renewable technologies have been taken from a number of sources. For most of these, the cost reductions that might occur over the next 20-40 years time have to be projected, with uncertainties being particularly large for wave and tidal power for which there is little commercial experience, and for photovoltaics where there may be technical step changes. The total economic energy resources available from renewables depends largely on the cost of competing fuels – the greater the cost of other fuels, the greater the ‘economic’ renewable resource. This is particularly so for wind and wave, which have large off-shore resources, and solar heating and photovoltaics. There are, however, narrow technical limits to some renewable sources, most notably hydro and waste biomass.

Table 2 summarises some costs and estimates for the potential of renewable electricity. This table is mainly based on *Technical and economic potential of renewable energy* *generating technologies: Potentials and cost reductions to 2020* (PIU, 2001). Of particular note is the projected cost of photovoltaics (PV) mounted on buildings for 2020. The tidal lagoon estimates are quoted in *A Severn barrage or tidal lagoons?* (FoE Cymru, 2004). These potentials and costs have been used as a guide to the inputs to the later modelling although the costs assumed in the modelling are generally higher than in this table; this reflects caution in using cost projections. However, it is to be noted that a 95% renewable system would be fully implemented some years after 2020 when costs will have been further lowered because of technology development and mass production.

Table 2 : Renewable energy technical and economic potential

		Cost	**Economic potential at this cost**	**Technical potential**	**Capacity Factor**	**Economic potential at this cost**	**Technical potential**
Source	**Technology**	**p/kWh**	**TWh**	**TWh**		**GW**	**GW**
Solar	Building PV	7.0	1	266	14%	0.4	216.9
Wind	offshore	2.8	100	3500	27%	42.3	1479.8
Wind	onshore	3.0	58	317	30%	22.1	120.6
Wave		4.0	33	600	40%	9.4	171.2
Tidal	stream	7.0	2	36	40%	0.5	10.3
Tidal	lagoon	2.5	24	24	61%	4.5	4.5
Hydro	small	7.0	2	40	80%	0.3	5.7
Biomass	mun. waste	7.0	7	14	60%	1.2	2.6
Biomass	landfill gas	2.5	7	7	60%	1.3	1.3
Biomass	energy crops	4.0	33		70%	5.4	0.0
Total			**266**	**4804**		**87.4**	**2012.9**

Biomass is a renewable energy source that can provide electricity at any time, because the energy is in a stored form. The following table shows estimates of the mass and energy content of waste and energy crop biomass. The amount of electricity that may be generated from this in CHP plant has been calculated using efficiency to electricity of 25% and a capacity factor of 45%.

Table 3 : Biomass potential

Biomass		**Mt**	**GJ/t**	**PJ**	**Eff(e)**	**TWhe**	**CapFac**	**GW**
Waste	Wood waste	4.5	13	59	25%	4	45%	1.0
	MSW	8.0	9	72	25%	5	45%	1.3
	Straw	3.0	14	42	25%	3	45%	0.7
	Sewage	0.4	15	6	25%	0	45%	0.1
	Animal waste	3.0	7	21	25%	1	45%	0.4
	Total	18.9		200		14		3.5
Energy crops		8.0	14	112	25%	8	45%	2.0
	Total	26.9	10	312		22		5.5

Based on: *Biomass Task Force report to UK Government, 2005*

MSW – Municipal Solid Waste

CHP

The potential output of CHP depends on low-temperature heat demands, and the fraction of these demands that might be met with available, cost-effective combustible fuels, or other source of high temperature heat.

The current UK CHP electricity output is about 27 TWh from 5.6 GWe capacity running at a capacity factor of 55%. Some estimates (e.g. *The Government's Strategy for Combined Heat and Power to 2010)* place the potential to be in the range 50-100 TWh for large scale and micro-CHP, corresponding to about 20 GW capacity, but:

- A major fraction of this CHP would use imported fossil fuels, mostly gas, which will become scarce and expensive, and remains carbon emitting.
- This assumes heat loads which may actually be smaller in scenarios with high energy efficiency, CHP potential depends on the overall scenario context.

Accordingly, in the scenario it is assumed that CHP potential is ultimately limited to that which may be fuelled with biomass — 5.5 GW at a 45% load factor producing 22 TWh of electricity. However, during the period leading to a fully sustainable, renewables-based system, gas and other fuels used for heating and electricity should be used in CHP plant where possible. A scenario in which gas CHP increases and then declines over the next 40-50 years may be envisaged. Heat distribution networks developed for CHP would facilitate the economic introduction of other heat sources such as electric heat pumps or solar energy as gas supplies become scarce.

Variations in the electricity and heat outputs of CHP are basically determined by variations in the heat load across the day, week and year. The electricity output of CHP may be manipulated by:

- altering the heat : electricity ratio of the generator within a range that depends on the type of technology
- using heat storage to decouple the CHP heat output from heat demand

This allows CHP to contribute to some electricity demand-supply matching.

Optional generation

Optional generation is needed if variable generation, storage and trade are insufficient to meet demand. It is possible to avoid any such generation by increasing the capacity of storage and international links. However, further analysis is needed to establish whether this would be economically optimal. In the optimised system, optional generation operates in an annual capacity factor range of 5-20%. Existing and new fossil could be used to meet any deficit of CHP and renewable electricity supply. Currently there are about 55 GW of main fossil stations, and about 10 GW of private generators. Some of these could be retained for the long term future, or new flexible plant could be built, depending on the economics. The coal stations provide strategic security since they can use indigenous reserves.

Table 4 : Current UK firm capacity (optional generation)

Type	Fuel	GW	Future fuel supply
Public (large)	Coal	19	large domestic coal reserve
	Oil	5	imported oil held in strategic reserves
	Dual fired	6	
	Gas	25	imported gas, some held in UK storage
Private (small)		~10	

Regional and international linkage

Currently it is assumed that there is sufficient diversity within the continental system that the UK can import or export, at any time, to the limit of the capacity of the international UK-France link (set at a maximum 6 GW as compared to the current 2 GW). This is a strong assumption, but the capacity of interconnection across and outside Europe will almost certainly increase.

System integration and optimisation

Operational issues

The design and operation of systems depends on the reliability with which demands and supplies can be predicted over different time scales, from minutes to months, and the sophistication of the control of demand and supply technologies. As the UK electricity system becomes increasingly integrated with the European system and systems further afield, the design and operation of the systems will become more complex.

Communications and information processing technologies are already adequate for the precise control of demand technologies, generators and storage. The accurate prediction of demands and supplies will become more critical, mainly because of the larger variable renewable component of supply and its consequences for the operational management of demands, storage and trade. However, prediction will improve with the refinement of weather and other data and of simulation models:

- weather forecasting will become more precise
- energy efficiency and demand management reduces the less predictable, weather dependent loads such as space heating and lighting

- demand prediction will become more accurate as models improve
- predicting outputs from variable sources will become more accurate

Demand and supply correlation

The planning of electricity supply must include detailed demand analysis, because:

- weather variables are correlated
- energy demands vary with time because of social activity patterns and weather
- renewable energy supply is weather dependent

The firm capacity of renewables is that amount of optional (biomass/fossil/nuclear) capacity that it is not necessary to build in order to meet demands with a certain reliability. The firm capacity of a renewable depends on the correlated variations in demands and renewable supply. Importantly, the variations in some demands depend on the same weather parameters as the outputs from some renewables. To illustrate:

- If solar PV were to meet space heating demand, its firm capacity would probably be close to 0%; if it were to meet air-conditioning demand it might be 50% because large air-conditioning loads occur at times of high insolation.
- Air conditioning load is negatively correlated with wind. However, a significant fraction of space heating is positively correlated to wind speed and wind power, because wind increases ventilation losses. Assuming a significant fraction of buildings use electric heat pumps, then the electricity demand from these houses would vary by several GW with wind speed. Note this ignores time lags due to building thermal mass and differences in location of demand and supply,

Load management

Load management is the process of manipulating demand with storage and interruption to better match supply. A portion of electricity demand may be moved if the net cost of a move is negative, accounting for differences in marginal supply costs, energy losses and other operational costs.

Electricity demand may be disaggregated into segments across sectors and end uses: each segment with a temporal profile, and load management characteristics such as energy storage capacity. Variable electricity supply comprises renewable sources and heat related generation, each with their own temporal profile. The mismatch between variable sources and demand can be met with: optional thermal generators characterised by energy costs at full and part load, and for starting up; traded import or export, and system or end-use storage.

The following graphs demonstrate the role that load management can play in a putative future system, integrating variable renewables and CHP into electricity supply on a winter day and a summer day. Heat and electricity storage (hot water tanks, storage heaters, vehicle batteries) can be used to store renewable energy when it is available, so that the energy can later be used when needed. Other demands, such as refrigerators, can be manipulated or interrupted. In this example of load management, only heat demands are managed with storage.

The graphs show how, by moving heat demands with storage, that the system demand profile can be matched to variable supply from CHP and uncontrollable renewables. The residual demand to be met by optional generators (conventional nuclear and fossil) is then flat. This means that these plant do not have to load follow, which wastes energy, and that the required installed capacity of these plant is reduced.

The **System** graph summarises:

- system demand (end use demand plus transmission losses)
- variable renewable and CHP supply (called ‘essential’ here)
- trade
- reserve requirement
- system storage (pumped storage)
- optional supply required to meet difference between demand + storage and variable supply

The **Demand** graph shows demand across the sectors (R-Residential; I_Industry; S-Services; O-Other) for combinations of technology and end use.

The **Marginal costs** graph shows the energy costs of generation, the costs of starting up plant, and the distribution costs (currently a simple constant).

The **Generation** graph shows the output from each generation source, in order from bottom to top: renewable sources; CHP; and optional generation ordered by increasing steady state marginal cost (excluding startup costs).

Figure 4 : Matching without load management: winter and summer's day

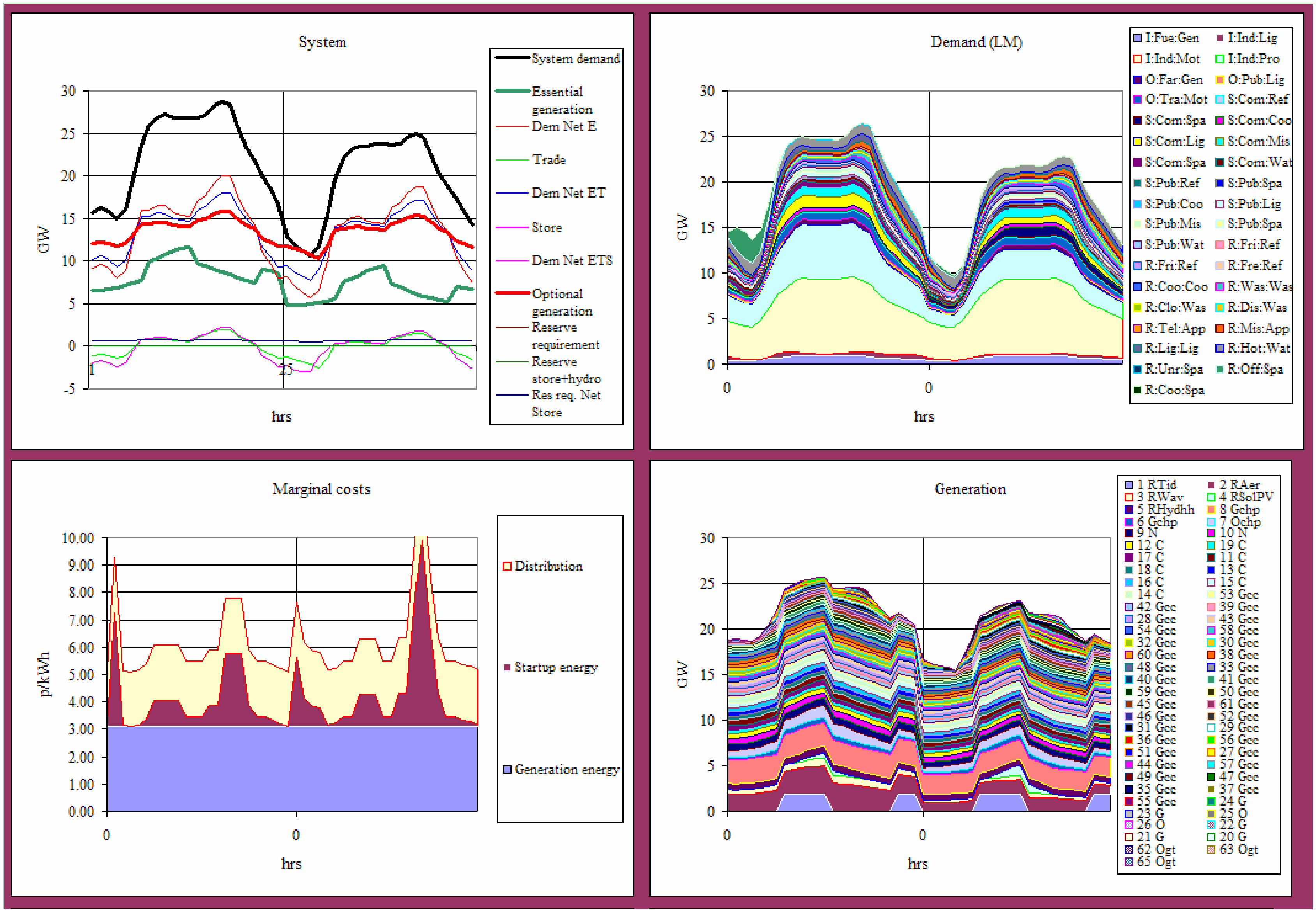
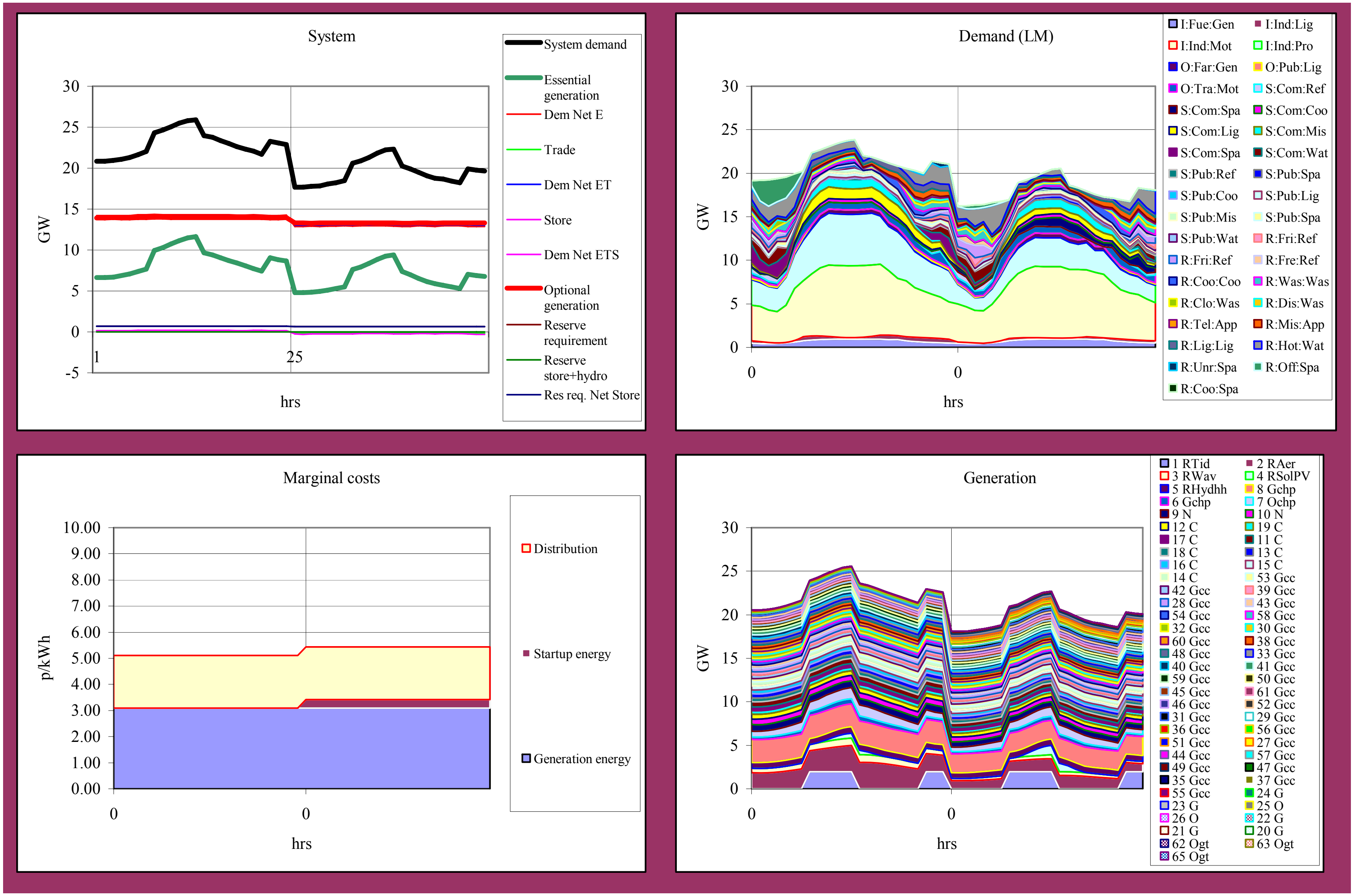


Figure 5 : Matching with load management: winter and summer's day



The load management simulation demonstrates how variable electricity supplies constituting about 50% of peak demand, using heat storage alone, can be absorbed such that the net demand met by optional generation is levelled. This indicates that large fractions of variable electricity supply can be absorbed into the electricity system without special measures other than the control of heat stores. Further investigation of other system configurations and renewable generation is required to establish the exact potential of load management.

An optimised system: summary

A model is used to:

- Simulate the hourly demands, renewable and optional generation, and storage trade flows
- Find the least cost mix of generators, stores and trade capacities. The annuitised costs of capital are calculated using a 5% discount rate.

The remainder of this section summarises the optimised system.

Technical

Figure 6. depicts the capacities of the generators and trade link, and of the electricity and heat stores.

Figure 6 : Generator capacities

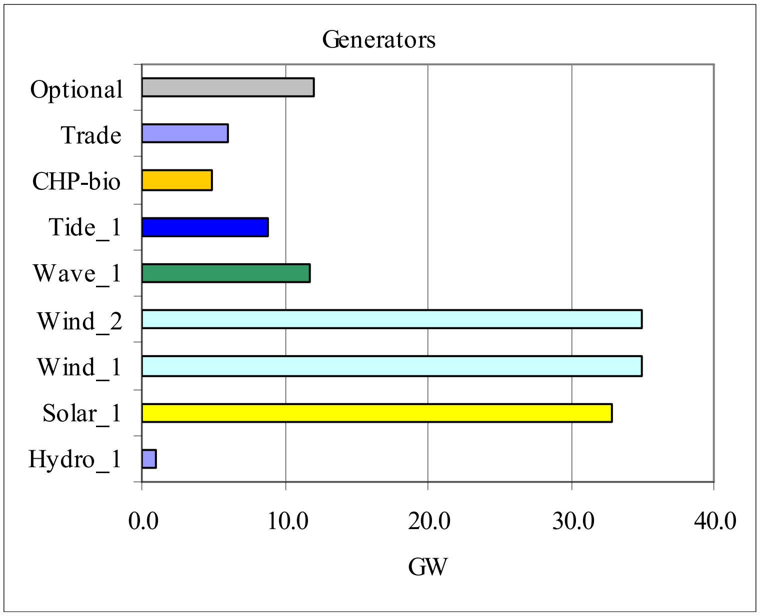


Table 5. summarises the annual energy flows of the system for a simulated year. The flows vary from year to year because of fluctuations in demand and renewable output because variations in the weather and renewable resources. 'Renewable' refers to electricity only renewable systems. 'CHP-bio' refers to biomass fuelled CHP.

Table 5 : Annual: technical summary

		TWh	
Demand		**282.2**	
	Transmission losses	16.9	
	Supply requirement	299.1	
Supply	Renewable	292.2	98%
	Spilled	-10.0	-3%
	CHP-bio	19.2	6%
	Optional	5.2	2%
	Storage	2.2	1%
	Country supply	**308.8**	103%
	Country surplus	9.7	
	Trade	-8.8	
	Country supply	**300.0**	

Economics

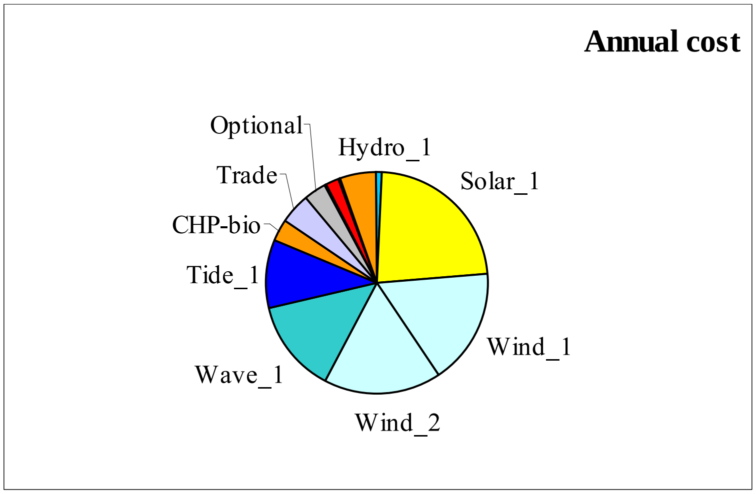
Table 6. shows the total cost of the system and the average unit price of electricity. Both of these will vary from year to year because of weather induced changes to demand; and to supply, particularly of trade and optional generation. The annual cost of the renewables does not change significantly, except for expenditure on maintenance that is related to energy output for that year. Negative energy costs arise because of export. On average the trade balance for the optimised system is near to zero.

Table 6 : Annual: economic summary

Annual cost	**G£**	
Capital	16.7	
Energy	-0.7	
Store	0.3	
Total	**16.2**	
Average	**5.4**	p/kWh

The pie chart shows the distribution of annualised expenditure summarised in Table 6.

Figure 7 : Annualised component costs



Optimised system: demand and technology details

Table 7.shows further details of the optimised system. Yellow cells contain assumptions; those with bold type are the values changed by the optimiser. The tan cells contain minimum and maximum allowable values. Of note are the energy generated, the capacity factors, and the unit cost of electricity generation shown in the last row. The negative numbers for trade arise because for this particular year electricity is exported.

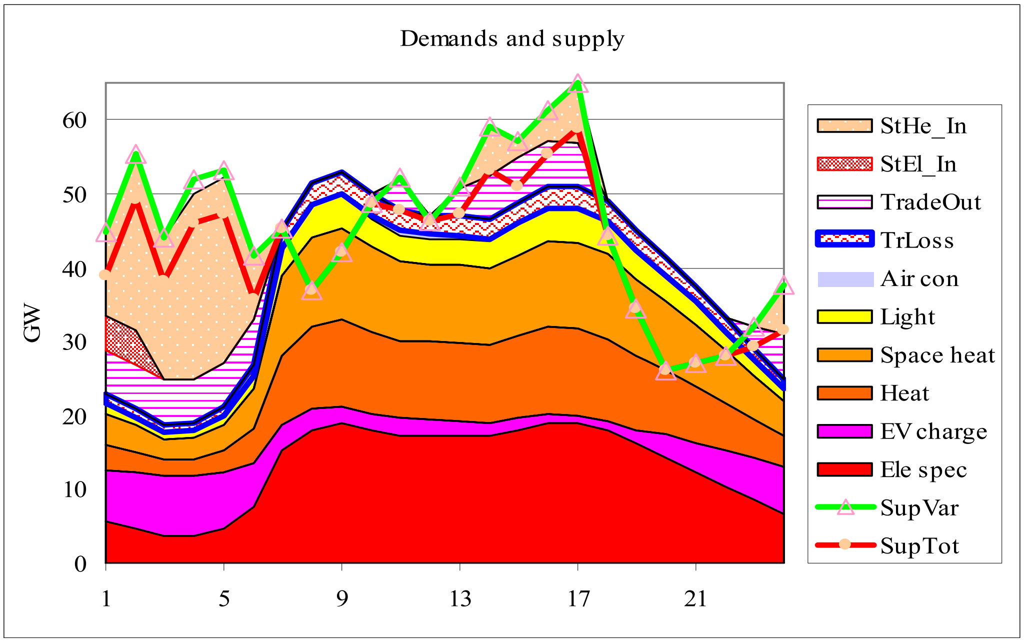
Table 7 : Optimised system details

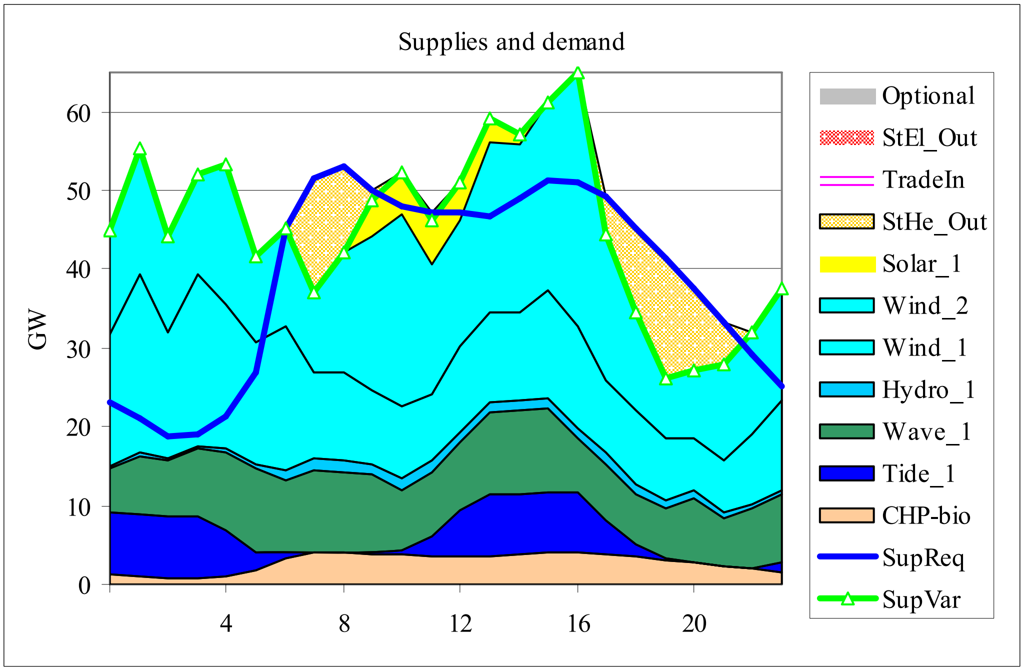
		Demands						**Supply**									**Storage**					
								Renewables									Electricity			Heat		
		Light	Heat	Space heat	Air con	EV charge	Ele spec	Hydro_1	Solar_1	Wind_1	Wind_2	Wave_1	Tide_1	CHP-bio	Trade	Optional	StEl_In	StEl_Sto	StEl_Out	StHe_In	StHe_Sto	StHe_Out
Capacity		GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	GWh	GW	GW	GWh	GW
Current		2.5	8.0	4.0	0.5	4.0	13.0	**1.0**	**32.9**	**35.0**	**35.0**	**11.7**	**8.8**	**5.0**	**6.0**	**12.0**	**4.6**	**10.0**	**6.3**	**24.9**	**300.0**	0.0
Maximum								1.0	55	35	35	12	10	5	6	50	100	400	100	100	999	
Minimum								0.6	0	0	0	0	0	2	2	0	2	10	2	0	10	
Efficiency								86%	25%	25%	25%	60%	60%		92%		88%	77%	88%	99%	97%	98%
Energy	TWh	22	69	35	5	37	114	7.5	41	93	84	35	32	19	-9	5						
Capacity factor								86%	14%	30%	27%	34%	42%	44%		5%	-5%		3%	-6%		
Unit capital cost	£/kW							2500	2000	1000	1000	2500	3000	1000	1500	200	100	400	100	10	50	5
Operating life	Yrs							100	30	20	20	20	25	25	50	35	20	20	20	30	30	30
Discounted life								19.8	15.4	12.5	12.5	12.5	14.1	14.1	18.3	16.4	12.5	12.5	12.5	15.4	15.4	15.4
Capital total	G£							2.5	65.8	35.0	35.0	29.2	26.5	5.0	9.0	2.9	0.5	4.0	0.6	0.2	15.0	0.0
Capital annuitised	G£							0.1	4.3	2.8	2.8	2.3	1.9	0.4	0.5	0.2	0.0	0.3	0.1	0.0	1.0	0.0
O&M cost	£/kW/a							25.0	20.0	20.0	20.0	50.0	30.0	20.0	30.0	4.0	2.0	8.0	2.0	0.1	0.5	
	G£							0.0	0.7	0.7	0.7	0.6	0.3	0.1	0.2	0.0	0.0	0.1	0.0	0.0	0.2	0.0
Energy cost (O&M, fuel)	p/kWh							0.1	0.1	0.1	0.1	0.1	0.1	1.0	10.4	6.9						
Energy cost	G£							0.0	0.0	0.1	0.1	0.0	0.0	0.2	-0.9	0.4	0.0	0.0	0.0	0.0	0.0	0.0
Total cost	G£							0.2	5.0	3.6	3.6	3.0	2.2	0.6	-0.2	0.6	0.0	0.4	0.1	0.0	1.1	0.0
Unit cost	p/kWh							2.1	12.1	3.9	4.3	8.4	6.8	3.3	-2.7	11.2	0.0	0.0	0.0	0.0	0.0	0.0

Optimised system: hourly performance

This section illustrates how the optimized system performs hourly for individual sample days, and across the year. The first two charts show a winter's day in which the variable supply of electricity from renewables and CHP is greater than demand, over the day. Surplus variable generation is exported and put into energy stores.

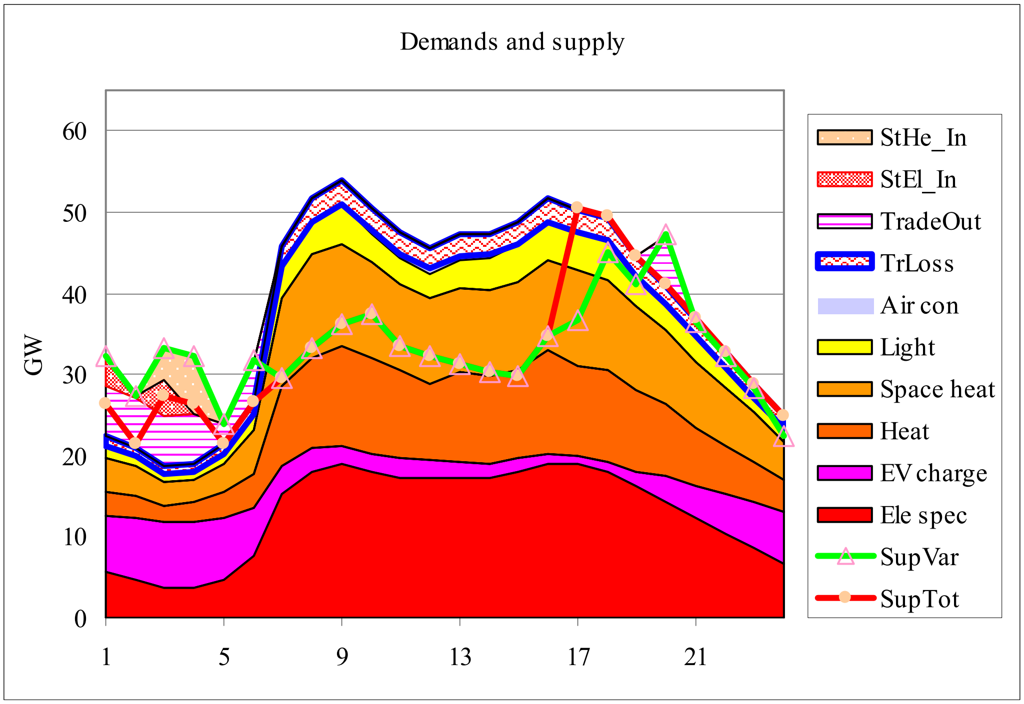
Figure 8 : Sample winter day: variable supply excess





This pair of charts shows a winter's day when demand is greater than variable supply over the day. The deficit is met with import, energy from stores, and optional generation.

Figure 9 : Sample winter day: variable supply deficit



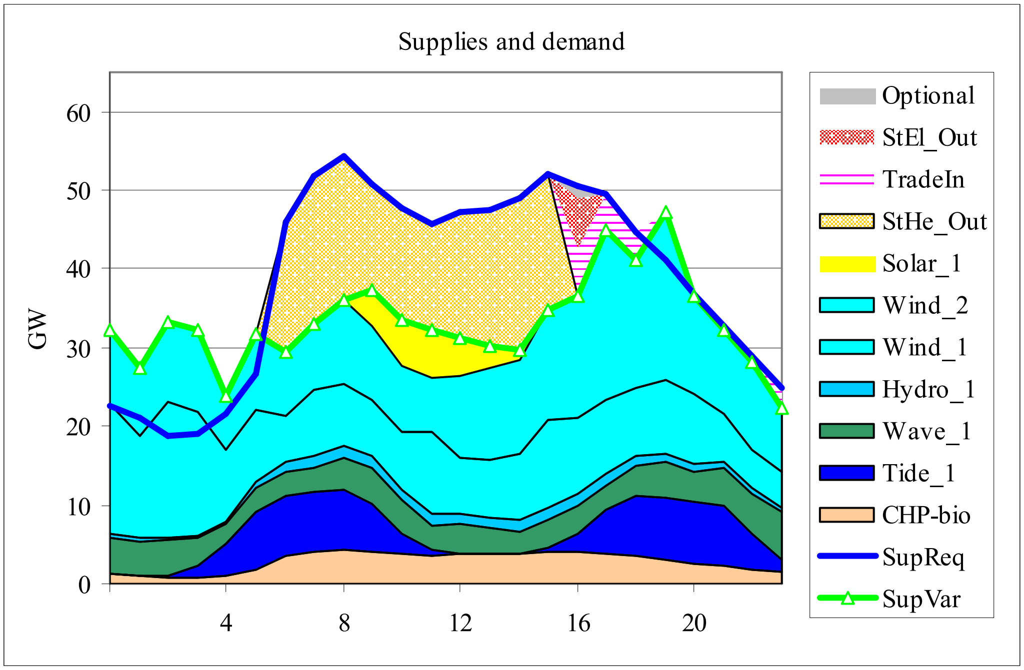


Figure 10, 11, 12 and 13 show the electricity system performance for five sample days in January, April, July and October. Figure 10. shows a set of random weather and renewable energy supply for the five sample days in the four months.

Figure 10 : Annual sample: weather and renewable energy

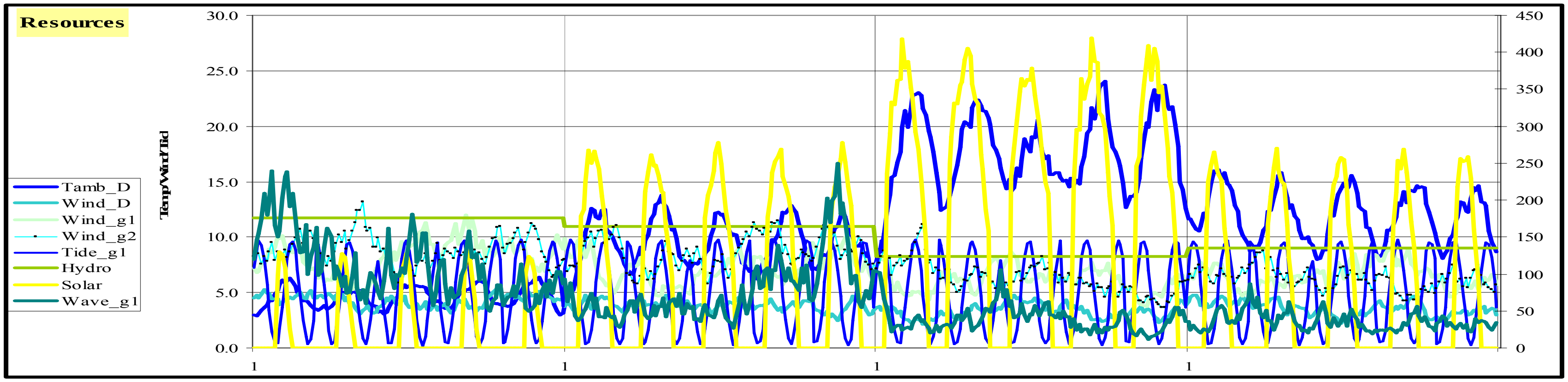


Figure 11 shows how the assumed demands vary due to socioeconomic activity patterns and weather.

Figure 11 : Annual sample: demands

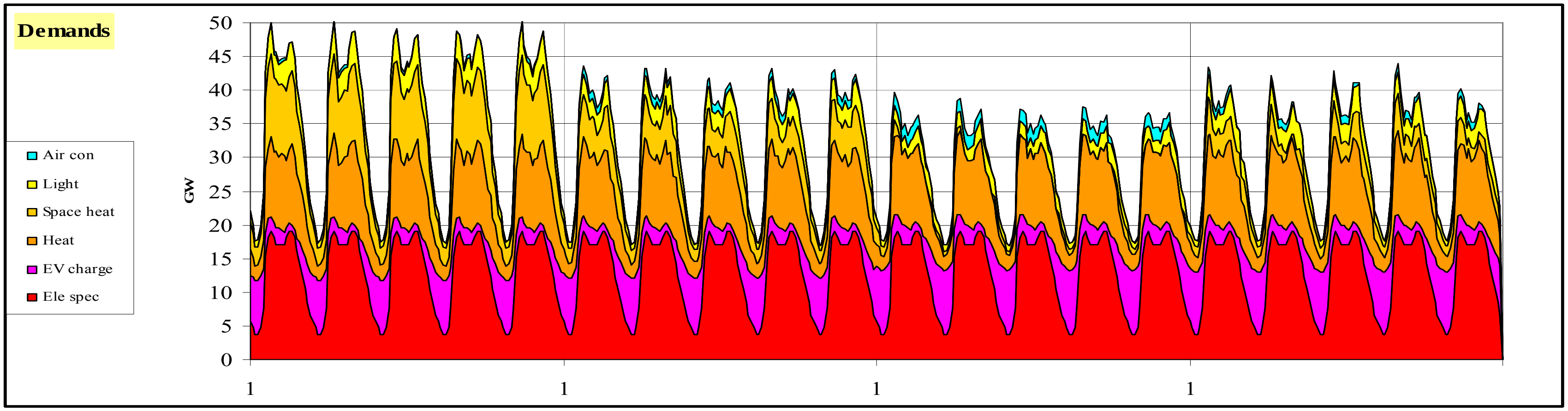


Figure 12. shows the generation from renewables, CHP and optional sources; trade imports are shown as positive; exports as negative.

Figure 12 : Annual sample — generation

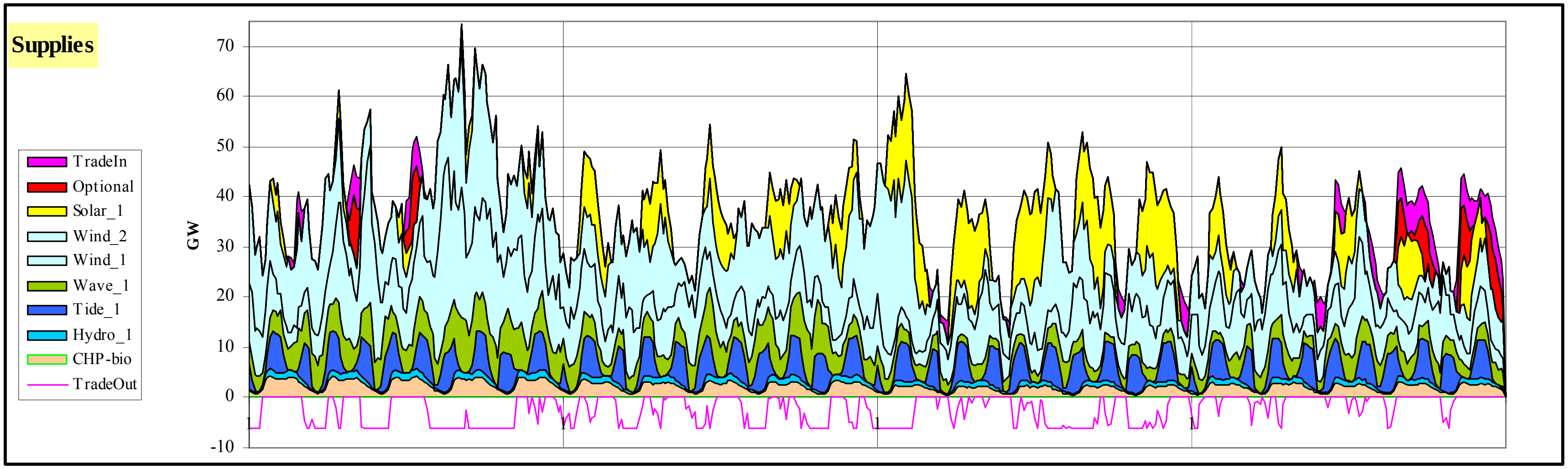
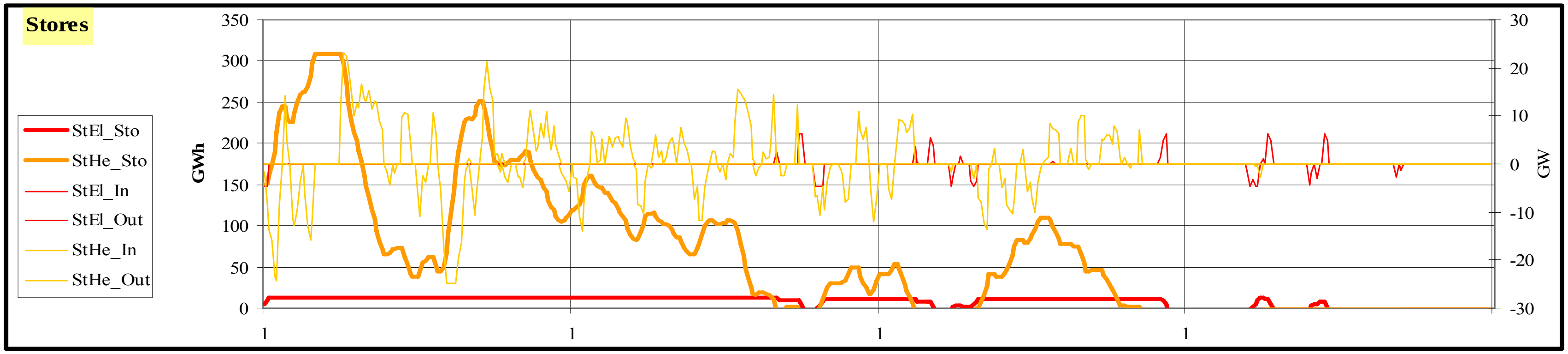


Figure 13. shows the energy stored (thick lines) and inputs and outputs from the stores.

Figure 13 : Annual sample —storage



Conclusions

This paper summarises some principal features of a sustainable electricity service system. It has been shown how indigenous renewable energy sources can provide up to 95% of electricity supply securely if storage, trade and optional generation are also deployed. It further demonstrates that the unit cost of electricity (averaging about 5.5 p/kWh) may not be excessive as compared to future fossil or nuclear generation costs. It is emphasised that the cost estimates for renewables in 10 or 50 years time are inevitably speculative, as they are for fossil and nuclear generation. However, there is more certainty about renewable energy costs because they are not dependent on finite fuel prices which will inexorably increase. The future unit cost of electricity will probably be higher than today in any scenario because of capital cost and fuel price increases: either in a high renewable future; or one with large fractions of fossil and nuclear generation.

The scenario is more secure than high fossil/fissile scenarios because it is almost immune to the unpredictable future prices and availabilities of finite fuels, and it incorporates a mix of low risk, reversible technologies

It is not claimed that this system is necessarily the best because it does not include all the possible options in terms of technologies or operational strategy. The optimal system depends on the many assumptions about future demands, and the performance and costs of generation, storage and transmission technologies. Changes in these assumptions will lead to different solutions. However, some of the costs and technicalities of a working system have been demonstrated; the challenge is to find better solutions.

Energy security can be defined as the maintenance of safe, economic energy services for social wellbeing and economic development, without excessive environmental degradation. Demand management and energy efficiency are the fundamental options to improve security. Most forms of energy supply are associated with some combination of technical, environmental or economic insecurity:

- Renewable sources are, to a degree, variable and/or unpredictable. However most renewable technologies are dispersed, mass produced, reversible (they can be removed without trace), and present no large scale risks.
- Fossil fuels produce greenhouse gases and are finite and will be increasingly imported. UK coal reserves are large, but coal has a high carbon content. Imported fuels suffer price volatility.
- Nuclear fuels are finite, and nuclear technologies present are effectively irreversible, and present potentially large risks.

Further analysis

This paper presents the results of work in progress.There are many aspects that warrant further investigation in order to test the robustness of the system, and seek different and better solutions.

Increased demand

The demand for electricity is the fundamental driver. Careful analysis of this is required, especially in the context of overall energy in which electricity may substitute for gas in the stationary sector, and liquid fuels in the transport sector. The correlations, positive or negative, between demand and renewables have significant impacts on costs.

If demand is increased, then so must supply. The PIU survey of renewable energy sources shows that to increase renewable output to 400-500 TWh or more over the next 40-50 years time may not be an unreasonable target. The off-shore wind and building photovoltaic resources, using proven technologies, are in excess of 1000 TWh. As supply increases so does the average unit cost of supply increases, but modelling indicates that the cost increase is not very steep.

Different renewable fractions

Systems with 100% renewable energy have been modelled and shown to be feasible. With such a penetration, the detailed analysis of demand-renewable correlations, renewable siting and technologies, storage and trade becomes more critical.

International electricity context

An extensive continental grid already exists, and increases in the capacity of connection between the UK system and the continental grid increases the benefits of diversity, at the cost of transmission. The advantages of extending the system include more demand and renewable supply diversity because of different weather and demand patterns (the latter includes the effect of time zones) in other countries. Some European countries have a large hydro component which is, to a degree, an optional renewable source and may be used for some matching of generation to demand.

Economics

If the performance and relative costs of the technologies changed, then so would the configuration of the optimum system. Assumptions about storage and photovoltaic technologies are perhaps the most critical.

Arguably, photovoltaic (PV) generation has the least environmental impact of the renewable sources. In addition, most PV would be sited near demand, on buildings, where maintenance and transmission needs and costs would be less than for the remote sources. An interesting question then is how a reduction in the relative cost of PV would increase its contribution in an optimised system.

Modelling of these aspects could be refined**:**

- Demand in terms of quantity, use patterns, weather dependency, control and correlation with renewable supply.
- Technologies and their controls: load management, storage and renewable energy.
- The spatial aspects of the system and transmission requirements.

Optimisation could include:

- Demand management decision variables such as interruptibility and efficiency costs.
- Control strategy parameters for operating demand management, storable renewables (hydro, tidal), stores, CHP and trade.