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The evolution of electricity demand and the role for demand side participation, in buildings and transport

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HIGHLIGHTS

- Evolution of UK electricity demand along 3 potential low carbon Transition Pathways.
- Electrification of demand through the uptake of heat pumps and electric vehicles.
- Hourly balancing of electricity supply and demand in a low carbon future.
- Demand side participation to avoid low capacity factor conventional generation.
- Transition Pathways to an 80% reduction in UK operational CO_2 emissions by 2050.

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ABSTRACT

This paper explores the possible evolution of UK electricity demand as we move along three potential transition pathways to a low carbon economy in 2050. The shift away from fossil fuels through the electrification of demand is discussed, particularly through the uptake of heat pumps and electric vehicles in the domestic and passenger transport sectors. Developments in the way people and institutions may use energy along each of the pathways are also considered and provide a rationale for the quantification of future annual electricity demands in various broad sectors. The paper then presents detailed modelling of hourly balancing of these demands in the context of potential low carbon generation mixes associated with the three pathways. In all cases, hourly balancing is shown to be a significant challenge. To minimise the need for conventional generation to operate with very low capacity factors, a variety of demand side participation measures are modelled and shown to provide significant benefits. Lastly, projections of operational greenhouse gas emissions from the UK and the imports of fossil fuels to the UK for each of the three pathways are presented.

1. Introduction

Foxon (this issue) describes the development of a set of three narratives outlining alternative pathways towards a low carbon economy in the UK. These are: a market-led pathway named Market Rules (MR); a government-led pathway known as Central Coordination (CC); and a civil society-led pathway, Thousand Flowers (TF). The pathways are politically and socially distinct, but all lead to a high degree of electrification, particularly in the transport and heating sectors, and thus the project has focused on the evolution of the electricity sector. In traditional scenario development for energy systems or climate change mitigation, a distinction is frequently made between thinking about possible changes on the 'demand-side' and the 'supply-side'. The former revolves around the lifestyles and consumption habits of the population, the stock of energy-using appliances, buildings and vehicles, and the fuel choices made within demand sectors or by consuming groups, leading to aggregate quantification of fuel and electricity end-use. On the supply-side, scenarios require analysis of the supply chains needed to deliver the requisite fuels and electricity to the point of use. This typically involves consideration of both infrastructures and primary resource inputs.

The Transition Pathways project has taken a slightly different approach. Whilst initial efforts followed the traditional model of

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demand side analysis followed by supply side, the primary focus here has been on interrogating and understanding the interplay between the two. The need for this has been driven by two underlying tenets: first that the inherent variability of renewable energy sources leads to a requirement for much greater flexibility on the demand side and second that a significant proportion of this generation may be in the form of small scale installations at consumer level. Thus the traditional distinctions between the demand and supply sides become blurred: consumers may become 'prosumers'—producing electricity onsite to meet at least some of their own demand and potentially exporting any excess. The required flexibility may come partly from this local generation, but in the main relies on consumers' willingness to change their consumption patterns. Opportunities for larger consumers to benefit economically by adjusting their demand patterns in response to price or other signals are already widely established in electricity markets, through half-hourly metering, time of day pricing and contracting of demand-response by the system operator. However there are potentially large and additional benefits to be realised from engaging small consumers, and with this in mind, the Transition Pathways project has focused particularly on the residential sector and personal transport.

The project has thus adopted an integrated process for developing pathways, following the steps below:

1. Development of 'narrative' descriptions of alternative pathways, in which the above changes take place to varying degrees (see Foxon, this issue).
2. Interpretation of the narratives into quantified models of energy demand on an annual average basis for the years from 2010 to 2050, including in particular increased electrification of heating and transport.
3. Interpretation of the narratives and annual demands to provide quantitative models of electricity supply and associated infrastructure, on an annual average basis.
4. Assessment of the proportion of generation that would be located at the consumer level.
5. Determination of prospective hourly demand and generation profiles based on the above, and including in particular an analysis of likely driving and electric vehicle (EV) battery charging patterns.
6. Iterative estimation of electricity supply and infrastructure needs required to maintain hourly balancing with the projected demand profiles, and with consideration of plant capital costs and operational carbon emissions.
7. Assessment of the potential for greater demand side participation in managing grid balancing.

As noted above, the project has followed an integrated and iterative process, but for the purposes of presentation, steps 3, 4 and 6 are reported by Barnacle et al. (this issue), while steps 2, 5 and 7 – the evolution of electricity demand – are the focus of the present paper. The next section provides an overview of step 2: modelling the use of fuels and electricity by the main sectors of the economy of the UK over the period to 2050, in terms of annual averages.

The paper then describes the application of the Future Energy Scenario Assessment (FESA) model to examine system energy balancing on an hourly time basis as the annual demands described above evolve up to 2050. Analysis of the resulting peak and base load patterns in relation to the available generation detailed by Barnacle et al. (this issue), serves to quantify the grid balancing challenge. The paper concludes with an initial assessment of the role of demand side participation in addressing this challenge, particularly with regard to the potential for time shifting of thermal demand in the built environment and scheduling of EV battery charging.

2. Annual demand quantification from pathways

A bottom-up, sectoral approach is taken, aggregated to provide overall trends in annual demand for the principal end-use fuels and electricity. As noted above, particular attention is given to residential energy use and private passenger transport, reflecting interest in the possibilities for decentralised generation and greater consumer demand response down at the smallest level of consumption. For residential energy use, a model of energy service demands is combined with a building stock model, and changes in demand are simulated as existing buildings are retrofitted with energy efficiency measures and as new buildings are erected with increasingly high thermal performance. The stock of energy-using appliances and heating systems is modelled, reflecting the characteristics of the different Pathway narratives. For passenger transport, detailed analysis of UK car use, including time and duration of travel, is undertaken through a probabilistic simulation model calibrated to the UK Time Use Survey (Ipsos-RSL and Office for National Statistics, United Kingdom Time Use Survey (2000) and the (Department for Transport, National Travel Survey (2002–2008). For the service sectors, industry and other transport modes, electricity use is projected based on the results of existing modelling by the UK's Department for Energy and Climate Change (DECC, 2010), tailored to match the trends described in the project's Pathway narratives.

2.1. Electricity demand for space and hot water heating

For domestic energy use, simulation models of energy service demand and building stock were developed at the University of Surrey. The models follow the broad structure of the DECC carbon calculator (DECC, 2010) but incorporate finer resolution of technical mitigation measures and their applicability, and allow representation of changes in end-user behaviours. Changes in the estimated demand over time reflect improvements to the building stock resulting from retrofitting and new build, following the steps outlined in the following sections.

2.2. Existing buildings

As a baseline, space and water heating demands for existing households before the introduction of energy efficiency measures are derived as a product of household number projections from 2000 to 2050, assuming a demolition rate of 0.0762% per yr (Kannan al. (2007), Kannan and Strachan (2009), and the average space and water heating demand for existing homes of 32.73 and 13.37 GJ/yr per household, respectively (Kannan and Strachan (2009); Kannan al. (2007)).

Savings in space heating are estimated based on the projected uptake of conservation measures for wall, cavity, floor and loft insulation as well as replacement of single with double glazing (Element Energy, 2009; Energy Efficiency Partnership for Homes (2008)). We assume that measures are typically applied in 'packages' and assume wall insulation is applied first, followed by loft, floor and then improved glazing. The pace and saturation levels for the uptake of measures were adjusted for each of the three pathways to reflect the narrative assumptions.

For water heating load calculation purposes, the uptake for water tank insulation is derived from the Energy Efficiency Partnership for Homes (2008). Finally, the residual electricity hot water and space heating demand are calculated.

Fig. 1 shows the modelled outputs and the effect of different assumed rates of uptake in energy efficiency measures on existing buildings in the three pathways. By 2050, energy demand for space and hot water is shown to have been reduced by 36%, 39% and 42% for Market Rules (MR), Central Coordination (CC) and Thousand Flowers (TF), respectively.

2.3. New buildings

Electric space heating and domestic hot water demand without efficiency improvements are calculated from projections for numbers of new homes and the typical water and space heating demand for current new build properties (Office for National Statistics (2005); Kannan al. (2007)). New home numbers rise from 2.3 million in 2010 to 11.3 million in 2050.

Following this, due to assumed reductions in the heating requirements for new build properties as a result of the progressive tightening of building codes in line with the zero carbon policy for new homes, as well as assumed retrofit improvements to older new build properties later in the time period, the average space and water heating demand for new homes is reduced by 5%, 10% and 15% every five years from 2015, for the Market Rules, Central Coordination and the Thousand Flowers pathways, respectively. In the short term, these reductions are lower than those needed for a zero carbon policy, but we model deepening reductions over the long term. The differences in demand reduction in the pathways reflect assumed variation in levels of success in overcoming barriers to achieving the zero carbon policy in practice (Monahan and Powell, 2011; Department for Communities and Local Government (2011). The final electricity demand for new build is then calculated as the product of the resultant average space and water heating demand and the projected number of new homes for each year. Fig. 2 shows the improvement in thermal efficiency in new build across the three pathways. By 2050, demand for space and water heating has reduced by 34%, 57% and 72% for Market Rules, Central Coordination and Thousand Flowers, respectively. Within Central Coordination and Thousand Flowers, the absolute energy use of the total stock of newly built properties has reduced. This reflects a decrease in average energy use to meet space and hot water demands per household from some 7.8 MW h/yr in 2010 to 2.2 MW h/yr by 2050.

2.4. Domestic space and hot water heating: Fuel and technology shares

Fuel and technology shares for domestic space and hot water heating for existing and new build homes are derived from the

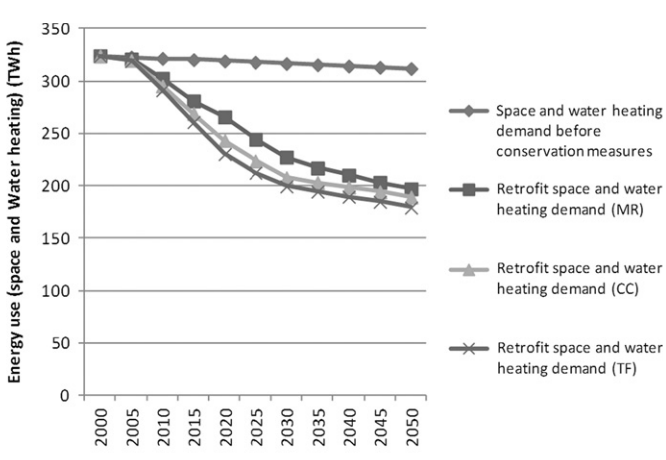

Fig. 1. Effects of energy efficiency measures on heating demand (retrofit buildings).

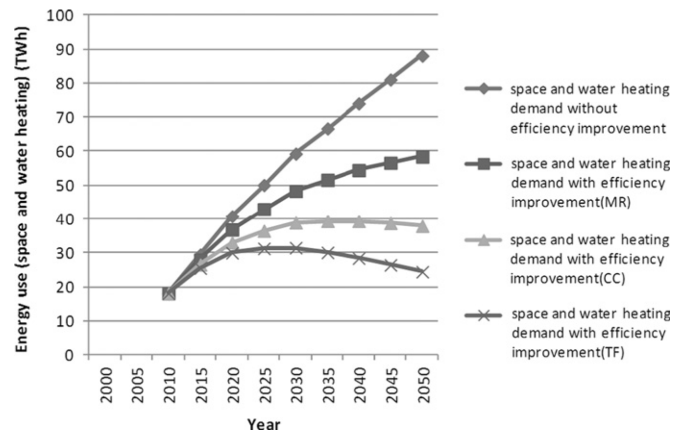

Fig.2. Effects of thermal efficiency improvements (new build).

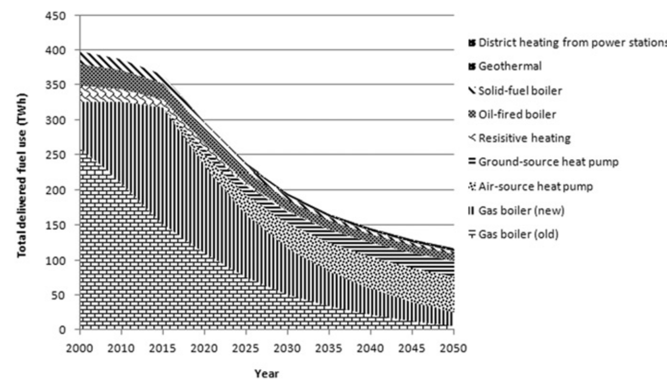

Fig. 3. Market rules: Technology share for heating demand. (*Note*: delivered fuel calculated at point of local use, so district heating from power stations characterised here by the delivered heat, while other CHP characterised by fuel input).

DECC: Energy Consumption in the UK, Domestic Data Tables (2010), for the base year 2000. For subsequent years 2010 to 2050, and for all the transitions pathways, the shares are derived from projected technology installation and retirement figures from the baseline DECC Alpha pathway. However, based on the transitions pathway narratives, the dominant non-electric technology for the Market Rules and Central coordination pathways is district heating, whilst Thousand Flowers features gas in form of community biogas CHP (DECC, 2010).

These technology shares are then used to derive the space and hot water demand met by each given technology for existing and new build houses. Finally, total delivered fuel use by technology for space and water heating is calculated using the percentage input energy efficiencies for each technology derived from the DECC calculator spreadsheet (DECC, 2010). Figs. 3 and 4 show the technology shares for meeting electric space and water heating demand for new and existing buildings in the Market Rules and Thousand Flowers only (Central Coordination is very similar to Market Rules).

Fig. 3 indicates that for Market Rules, the dominant technologies for heating in 2050 are air and ground source heat pumps, which are then assumed to account for 77% and 73% of total delivered fuel use for existing and new build homes, respectively. Although the installation of new gas boilers steadily declines from 2020, it still accounts for 4% and 18% of total delivered fuel use for existing and new build homes, respectively, by 2050. The projections for Central Coordination are very similar to those for Market Rules.

The Thousand Flowers pathway, Fig. 4, shows a significant increase in total delivered fuel use compared to the other pathways. This is due to the strikingly different technology mix, in which building-scale and community-scale CHP options are now dominant, with only a 6% penetration of heat pumps by 2050. Heat pumps use a small amount of high quality energy (in the form of electricity) to deliver low quality heat from the ground into a building, thus Market Rules and Central Coordination feature relatively low levels of purchased energy. In contrast, Thousand Flowers features a wider range of technologies, higher levels of purchased energy and lower use of electricity for heating.

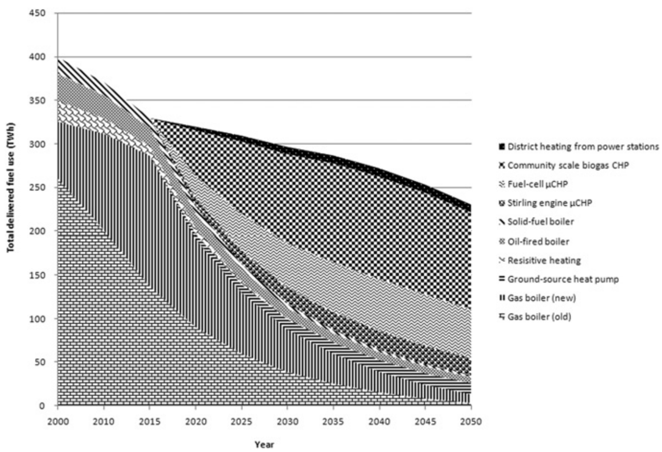

Fig. 4. Thousand Flowers: Technology share for heating demand. (*Note*: delivered fuel calculated at point of local use, so district heating from power stations characterised here by the delivered heat, while other CHP characterised by fuel input).

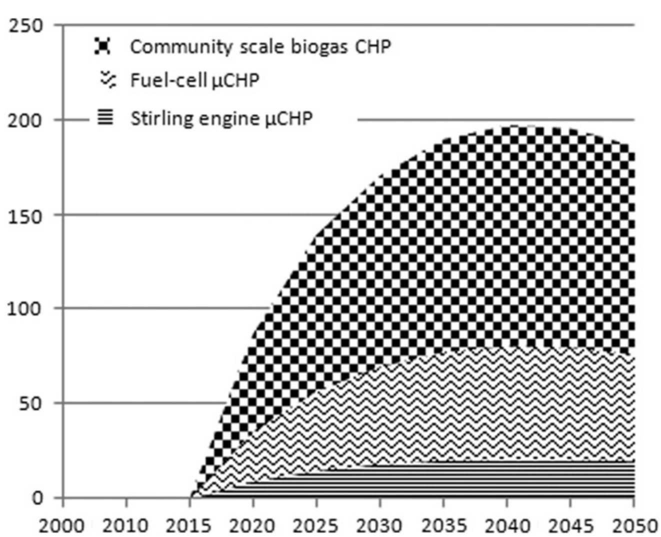

Fig. 5. Thousand Flowers: Electricity supplied by CHP.

By 2050, community scale biogas CHP takes the largest share in Thousand Flowers and accounts for 48% of total delivered fuel use, with fuel cell CHP accounting for 25%. These projections for CHP installations especially for biogas production either from the anaerobic digestion of farm waste or from algae production represent a considerable effort in community based renewable energy production in line with the Thousand flowers narrative. This implies that the current barriers to biogas production such as planning and regulations issues, low incentives from the FITS and the RHI, problems associated with CHP connections to the national gas grid, high capital cost and limited access to capital amongst others have been overcome so that the projected biogas potential of about 100 TW h by 2050 (DECC, 2010) is realised in this pathway. Further, by 2050 some 2.3 million households are projected to be heated through connection to a large scale district heating network fed through heat recovery that has been added to remote large scale power stations.

Fig. 5 illustrates the local electricity production estimated for Thousand Flowers, from the variety of local CHP installations. By 2035 the annual CHP electricity output exceeds the total annual average electricity use by the residential sector, and thus the sector becomes a net exporter to other local commercial consumers. The electricity associated with heat injected into district heat networks from large power stations is not accounted for here, as it is assumed that these are primarily power-generating stations and the heat recovery is incidental.

2.5. Electricity demand from domestic appliances

Domestic appliances cover equipment for lighting, cooking, cooling (fridge-freezers, refrigerator and freezers), wet appliances (washing machines, dryers and dishwashers), and brown appliances (TV, video/ DVD players, set top boxes, ICT, telephone chargers, etc). The electricity use of the existing stock of appliances in existing houses is derived for the base year 2010 from Energy Consumption in the UK (ECUK) (2008). This indicates what existing appliances would hypothetically consume each year before reductions resulting from energy efficiency and demand side participation. Additional use from new households is estimated based on socio-demographic figures (Office for National Statistics, 2005; Boardman (2007) and Shaw, 2004) as well as additional use due to assumed growth in appliance uptake based on UKERC MARKAL modelling (Kannan al. (2007)). These figures are further adjusted to take into account reductions in use due to improved appliance efficiency. Percentage reductions in use due to improvement in appliance efficiency and consumer behaviour varies between the pathways; the lowest percentage reduction is assumed for Market Rules, followed by Central Coordination and Thousand Flowers, which sees the highest percentage in use reduction. Fig. 6 shows the trend in electricity demand by domestic appliances for the three pathways.

From Fig. 6, Market Rules shows a slight increase in domestic appliance electricity use compared to the other pathways. This is

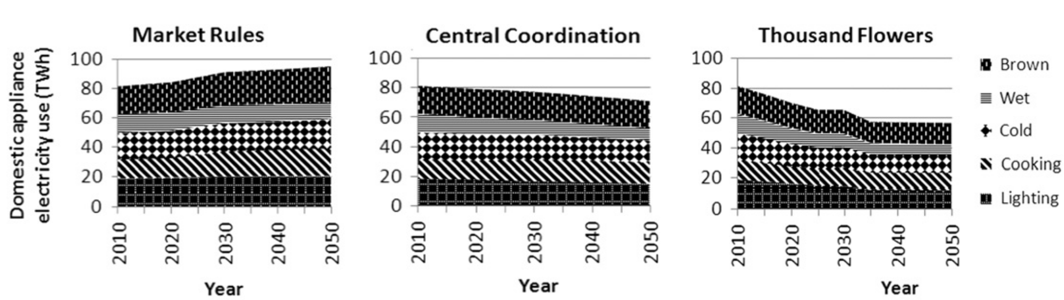

Fig. 6. Trend in domestic appliance electricity use.

due to an assumption of no changes in consumer behaviour which accounts for 10% and 30% reduction in electricity demand from appliances in Central Coordination and Thousand Flowers, respectively. Using lighting appliances as an example, Fig. 7 illustrates the impact of improved appliance efficiency and changed consumer practices or behaviour on the increasing use of electricity for lighting from new households (socio demographic growth) and assumed growth in new appliance uptake for the three pathways.

2.6. Electricity demand by transport

In the transport sector, electricity demand is derived from the DECC pathways (DECC, 2010). For Market Rules, travel activity in terms of overall mobility and mode shares is consistent with past trends. Internal combustion engines (ICE) for buses are assumed to be totally phased out by 2040, and an increasing share of ICE-hybrids is expected, growing to 55% by 2025 and 100% by 2040 due to economies of scale, and with no pure electric buses. Electric rail for passengers increases from 64% to 73% by 2050 with most freight still carried by diesel trains.

For Central Coordination, internal combustion engines for buses are phased out earlier by 2030, whilst ICE-hybrids grow to 73% by 2025 and then 78% by 2050. In addition, pure electric buses and fuel cell buses each account for 11% of passenger travel by 2050. Reflecting assumptions about the availability of alternatives to travel (teleconferencing, localisation of work and recreation), there is a 5% reduction in total distance travelled in 2050. For market rules and central coordination, public transport, walking and cycling accounts for 17.6% and 24.3%, respectively, whilst travel by car as a driver or passenger accounts for 80% and 74%, respectively.

For road vehicles, in Market Rules by 2050 the majority (54%) of car and van distance travelled uses plug-in hybrid electric vehicles (PHEVs) with ICE vehicles still significant (35%), and a modest proportion of pure EVs (10%) and fuel cell vehicles (1%). In central coordination, car and van distances travelled by pure EVs and fuel cell vehicles increase to 28% and 20%, respectively, with a less significant proportion travelled by ICE vehicle at 20% by 2050. This assumes a supportive policy framework along with relevant supporting infrastructure and a reduction in battery cost, and recycling as would be required for environmental acceptability.

In Thousand Flowers, passenger cars are entirely EVs or powered by a breakthrough in fuel cell technology, based on DECC trajectory 4 for transport technology (DECC, 2010). This assumes significant reductions in battery costs or hydrogen technology costs and the availability of appropriate support infrastructure. ICE light duty vehicles are completely removed from the market. By 2050, around 80% of passenger car distance is powered by grid electricity, with the remainder accounted for by fuel cells (which could be acting as the range extender in PHEVs rather than an ICE range extender as in other plug-ins). Moreover, a radical mode shift also occurs such that public transport and cycling account for 36% of all distance travelled by 2050, and travel by car as a driver or passenger accounts for only 62%. The bulk of the surface passenger transport system is electrified apart from buses, which are shared roughly equally across electric vehicles (EVs) and conventional/EV hybrids, potentially using alternative fuels where possible. The last ICE buses are replaced by 2030. The whole rail network is powered by electric traction by 2050.

The three different pathways are characterised by level of behaviour and electrification as described above. For calculation purposes these have been converted into a percentage take up, as summarised in Tables 1, 2 and 3.

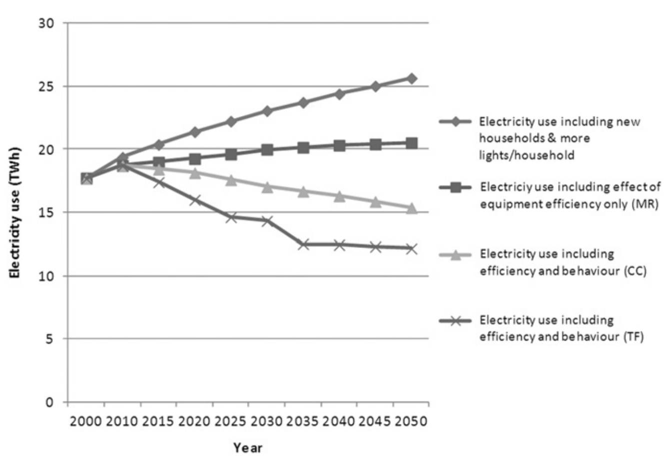

Fig. 7. Factors affecting electricity use of appliances (lighting).

2.7. Electricity demand by services and industry

Electricity demands for agricultural and industrial process, and other commercial uses are derived from the MARKAL scenarios (Kannan et al., 2007) and the DECC pathways (DECC, 2010).

In Market Rules and Central coordination, it is assumed that space heating demand per building in the non-domestic sector drops by 20% by 2050, due to some improvement in average new build demand, some uptake of insulation measures in the existing stock, and behaviour change as outlined above. Commercial space heating, cooling and hot water demand are met by a mixture of fuels, including gas, electricity and heat supplied from a district heating network. For Industrial electricity demand, it is assumed that historical trends in economic output continue. Moderate improvements in energy use per unit of economic output and process emissions are assumed, and energy use remains almost constant (falling just 3% by 2050) while economic output increases in most sectors (DECC, 2010).

Central coordination assumes a smaller, highly efficient industrial sector and that lower levels of output would be accompanied by lower energy intensity as the least efficient plants shut first.

Table 1
Projection number of EVs and PHEVs for Market Rules (in millions) with fuel and electricity used.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Petrol/diesel ICE cars	34.1	34.5	35.8	32.5	28.4	25.5	22.2	18.8	15.2
Electric cars (PHEV)	0.0	0.2	0.4	5.0	10.0	13.0	15.9	19.6	23.5
Electric cars (EV)	0.0	0.2	0.7	1.2	1.6	2.7	3.8	4.1	4.3
Hydrogen FCV cars	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.4
Total number Of cars	34.1	35.0	36.9	38.7	40.0	41.2	41.9	42.7	43.4
Liquid fuels used by cars (TW h)	350	315	288	225	164	139	114	92	71
Electricity used by cars (TW h)	0.0	1.2	2.3	10	18	23	28	32	38
Hydrogen used by cars (TW h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.9

Table 2
Projection number of EVs and PHEVs for Central Coordination (in millions) with fuel and electricity used.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Petrol/diesel ICE cars	34.1	34.0	34.7	26.0	16.5	15.6	14.5	11.1	7.7
Electric cars (PHEV)	0.0	0.2	0.4	8.4	16.7	14.6	12.2	12.3	12.3
Electric cars (EV)	0.0	0.2	0.7	1.8	3.0	5.3	7.7	9.2	10.8
Hydrogen FCV cars	0.0	0.0	0.0	0.6	1.3	2.6	3.8	5.8	7.7
Total number of cars	34.1	34.4	35.7	36.9	37.6	38.1	38.3	38.4	38.5
Total liquid fuels used by cars (TW h)	347	309	278	191	114	100	85	63	43
Total electricity used by cars (TW h)	0.0	1.1	2.2	17	30	29	29	31	33
Hydrogen used by cars (TW h)	0.0	0.0	0.0	2.0	3.6	6.2	8.3	12	15

Table 3
Projection number of EVs and PHEVs for Thousand Flowers (in millions) with fuel and electricity used.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Petrol/diesel ICE cars	34.1	33.2	33.0	22.4	11.5	8.7	5.9	2.9	0
Electric cars (PHEV)	0.0	0.2	0.3	7.8	15.0	12.7	10.4	5.1	0
Electric cars (EV)	0.0	0.2	0.7	3.3	6.1	9.7	13.0	19.0	24.7
Hydrogen FCV cars	0.0	0.0	0.0	0.6	1.2	2.2	3.3	4.8	6.2
Total number of cars	34.1	33.7	34.0	34.1	33.8	33.3	32.5	31.7	30. 9
Liquid fuels used by cars (TW h)	343	300	261	164	82	59	38	17	0.0
Electricity used by cars (TW h)	0.0	1.4	2.1	19	33	34	35	36	37
Hydrogen used by cars (TW h)	0.0	0.0	0.0	1.8	3.2	5.3	7.0	9.6	12

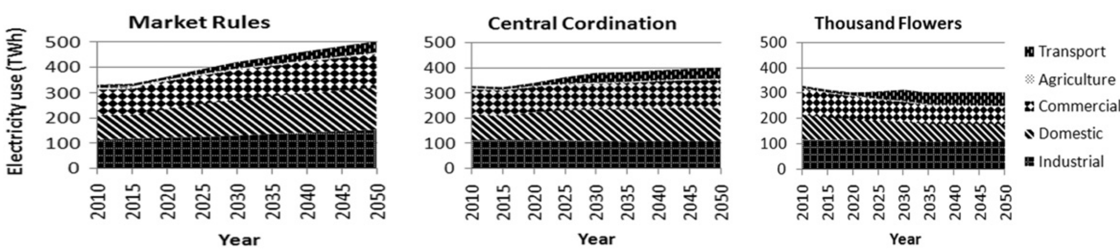

Fig. 8. Trend in electricity use per sector.

Heavy emitting industries decline and overall output falls to two-thirds of 2007 levels. Energy intensity and process emissions decline dramatically, driven by high energy and carbon prices. Industrial energy demand is 2.5 times lower by 2050, leading to large emissions reductions. However, there is a higher level of imported goods, which will increase attributed emissions if imported embodied energy is taken into account. (DECC, 2010).

In Thousand Flowers, refurbishment of the existing non-domestic building stock involves complete replacement of the building fabric and building services, achieving a 40% reduction in per building service demand for space heating. New build achieves 90% reductions in space heating. In this pathway there is moderate electrification of heating, but biogas is the dominant non-electric fuel. It is assumed that total UK demand for non-domestic lighting and appliances is reduced by about 30% by 2050, by extremely ambitious efficiency measures; for example demand for energy for lighting could be reduced by 50% through widespread use of LEDs (DECC, 2010).

For industry, Thousand Flowers assumes a smaller, highly efficient industrial sector and that lower levels of output would be accompanied by lower energy intensity as the least efficient plants shut first. Heavy emitting industries decline (being replaced by imports) and overall output falls to two-thirds of 2007 levels. Energy intensity and process emissions decline dramatically, driven by high energy and carbon prices. Industrial energy demand is 2.5 times lower by 2050, leading to large emissions reductions.

2.8. Overall electricity demand

Fig. 8 shows the overall trend in final electricity use for each sector for the three pathways, and hence the projections for total national electricity use, drawing together all of the preceding analysis. There are some clear trends: enhanced efforts for energy efficiency contribute to lower trends in Central Coordination and Thousand Flowers for overall electricity use. However embedded within this there is also greater use of non-electricity sources for heating, notably CHP, within Thousand Flowers. The electrification of transport is evident in all pathways, with the absolute growth in transport electricity use greatest in Thousand Flowers.

These annual average demands provide the starting point for analysis of the electricity supply requirements for the pathways (Barnacle et al., this issue). They also form the starting point for elaboration of the temporal load profiles and exploration of demand-supply balancing issues, as discussed in the next section of this paper.

3. Hourly supply and demand balancing

Having quantified annual energy demands for the three pathways, our investigation now moves on to consider the hourly profiles of these demands. Coupled with anticipated changes in generation mix, principally a large increase in the proportion of

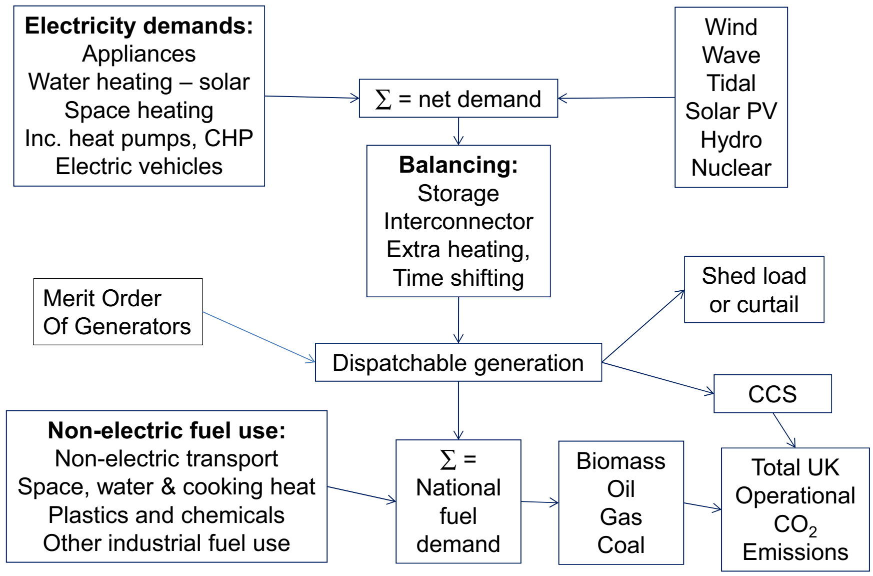

Fig. 9. Overall structure of FESA and data flows.

wind generation as discussed in (Barnacle et al., this issue), the implications for generation capacity requirements are considered.

3.1. The FESA model

This investigation has used and developed FESA (Future Energy Scenario Assessment) which is an hourly time-step model of the UK power system treated as a single node at which supply and demand are balanced, (Barton and Gammon, 2010). Electricity demand data from 2001 was provided by the National Grid and downloaded in 2005 (National Grid August 2011), with half-hourly data converted into hourly data. Being actual data, this includes all weather and calendar-related effects for the year 2001. Added to this, as necessary, were the space and water heating profiles for each day, and their effect on heat pump electricity use and resistive heating taking into account ambient temperature variations for each day. Before compensating for ambient temperature effects, today's temperature effects had to be subtracted. This mainly consists of the effects of off-peak heating as described in Figs. 12, 13 and 18. Temperature data for the year 2001 came from the Rutherford Appleton Laboratory in Oxfordshire, adjusted to the central England mean temperature to make the data more representative. The intention was to capture temperature impact on the bulk of UK housing, commerce and industry, which is mostly located in central and south-eastern England. The net electricity demand, excluding the estimate of today's electric heating, was scaled to give the same quantified annual totals previously estimated from the narratives for each pathway.

Electricity supply from variable and uncontrolled sources (renewables, CHP) and also from the inflexible portion of nuclear is subtracted from demand to calculate a net demand in each hour of the year as shown in Fig. 9. FESA uses real, concurrent weather data from many weather stations around the UK to calculate the renewable potential. Data includes wind speeds, wave heights, solar irradiance and temperature data to calculate electricity generated by CHP.

Wind speed data from the BADC database, (National Environmental Research Council (NERC), 2004) was used to predict both onshore and offshore wind power, 37 stations being used for onshore wind, and 36 coastal stations being used as proxy for offshore sites, all available coastal stations being used. The wind power in each region (corrected for turbine hub height and offshore wind profile) was weighted by region according to the resource in each region. This resource was determined by average wind speeds but also limited by water depth, distance from shore and areas of sea required for shipping, fishing and MOD activities. The modelling of wind power was carried out in a similar way to Graham Sinden's analysis (Sinden, 2007) except that is Sinden used data from 34 years. Nevertheless, year-to-year variations in wind speed are much smaller than hour-to-hour variations within a single year, and a comparison between the two works provides a good validation of FESA, see Appendix A.4. Wave heights at 6 locations off the west coast of Great Britain were used to predict wave power output in each hour of the year. Solar irradiance data measured at 32 sites was used to predict output of both photovoltaics and solar water heating systems.

Demand Side Participation (DSP) is an integral part of FESA, modelling the 'smart grid' and 'smart loads' that are an integral part of UK government policy, (Ofgem, 2010). FESA uses time shifting and energy storage to reduce variations in demand as described in Section 4. However, default profiles of electricity demand are used as the starting point, to be modified by the DSP implementation.

Default diurnal profiles of both heat demand and domestic electricity use are also assumed, based on measured energy use in homes, with and without time-of-day electricity pricing such as Economy-7 (Elexon Ltd, 1997), as described below.

The heat demand profile was based on heat flow measurements in a district heating scheme serving a social housing complex, (Woods and Dickson, 2004). The data was initially recorded as diurnal profiles for each month of a year. For FESA it was assumed that in high summer (July and August), heat was only required for water heating, whereas for the rest of the year, some space heating was also required. The profile of space heating was calculated by subtracting the July profile from the January profile, Fig. 10.

The profiles of Economy-7 heat demand were calculated from the difference between Economy-7 homes and flat-rate tariff homes. First, the profiles for unrestricted (flat tariff) electricity loads, Fig. 11, were subtracted from the Economy-7 load profiles, Fig. 12, to give the average summer and winter Economy-7 effect, which was assumed to be all for heating. Then, as with the district heating data, the summer non-appliance home energy profile was

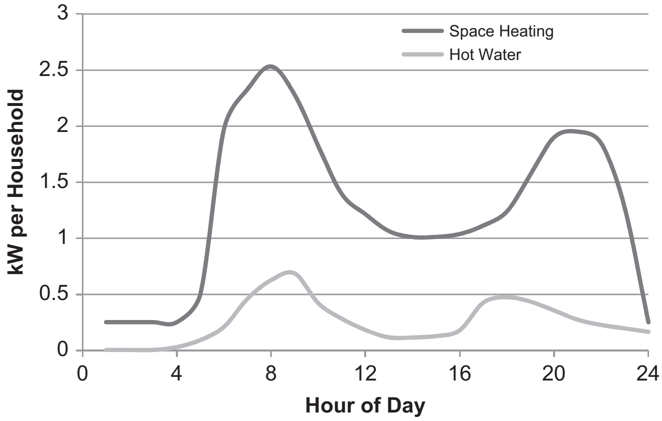

Fig. 10. FESA profiles of domestic heat demand, unrestricted (Woods and Dickson, 2004).

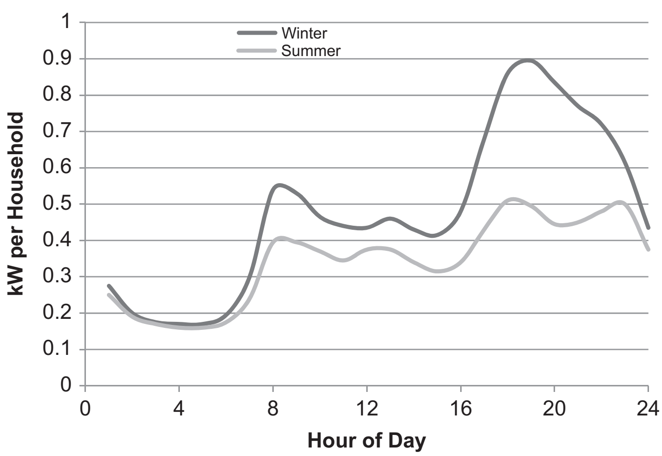

Fig. 11. Profiles of domestic electricity load on flat tariff (Elexon Ltd, 1997).

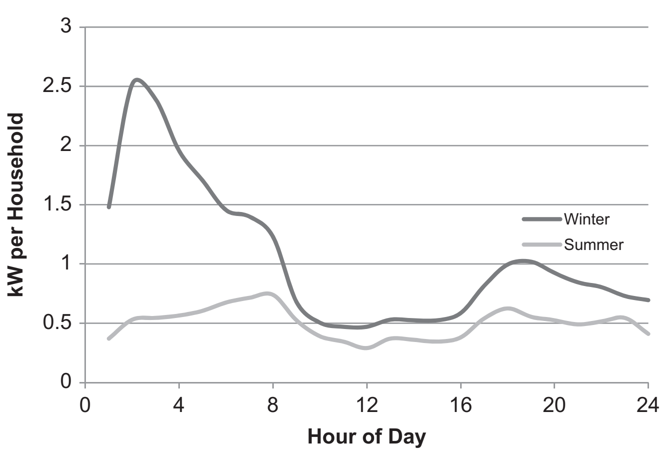

Fig. 12. Profiles of domestic electricity load on Economy-7 tariff (Elexon Ltd, 1997).

assumed to be solely for water heating, whereas the winter profile represents both space heating and water heating. The summer Economy-7 profile was subtracted from the winter Economy-7 profile to obtain an Economy-7 profile for space heating only, Fig. 13. As expected, almost all the extra electricity is used during the night time and morning hours (midnight to 8 am), although a little extra electricity gets used during the daytime too, perhaps as people occasionally run out of hot water, Fig. 13.

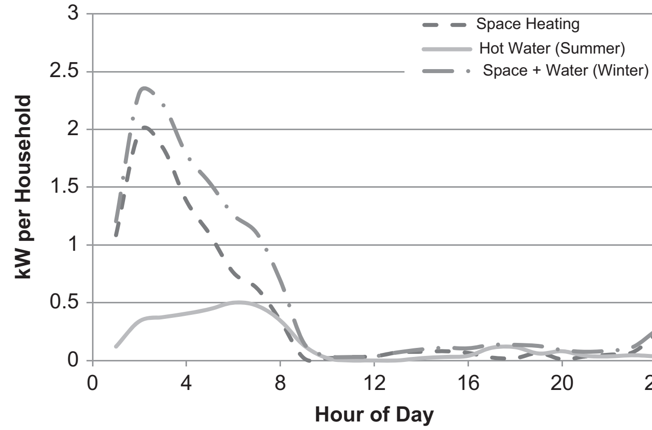

Fig. 13. FESA calculated profiles of electricity used for domestic heating with economy-7 price tariff.

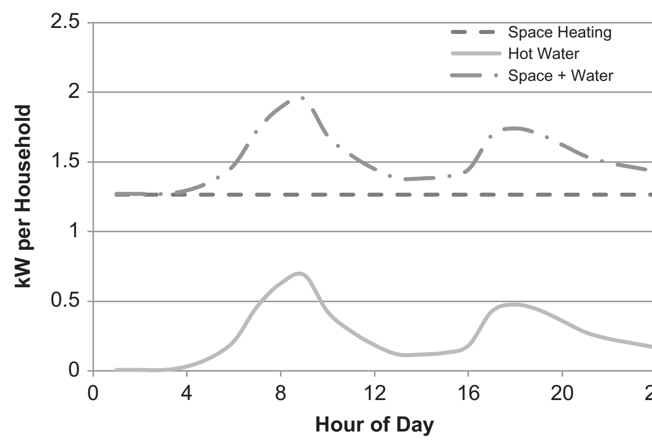

Fig. 14. FESA default profiles of heat pump electricity demand (and CHP electricity generation).

3.2. Heat pumps

The default electricity demand profile of heat pumps is simply a flat profile for space heating, plus a peaky on-demand profile for water heating, Fig. 14. Whereas water heating might be done shortly before the hot water is required, it was assumed that space heating would be done continuously, maintaining a near-constant internal air temperature in dwellings. The reasons for selecting these particular default load profiles are outlined in Appendix A.6.

3.3. Resistive heating

Resistive heating is modelled using typical Economy-7 profiles, Fig. 13 up until 2020. With the advent of DSP, the default profile changes to a flat heating profile for space heating and an unrestricted profile for hot water, as shown in Fig. 14. This is the same philosophy as used for heat pumps, Section 3.2. When smart metering becomes available, time-shifting is done differently each day, based on both general electricity demand and availability of renewable and low-carbon electricity. Time shifting of water heating is done by making use of the inherent storage in hot water cylinders in those households that have them, assumed to be 50% of total household numbers.

3.4. CHP

The default CHP profiles are the same as for heat pumps: CHP space heating is modelled as a flat diurnal pattern, scaled by the average temperature difference between the no-heat temperature and the external ambient temperature for each day. CHP water heating is run in response to hot water demand as a default position. See Appendix A.6 for the explanation.

Thus, because CHP has the same default profile as heat pumps, if the annual total electricity generated by CHP were equal to the annual total electricity used by heat pumps, the two should cancel each other out, both annually and in each hourly time step, but this option has not yet been explored in any of the three Pathways. Market Rules and Central Coordination have more heat pumps than CHP and Thousand Flowers have a great deal of CHP but no heat pumps.

When smart metering is available, both heat pumps and CHP are given changed profiles in order to minimise the peaks and troughs in net electricity demand to be covered by dispatchable generation. The default profiles described above are therefore of limited impact when smart metering and smart DSP is used.

3.5. Modelling of non-electric sectors and total operational carbon dioxide emissions

Since FESA includes all sectors of the energy economy, including transport, space and water heating, commerce, industry and agriculture it can calculate aggregate energy use and also the associated total operational carbon dioxide emissions. FESA also makes an attempt to predict UK production of coal, oil and gas into the future, and is able to estimate net imports of these fuels.

3.6. Electric vehicle (EV) modelling

Two alternative electric vehicle charging profiles have been calculated, and added to today's demand profile for other electricity uses in the home, as shown in Fig.15.

In the first profile, 'Charge On Arrival Home', a probabilistic model has been developed based on Monte Carlo simulation (MCS) and used to investigate the impacts of EVs and PHEVs battery charging demand on energy demand in the UK (Huang and Infield, 2009). The EV battery charging model at this stage simulates individual domestic cars charging in an uncontrolled manner; vehicles are charged immediately on return home until fully charged and charging is assumed to be only available at the home. The model calculates the expected charging demand as a function of time of day, and indicates the impact on domestic demand profiles. As seen in Fig.15, this results in a large increase in peak demand in the early evening.

In the FESA model, anticipating that price signals or prohibition will reduce peak charging, a second, flatter charging profile

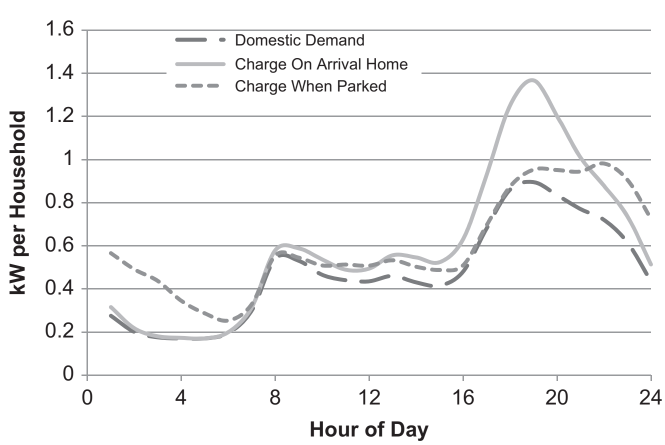

Fig. 15. Profiles of non-transport electricity demand with two possible EV charging profiles added, for Market Rules pathway in year 2050.

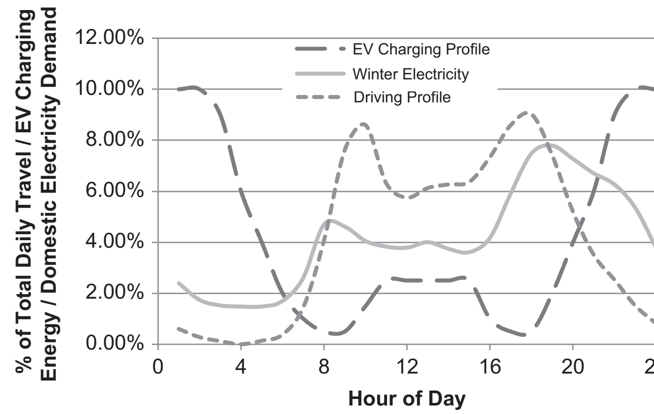

Fig. 16. FESA modelled EV Charging profile compared to driving profile (Acha et al., 2011) and winter day electricity profile (Elexon Ltd, 1997).

'Charged When Parked' is used for EVs and PHEVs. This profile is based on the weekday usage profile of cars and vans. The electricity used to charge vehicles is spread out over the entire period that the vehicles are typically stationary on a weekday, being an approximate mirror image of the driving profile, Fig. 16. This assumes that vehicles will not all be charged up soon after they arrive at their destination, but that charging will be spread out throughout the evening and night, with smaller amounts during the daytime. In this model, even in the default profile, some effort has been made to avoid charging electric vehicles at times of peak electricity demand, Fig. 16.

Nevertheless, there is an additional load due to EV and PHEV charging, especially in the late evening, which coincides with a higher-than-average general domestic electricity load, although not nearly as much as when vehicle charging is allowed to take place as soon as cars arrive home, Fig.15.

3.7. Summary of default and modified demand profiles

Even before accounting for the use of DSP and smart loads, the above demand profiles make some attempt to minimise diurnal variations in net demand. The philosophy was that if the 'smart grid' fails to materialise, and smart meters merely mean improved information for the consumer and accurate billing, time-of-use (TOU) tariffs or prohibition will still be used to create electricity demand profiles that are as smooth as possible. However, being based only on time of day, these profiles can only compensate for diurnal patterns in demand, not weather related variations in renewable energy supply like wind and PV.

If the 'smart grid' does materialise, the default profiles can be more relaxed—after all, the times of natural, unconstrained peak demand might sometimes coincide with peak availability of renewable electricity. DSP can then modify the default profile as needed on each day. Table 4 shows a summary of the default demand profiles.

4. Demand side participation

Demand side participation (DSP), sometimes call demand side management (DSM), will be crucial in balancing power systems with high penetrations of time variable renewables. As the amount of variable renewable energy increases, (wind, wave, tidal and solar power) the associated variations in net electricity demand (after renewable and inflexible generation has been netted off) also increase as described in Barnacle et al. (this issue). The addition of these renewable sources of electricity,

Table 4
Origins of default demand profiles used in FESA.

Component of demand	Pre-2020 and without the smart grid	Post 2020, if the smart grid is achieved
Resistive hot water heating	As today's Economy 7	Hot water on demand, (Woods and Dickson 2004)
Resistive space heating	As today's Economy 7	Flat profile based on 24-h average ambient temperature
CHP water heating	Hot water on demand, (Woods and Dickson 2004)	Hot water on demand, (Woods and Dickson 2004)
CHP space heating	Flat profile based on 24-h average ambient temperature	Flat profile based on 24-h average ambient temperature
Heat pump water heating	Hot water on demand, (Woods and Dickson 2004)	Hot water on demand, (Woods and Dickson 2004)
Heat pump space heating	Flat profile based on 24-h average ambient temperature	Flat profile based on 24-h average ambient temperature
Electric vehicle (EV and PHEV) charging	When parked, inverse of driving profile	When parked, inverse of driving profile

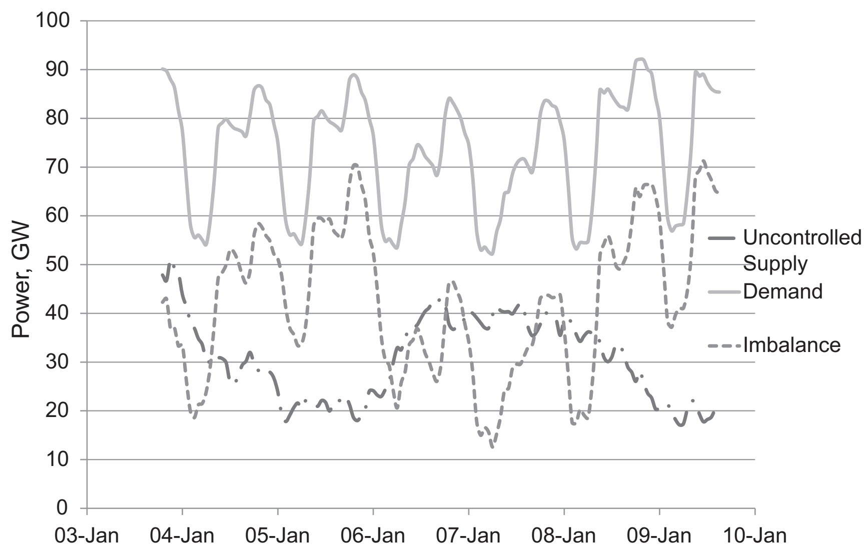

Fig. 17. Uncontrolled supply compared to total electricity demand in early January in Market Rules pathway, year 2050.

together with electric vehicle charging, greater use of combined heat and power (CHP) and heat pumps, cause the range of variation of net electricity demand to approximately double (Barnacle et al., this issue). The main points to note are:

- The challenge of grid balancing is greater than in today's electricity system.
- DSP significantly reduces the size of peaks and troughs of electricity.
- Although the extremes of net demand and net surplus are each reduced by 10 GW or more, the capacity factors of low carbon generation are not significantly improved by DSP.
- DSP reduces the number of hours of electricity surplus in the Thousand Flowers pathway but only from 2973 h per year to 2583 h per year (34% to 29% of the time).

Roberston et al. does not explain the timescales of this extra variation in demand. Whereas energy demand patterns are largely diurnal reflecting human activity patterns and could be attenuated by fixed time-of-use tariffs, the time variable, weather driven, renewable sources require a more sophisticated, responsive approach to demand side participation (DSP). As shown in Fig. 17, uncontrolled sources of generation vary across a wide range of time scales and often in ways that are not strongly correlated with time of day.

In all three pathways, and in the FESA model, smart meters are assumed to be ubiquitous from 2020 onwards in line with present government policy, (Ofgem, 2010; Energy Efficiency News, 2008).

Furthermore, it is hoped that smart meters will pave the way for smart grids (Hendry and Mogg, 2010; Ofgem Smart Metering Team & E-Serve (2010). The proposed functional requirements will support 'a real time remotely configurable tariff structure', Ofgem Smart Metering Team & E-Serve (2010); Ofgem Smart Metering Team (2011).

The meters might presumably be able to communicate with controllable loads and enable demand side participation (DSP), although details are still uncertain. Therefore FESA includes the same DSP options from 2020 onwards for all three pathways. The DSP takes the form of time-shifting of electricity loads from periods of peak demand to off-peak, and from periods of low renewable energy supply to periods of higher renewable energy supply. Results of DSP are compared with the default case where no DSP is allowed.

4.1. Operation of real and virtual energy stores in FESA

The following loads are regarded as being time-shifted within FESA, and thus constitute a virtual energy stores available to complement centrally provided pumped storage in the UK:

- water heating;
- space heating;
- EV and PHEV charging.

In each pathway, each of these components was assigned an estimated energy capacity in GW h and a power capability in GW based on its characteristics and parameters drawn from the DECC calculator models (DECC, 2010) and demand side quantification outlined earlier in this paper.

4.2. Water heating

In all three pathways, the hot water energy capacity is equal to the total hot water use (domestic and commercial) per day, divided by 2 since it is assumed that only half of all hot water is stored in hot water cylinders. The associated virtual electricity storage capacity, C is calculated from this using the proportions of heating technologies in use and their conversion efficiencies:

$$C_{hw} = \frac{Hot\_water}{2} \times \left\{ \%RH + \frac{\%HP}{COP} + \frac{\%CHP \times \eta_e}{\eta_h} \right\} \quad (1)$$

where C_{hw} is the energy capacity of virtual storage, GW h; Hot_water the total daily hot water demand, GW h; RH the Resistive heating; HP the Heat pump; COP the Coefficient of performance; CHP the Combined heat and power; η_e the CHP electrical efficiency; η_h the CHP thermal efficiency

Furthermore, it is assumed that this hot water may be heated up electrically over a period of 7 h as in today's Economy-7 tariff systems. Hence the maximum power is one seventh of the capacity, $C_{hw}/7$ GW.

4.3. Space heating

In all three pathways, the energy storage associated with space heating is equal to the total average space heating in the UK (domestic plus commercial) per hour. It is observed that if heating or cooling is turned off for more than an hour, the room temperature is likely to drift outside of thermally comfortable limits, although this will depend on levels of thermal insulation and exposed building thermal mass and should be subject to further investigation.

Although space cooling (not heating) is needed in summer, and more space heating is required in winter, and more heating or cooling is used in the daytime than at night, the amount of energy is calculated the same at all times of day and all times of the year, regardless of ambient temperature. This simplification adopted by FESA, is partly justified by the use of heat pumps for cooling as well as heating. Again, the associated virtual electricity storage capacity, C is calculated from this using the percentages of heating technologies used and their conversion efficiencies:

$$C_{sh} = \frac{Space\_heat}{24} \times \left\{ \%RH + \frac{\%HP}{COP} + \frac{\%CHP \times \eta_e}{\eta_h} \right\} \quad (2)$$

where C_{sh} is the energy capacity of virtual storage, GW h; $Space$-$heat$ the total daily average space heating demand, GW h

This time the power rating of the virtual store is $C_{sh}/1$ GW, since the heating or cooling can be deferred by up to 1 h.

4.4. Electric vehicle charging

In all three pathways, the storage capacity, C_{ev} of electric vehicles is the entire amount of electricity used per day for EV and PHEV charging. This could have been taken from the DECC calculator model, but was instead estimated from FESA's estimates of miles driven on electric power, penetration of electric vehicles and electricity consumption per mile because the FESA figures were based on the physical characteristics of the vehicles. However, the resulting capacity was close to the DECC total daily electric vehicle charging energy.

As vehicles will be typically charged up over periods of 7 h at home, the deferrable power was $C_{ev}/7$ GW.

4.5. Real and virtual energy stores and their operation

The UK electricity system already includes some energy storage in the form of four pumped hydro facilities, Table 5, and a further facility is under construction (Lannen, 2012)

All the forms of load time-shifting through DSP are modelled by equivalent virtual energy stores. All the capacities were summed and their estimated power ratings were summed, together with the real pumped storage, to give a total energy storage capacity as shown in Table 6 for each pathway in 2050.

Table 5
Existing pumped hydro energy storage facilities in the UK.

Pumped storage site	Energy capacity (GW h)	Power rating (GW)
Dinorwig	11.76	1.68
Ffestiniog	2.52	0.36
Ben Cruachan	9.68	0.44
Foyers	0.90	0.30
Total	24.86	2.78

Table 6
Total energy storage capacities and power ratings for all 3 pathways in 2050.

Pathway	Market Rules		Central Coordination		Thousand Flowers	
	Energy (GW h)	Power (GW)	Energy (GW h)	Power (GW)	Energy (GW h)	Power (GW)
Water heating	62	9	61	9	107	15
Space heating	10	10	10	10	14	14
EV & PHEV charging	74	11	74	11	96	14
Pumped hydro	25	3	25	3	25	3
Total	172	33	169	32	241	45
Limited power, P_{MAX}		22		22		32

The actual power rating of the total storage was limited in the FESA model to prevent the store filling and emptying too quickly. The limited power rating was the total capacity, $C_{TOT} \times \pi/24$. this allows for the store completing a sine wave pattern of filling and/or emptying over a period of 24 h. This modified power rating is also shown in Table 6.

Table 6 shows that the storage capacity and power contributions from water heating and electric vehicle charging are far larger than for today's pumped storage. Space heating and pumped storage make smaller but significant contributions.

It should be noted that traditional electricity storage heaters have a much greater potential for load shifting *per household* than do heat pumps and CHP. Storage heaters use resistive heating and use modern high performance materials that can store a great deal of heat at very high temperature (several 100 °C) in a small volume. In contrast, heat pumps have much reduced COP, and CHP has reduced electrical efficiency if their heat delivery temperatures are much higher than ambient. Heat pumps and CHP therefore deliver only low-grade heat, and low grade heat is harder to store as sensible heat, having lower energy density per volume due to the smaller temperature range of operation (Hasnain, 1998; Fernandes et al., 2012). Hot water can be stored in a cylinder at 60 °C but the daily space heating requirement of a dwelling far exceeds the storage capacity of a hot water cylinder of reasonable size, space heating demand being larger than water heating demand, (Infield et al., 2007; Kalogirou, 2004) Phase-change heat stores are promising, but may or may not the technology improvement required to make them attractive.

Note that the reduction of energy use in space heating, due to improved insulation, and by switching to heat pumps and CHP will reduce the storage volumes required, but will also reduce the ability of the electricity grid to time-shift demand by reducing the power level of demand power or generating capacity that can be turned on and off. Even today, when Economy-7 electricity use is subtracted from the national grid hourly demand numbers, the residual load profiles are more extreme: peak demand is virtually unchanged but minimum demand is much lower, Fig. 18.

In FESA modelling, the store empties and fills according to the rise and fall of net electricity demand after subtracting uncontrolled generation. The program looks at the 24-h average level of net demand, D_{MEAN} 12 h behind to 12 h ahead of present time. The power from or to the store in any hour is dependent on the deviation of demand, D from this mean:

$$\Delta D = D - D_{MEAN} \tag{3}$$

The power from/to the store is modified by the state-of-charge of the store, SOC, in relation to the total energy capacity, C_{TOT} such that the store tends towards its middle position, never full and never empty:

When $\Delta D > 0$, the store is discharging,

$$\text{powerfromstore,}\ P_{STORE} = \text{MIN}\left(\Delta D \times \frac{SOC}{C_{TOT}/2}, P_{\text{MAX}}\right) \tag{4}$$

When $\Delta D < 0$, the store is charging,

$$\text{power to store} - P_{STORE} = \text{MIN}\left(\Delta D \times \frac{(C_{TOT} - SOC)}{C_{TOT}/2}, P_{\text{MAX}}\right) \tag{5}$$

The effect of storage can be seen in Fig. 19, where the peaks and troughs of demand are reduced and the resulting net demand has a smaller range over the time period shown. Over the whole year, this results in a reduction in total generating capacity required to meet peak demands and a reduction in the size of energy surpluses at times of low demand and high renewable energy supply as shown in Table 7 and discussed further by Barnacle et al. (this issue). This reduction in variation is relative to a base case in which electricity demand related to heating and EV charging has already been partially levelled or time shifted based on time-of-day as described in Section 3.

Note that the operation of the DSP and energy storage has not been optimised: net changes in demand from one hour to the next

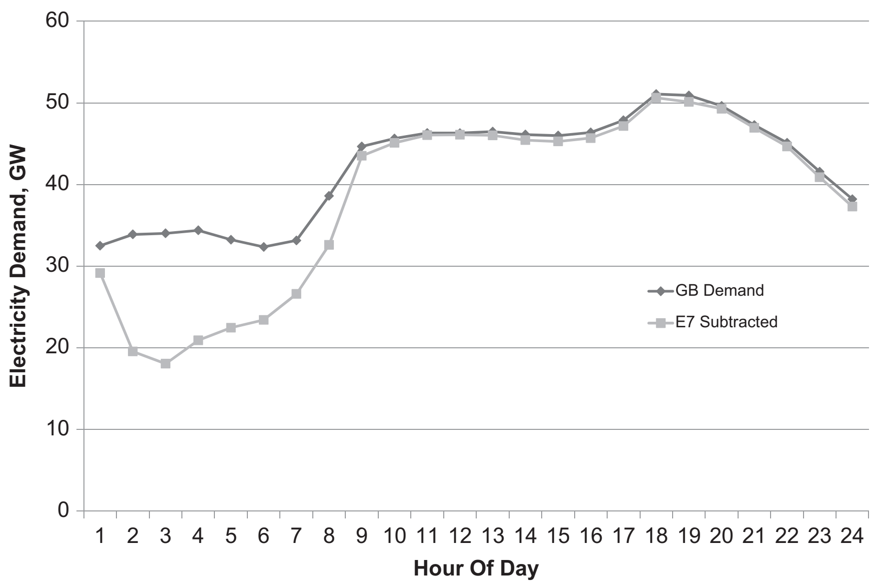

Fig. 18. Great Britain electricity demand (excluding self generation) with estimate of effect of Economy 7 heating, on winter peak day, 17th December 2001.

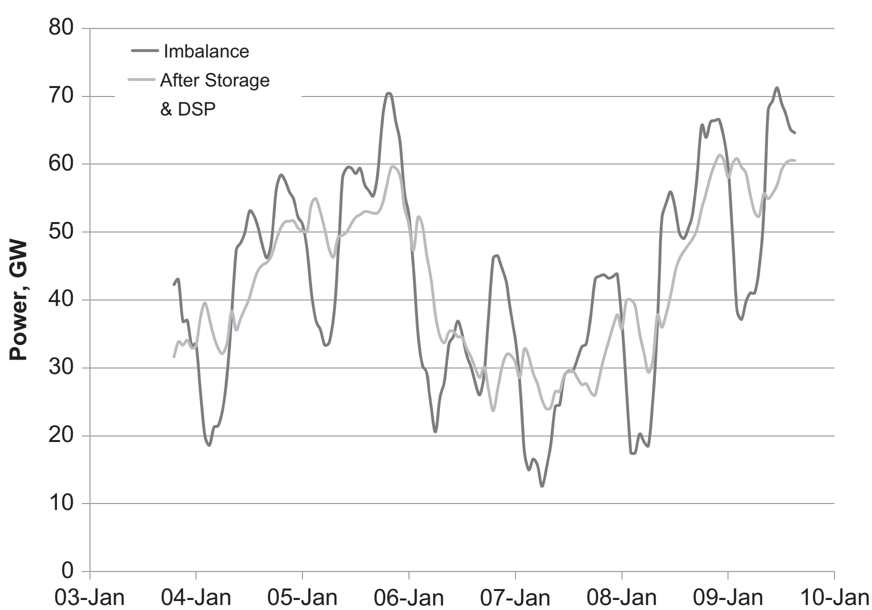

Fig. 19. Effect of storage and DSP smoothing on net demand in the first week of January 2050, Market Rules pathway.

Table 7
Potential benefit of an extra 500 GW h of pumped storage.

	Min. demand (GW)	Max. demand (GW)	Range (GW)	Generation capacity saved, (GW)
Market rules				
Net demand	−19.25	82.53	101.79	
With DSP	−9.31	73.11	82.42	10.5
Extra hydro	−4.19	68.60	72.80	15.5
Central coordination				
Net demand	−15.05	66.02	81.07	
With DSP	−5.48	56.70	62.17	10.4
Extra hydro	−3.70	53.73	57.42	13.7
Thousand Flowers				
Net demand	−44.41	37.56	81.96	
With DSP	−28.36	26.83	55.19	11.9
Extra hydro	−23.67	25.94	49.61	12.9

are still rather large, especially where the store changes from charging to discharging or vice-versa. The DSP and storage is also restricted to smoothing demand over a period of 24 h because most forms of DSP are unlikely to be able to shift demand by more than a few hours, and because many forms of generation and demand (hot water demand, EV charging, other electricity demand, CHP, solar PV, and even tidal power) have natural cycles of about 24 h. Future work should be able to improve the DSP and storage control algorithms to further reduce peaks and troughs of net demand.

4.6. Potential for expansion of pumped hydro storage

Scottish and Southern Energy plc have recently expressed an interest in building new pumped hydro schemes to meet the challenge of wind power variability, (Lannen, 2012). These proposed schemes at Sloy (60 MW), Coire Glas (300 MW to 600 MW) and Balmacaan (also 300 MW to 600 MW) would represent a significant increase in the UK's pumped storage capacity but are still a small fraction of the estimated potential: A study by the Energy Systems Research Unit (ESRU) at Strathclyde University has highlighted the possibility of converting conventional hydro power into pumped hydro, (Day et al., 2009). This conversion is only suitable for hydro sites with a lake at the top and bottom of a hill, but might add as much as 500 GW h to the pumped storage capacity. FESA was used to model this extra storage, with an assumption that the power rating of the additional demand and generation is conservatively $+/-10$ GW. This option, applied to year 2050 only of each pathway further reduced the range of net demand, and reduced the generating capacity required in all three pathways as shown in Table 7. Most of the numbers in Table 7, including the benefit of DSP before extra pumped hydro are also shown in graphical form in Barnacle et al. (this issue). Note that the peaking generation capacity saved can sometimes be even greater than the reduction in peak demand, because generation availability factor has to be taken into account.

It should be noted that this use of this additional pumped hydro has not been optimised. With a more sophisticated control strategy, storing energy over periods greater than 24 h and possibly with a larger pumping/generating capacity, extra pumped hydro might be more effective at further reducing the generating capacity required of fossil fuelled generation plant. It should also be noted that the calculated savings in generating capacity are based on an availability factor of 90% in fossil fuelled generators but 100% availability of pumped hydro.

4.7. Other DSP options

The DSP options explored in FESA to date have only involved time-shifting demand, but not modal shifts in demand from one form of energy to another at times of extremely high or low net demand. Other options for future study could usefully include:

- Vehicle-to-grid technologies (V2G)
- PHEVs using all fuel and no electricity at times of high demand/low supply
- Heat pumps with backup gas-fired boilers
- CHP systems with an alternative of heat pumps or resistive heating
- Hydrogen production via electrolysis of water at times of over-supply

The options explored in Transition Pathways also excluded more profound changes in behaviour in response to electricity availability, such as:

- Thermostat changes
- Washing machine and dishwasher use changes
- Journeys not made when energy is in short supply
- Resource sharing
- Other appliances not used

Therefore, there is scope for much greater DSP and energy storage functionality that might enable more radical changes to UK energy supply and greater deployment of renewable energy sources.

5. Primary energy demands, imports and operational carbon dioxide emissions

The DECC calculator and FESA both model the whole energy economy and all energy use, but using somewhat different approaches and different levels of granularity. The DECC calculator models many more sectors and in much more detail but looks at annual averages only, modelling severe cold-spell wind calms in a simplistic manner. On the other hand, FESA models every hour of one typical year but looks at different sectors of the economy in a very simple way. On the calculation of emissions, DECC looks at all operational greenhouse gases (GHGs) whereas FESA looks at operational carbon dioxide only. The two models use subtly different emissions factors. For domestic energy production the models make different assumptions and also use different depletion rates of coal, oil and gas extraction. The two models will never produce identical results. Nevertheless, it is reasonable to expect a degree of consistency and the DECC calculator and FESA can provide some mutual validation as both can calculate primary energy supplies, imports and operational greenhouse gas emissions for each pathway, as shown in Table 8.

5.1. Operational emissions of greenhouse gases and carbon dioxide

Note that FESA calculates operational carbon dioxide emissions based on total fossil fuels used in the UK in all sectors of the economy. Unlike the UK government official targets, FESA does include aviation and international shipping and is thus more complete than the assessment for the government target. On the other hand, FESA does not include non-CO_2 greenhouse gases, as included in the DECC model, or upstream emissions associated with fossil fuel extraction and fugitive emissions. There are therefore differences between the operational greenhouse gas

Table 8
Primary energy demands, imports and operational emissions.

Units TW h unless otherwise stated	2007		Market rules 2050		Central coordination 2050		Thousand Flowers 2050	
	DECC	FESA	DECC	FESA	DECC	FESA	DECC	FESA
Primary energy demand								
Coal	475.4	446.2	478.4	305.3	440.7	119.2	439.7	52.8
Oil	906.6	849.5	635.9	488.6	491.9	378.3	437.6	326.7
Gas	1,048.9	961.2	132.3	347.3	23.1	255.8	249.4	191.1
Biomass	98.5	26.0	336.7	89.4	336.7	89.4	336.7	351.7
Electric.	181.1	60.0	951.5	329.7	894.5	285.5	135.7	145.4
Total	2710.5	2342.9	2534.8	1560.4	2187.0	1128.2	1637.9	1067.7
Primary energy imports								
Coal	276	298.4	354	295.0	316.3	108.9	315	42.5
Oil	−100	−133.0	503	441.1	359.3	330.8	305	279.1
Gas	169	77.4	31	250.0	−78.4	158.4	148	93.7
Biomass	4	1[a]	70	18.6[a]	70.0	18.6[a]	70	85[a]
Electric.	5	11.5	−189	20.8	−207.0	22.4	−112	14.6
Total	354	255.3	769.4	1025.4	460.1	620.4	726	514.9
Reduction in operational GHGs or CO_2 emissions over 1990 levels	5%	14%	67%	72%	78%	81%	74%	83%

[a] FESA does not include an estimate of biomass grown, Therefore, biomass imported is calculated here on the amount of biomass used multiplied by the percentage imported as in the DECC model.

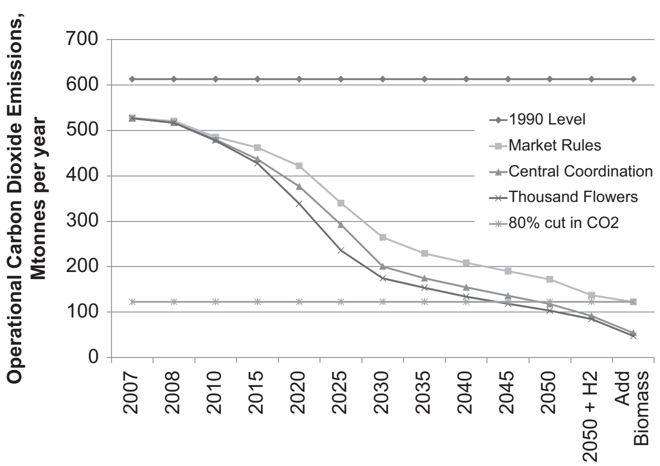

Fig. 20. Total UK operational CO_2 emissions trajectories in each pathway calculated by FESA.

emissions calculated by the DECC model and the operational carbon dioxide emissions calculated by FESA.

Table 8 shows that with both calculations, the Market Rules pathway fails to meet the 80% cut in operational CO_2 emissions (FESA) or operational greenhouse gas emissions (DECC). In the DECC calculator, the other pathways also fail to meet the target, despite the energy efficiency measures, modal shifts and shift to low carbon sources of energy. This may be because of the different assumptions made and the discretised levels of 'effort' from 1 to 4 in the DECC calculator, but also because other greenhouse gases such as methane, nitrous oxide and emissions due to land use are more difficult to mitigate. FESA trajectories of operational CO_2 emissions for all 3 pathways are shown in Fig. 20. The baseline data for year 1990 is not readily available in the form that FESA calculates it. The FESA baseline of 612.94 Mt of CO_2 is the sum of UK domestic operational carbon emissions of 161.5 Mt of carbon published in Annex B of the 2007 Energy White Paper (Darling, 2007), multiplied by the ratio of molecular weights (44/12) and aviation and shipping from Fig. 3.1 of the first report by the Committee on Climate Change (2008).

This failure of the Market Rules pathway to achieve an 80% cut in operational CO_2 emissions, and doubts over the other pathways achieving 80% cuts in GHGs, raise the question of what else might be done to achieve the required cut in greenhouse gas emissions. FESA has been run for two additional scenarios, also shown in Fig. 20. First, all non-aviation, non-electric transport energy is provided by hydrogen fuel cells by 2050, the hydrogen coming from reformed natural gas with CCS. Second, an extra 300 TW h per year of biomass is used and converted to liquid fuels, primarily for aviation. Each of these two measures reduce UK operational emissions by approximately 4% of 1990 levels, and enable the Market Rules pathway in FESA to reduce operational emissions from 28% to 20% of 1990 levels.

5.2. Imports of fuel

Table 8 also shows the amounts of each fuel imported by the UK in 2050. Despite the differences between FESA and DECC assumptions, a clear picture emerges of increased total imports of energy in all three pathways. The reductions in energy demand, increases in renewable and nuclear powered generation, and increases in biomass cultivation are not enough to compensate for reductions in extraction of coal, oil and gas. By 2050, according to the Transition Pathways analysis, the UK will be importing between 500 TW h and 1000 TW h of energy per year, compared to today's 250 TW h or 350 TW h.

6. Conclusions

Annual energy demands for each of the three pathways out to 2050 have been quantified and aligned with the DECC calculator. This demand data has been balanced on an annual basis against supply including renewable and uncontrolled electricity generation as described by Barnacle et al. (this issue). However, the development of this data into hourly profiles, using FESA, shows that all three pathways present considerable grid balancing challenges.

The results for year 2050, without application of significant demand side participation, show:

- Peak levels of net demand can be very high: up to 83 GW in Market Rules and up to 66 GW in Central Coordination but only 38 GW in Thousand Flowers.
- In all three pathways, a significant amount of generating plant has to operate at very low capacity factors (less than 10%): −32 GW in Market Rules, 26 GW in Central Coordination and 17 GW in Thousand Flowers.

- All three pathways result in significant electricity surpluses, peaking at 19 GW in Market Rules, 15 GW in Central Coordination and 44 GW in Thousand Flowers.
- In Market Rules and Central Coordination, these surpluses last up to 400 h per year, but in Thousand Flowers, surpluses occur for 2973 h per year, or 34% of the time.

Time shifting of demand through demand side management/participation significantly reduces the amount of variation in net demand:

- In all three pathways it reduces the peak of net demand by about 10 GW.
- The amount of generating capacity operating at less than 10% capacity factor is reduced to 27 GW in Market Rules, 20 GW in Central Coordination and 10 GW in Thousand Flowers.
- The maximum surplus power is reduced to 9 GW, 5 GW and 28 GW, respectively.
- The times of surplus in Market Rules and Central coordination are reduced to just over 100 h each, but unfortunately the Thousand Flowers pathway remains in surplus for 2583 h or 29% of the time.

Demand side measures explored in the Transition Pathways project were restricted to time shifting of demand by at most a few hours. There are policy implications associated with hourly load balancing, which cannot be considered as part of the existing Short Term Operating Reserves programme, the only fully operational programme for DSP run by the National Grid. The Short Term Operating Reserves programme is not designed specifically for DSP. It is designed for generators to participate with the operational parameters structured to suit them. For example, some sites are not able to turn off equipment once it is operational, but they may be able to delay the start of large energy-consuming equipment. There currently does not exist any programme in the UK that allows the grid to take advantage of these kinds of resources. This might be partly addressed by the introduction of capacity mechanisms within the Electricity Market Reform. Other measures such as dynamic shifting of demand between electricity, gas and liquid fuels, according to the availability of electricity, could make much greater reductions in variation in net electricity demand.

The Market Rules pathway does not quite achieve an 80% reduction in operational CO_2 emissions by 2050. Other mitigation measures may be necessary such as more hydrogen production with CCS for use in transport, and greater use of biomass energy, Fig. 20, although there are a number of causes for concern about CCS, not least the potential cost. The other pathways are predicted by FESA to achieve an 80% reduction in operational CO_2 emissions but may not quite achieve an 80% reduction in GHGs, including non-CO_2 GHGs, without further measures.

All three pathways result in an increase in the total amount of energy that the UK must import in the coming decades, from about 300 TW h in 2007 to 500 TW h, 600 TW h or even 1000 TW h per year in Thousand Flowers, Central Coordination and Market Rules, respectively.

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Appendix A: Description of future energy scenario assessment (FESA) model

A.1. Physical basis of FESA

In the future, a combination of energy storage technologies, controllable loads and controllable generation will supply grid balancing services to the electricity grid. Many of the technologies incorporate an element of energy storage in which the current state of the system depends on the energy balance over the previous hours and days. Similarly, optimum dispatch decisions such as whether to discharge a store or to turn on a generator depend on forecast supply and demand over the coming hours and days. Therefore a time step model is required using realistic data. The interactions of electricity with the heating and transport sectors require that a model also includes the energy use of other sectors of the economy: industrial, commercial and domestic heating and transport energy use. FESA satisfies the above requirements and more, incorporating the following features:

- Hourly time stepping energy model over one calendar year.
- Weather-related wind power, solar PV, solar thermal, electricity demand and heat demand based on data from a real year: wind speeds, solar irradiance, ambient temperature and electricity demand.
- All data measured in the same year: 2001.
- Realistic tidal power too, varying with daily and lunar cycles.
- Merit order of despatch of generating technologies.
- All sectors of the energy economy: electricity, heating, transport, commercial and industrial.
- Combined heat and power and heat pumps.
- Electric vehicles and plug-in hybrids.
- All forms of renewable energy relevant to the UK: wind, solar, biomass, hydro, wave and tidal.
- Minimum and maximum powers of conventional generation including nuclear power turn-down ratio.
- Pre-combustion and post-combustion CCS.
- Hydrogen production including electrolysis and steam reformation.
- Hydrogen use including vehicles and as an industrial gas.
- International Imports and exports of electricity through interconnectors.
- Data and models specific to the UK.
- Calculation of operational CO_2 emissions.

A.2. Limitations of FESA

- At the moment, FESA lacks capital and operating costs and therefore lacks any way of comparing investment decisions across pathways.
- Transmission and distribution losses are not explicitly included. They are included in general electricity demand.
- FESA is a single point model. Geographical diversity is not modelled and neither are transmission constraints. Renewable energy resources are based on a geographically weighted average of the resource in each region of the UK.

A.3. FESA compared to other models

There are hundreds of energy system models in use around the world. Here FESA is compared with some well-known models that are most similar:

The DECC 2050 Calculator (DECC, 2010) includes all sectors of the economy but lacks the time resolution of a time-step model.

It considers wind calms and periods of high demand but not surpluses of electricity. The most recent version does include cost data to enable one pathway to be compared with another.

EnergyPLAN (2012) is a time-step model similar to FESA in many ways but, lacks minima and maxima of powers for each generation technology, is not specific to the UK and lacks a calculation of operational greenhouse gas emissions.

ESME (ETI, 2012) has many more subdivisions of energy conversion technologies but is unsuitable for energy storage models since it lacks an hourly time-step calculation.

GTMax, 2012 is an hourly time-step program but lacks models of energy uses outside of the electricity sector (industry, transport and heating).

MARKAL and TIMES (ETSAP, 2012) provide whole system models but lack true time step modelling beyond 1 day.

Mesap PlaNet (Seven2one, 2012) is a time step model but lacks models of heating and industry. It also lacks details such as minima and maxima of generating power.

ORCED, 2012 lacks models of industry or heating. It also lacks models of tidal or wave power.

ProdRisk (SINTEF, 2012), SimREN (iSUSI, 2012), SIVAEL (Energinet, 2012) and WASP (IAEA, 2012) are all similarly weak in modelling energy use outside of the electricity sector.

STREAM (Ea Energy Analyses, 2012) and UniSyD (Leaver et al., 2009) both lack good modelling of many different types of storage and are not specific to the UK.

A.4. Validation of FESA

FESA is a deterministic model with no Monte-Carlo type random element. Therefore it will always give the same outputs for a given set of inputs. The overall outputs such as total annual electricity from each type of generation were validated by comparison with the supply side and demand side models described in this paper and others in this special issue and as illustrated in Fig. 21.

The small differences between the FESA model and the supply and demand side models of the Transition Pathways are due to:

(i) Small numerical errors and small remaining differences between the models across the consortia—the convergence between models was achieved by collaborative iteration.
(ii) The electricity generation in FESA was slightly larger than electricity use due to electricity surpluses lost to curtailment, especially in Thousand Flowers pathway.

The weather dependent time series are more difficult to validate but the wind power time series (the largest components of renewable energy) have been validated by comparison with a similar calculation of nation-wide wind power, (Sinden, 2007).

The turbine power curves of FESA and Sinden's work are compared in Fig. 22 and the long-term distributions of UK wind power are shown and compared in Fig. 23.

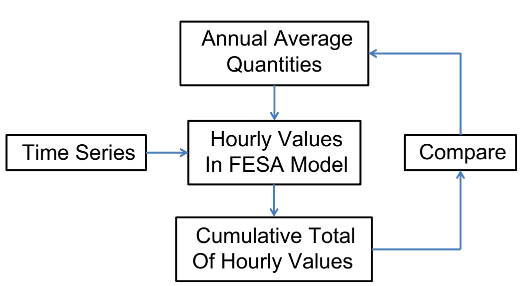

Fig. 21. Overall FESA consistency validation process.

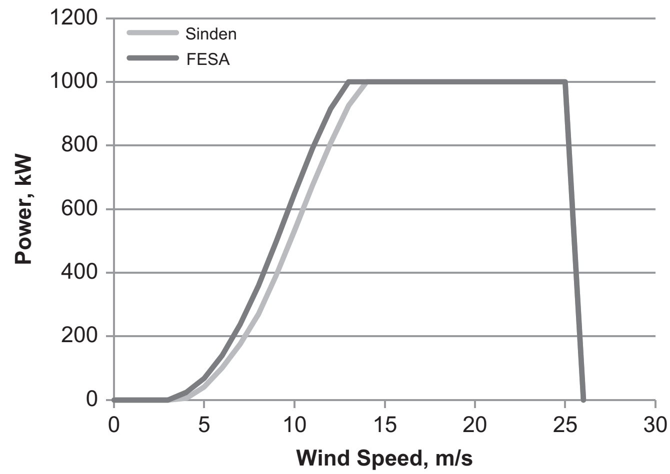

Fig. 22. Turbine power curve of FESA model compared with that used in work by Graham Sinden (both normalised to 1000 kW rated power).

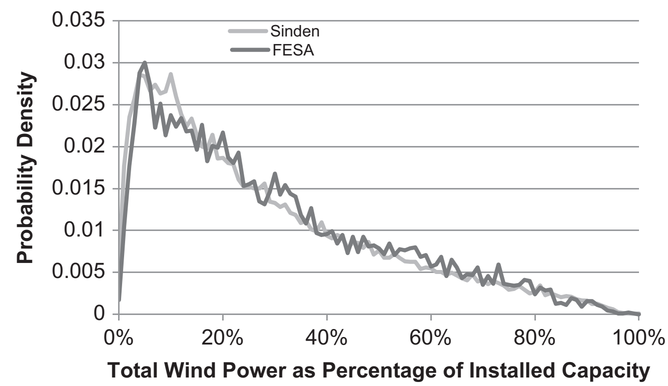

Fig. 23. UK wind power distribution from FESA model compared with that from Graham Sinden's work.

Fig. 22 shows that the two power curves are very similar. In fact, all modern large wind turbines have very similar shapes of power curve. Graham Sinden's power curve is tuned to slightly higher average wind speeds but this effect is incidental since FESA and Sinden used different wind speed extrapolations to turbine hub height.

Fig. 23 shows remarkable similarity in wind power distribution. The FESA model has a very slightly sharper peak but is based on just 1 year's wind speed data whereas Sinden's work is based on 34 years.

A.5. Electrical demand data

Half-hourly electrical demand data for Great Britain in year 2001 was downloaded from the National Grid Company. Half-hourly data was paired up and averaged to give hourly data suitable for FESA. An estimate of temperature-dependent off-peak night-time electrical heating was made and this was subtracted from total 2001 demand to give the electricity demand from all other appliances in each hour of the year, Fig. 18. This demand time series was scaled up for the UK for each year and for each pathway modelled.

A.6. Heating technologies

The proportions of heat pumps, CHP, resistive heating and boilers, together with the average temperature in day, were used to calculate energy demands in each hour of the day by fuel type for space heating and water heating. As described in Sections 3.2 and 3.4 default profiles (before DSP) were assumed for CHP and heat pumps for each of these applications based on assumed physical limitations. Space heating technologies were assumed to have flat diurnal profiles whereas water heating technologies were assumed to follow a peaky daily profile based on hot water use, Fig. 10. These assumptions were a simplification for modelling purposes and a compromise between today's on-demand heating profiles, Fig. 10, and flatter profiles that might make the grid balancing problem easier. The move to a flat default profile had pros and cons as follows. It should also be remembered that these are merely the default profiles before smart DSP measures are applied.

A.6.1. Reasons for choosing a flat default heat profile for space heating

- Space heating demand is much larger than water heating demand when averaged over the year and extremely high in cold weather. If space heating were allowed to follow a pattern of unrestricted demand, as in Fig. 10, the electricity system would experience very large peaks of demand (heat pumps) or large electricity surpluses (CHP).
- Large peaks and troughs of heat demand would stress the local distribution network, exceeding its upper voltage limit (CHP) or lower limit (heat pumps).
- It has been suggested that heat-led CHP varying through the day would generate electricity when it is needed most, in the morning and the early evening. However, if space heating CHP is allowed to vary in this way, the electricity generated is so large in cold weather that it would exceed the electricity demand and result in a surplus, even at those times of peak demand.
- Running space heating technologies constantly through 24 h will approximately result in constant internal room temperatures and good thermal comfort.
- The manufacture and installation of CHP systems and heat pumps capable of delivering the winter peak level of heat, and varying hour by hour is likely to be prohibitively expensive. The ground loop for ground-source heat pumps is likely to be particularly expensive.
- CHP systems work more efficiently and reliably if not cycled too often, (Hawkes et al., 2007).

A.6.2. Reasons for choosing a time-varying heat demand profile for water heating

- Water heating demand is very time dependent, with a large peak in the morning and a smaller peak in the evening as shown in Fig. 10. If CHP is heat led and allowed to follow this pattern, then the electricity will almost coincide with the peaks of domestic electricity use and thereby minimise the demand on central electricity generation.
- Water heating currently needs less heat than space heating and therefore can be accommodated by heat pumps responding almost instantly to hot water use.

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