Assessment of Electricity Demand-Side Management Technologies

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Table of Contents

1. Introduction 4
2. Methodology 4
   2.1 Department of Energy and Climate Change's 2050 Pathways Tool 4
3. Plug-in Vehicles 4
   3.1 Current Energy Demand In Transport 4
   3.2 Low Emission Vehicle Types 5
   3.3 DECC 2050 Scenarios for Vehicle Uptake 6
   3.4 Low Emission Vehicle Uptake Effect Upon Electricity Demand 6
   3.5 Discussion Points 9
4 Smart Meters 10
   4.1 Smart Appliances 10
   4.2 Smart Ground Source and Air Source Heat Pumps 12
   4.3 Grid Frequency Response 13
   4.4 Discussion Points 13
5. Electricity Storage 14
   5.1 Storage Technologies 14
   5.2 Pumped Hydropower Resource Projections 15
   5.3 Car Battery Resource Projections 15
   5.4 Hot Water Resource Projections 16
   5.5. Discussion Points 16
6 Overall Conclusions 16
7. References 17
8. Appendix 17

1. Introduction

With challenges of energy security and climate change ever present, the UK's strategy for a low carbon and sustainable future looks set to change the way we think about using energy resources. Important in the UK's strategy for decarbonising the electricity supply are nuclear power, carbon capture and storage(CCS) technology and renewable generation capacity. There are inherent challenges in this strategy, such as nuclear power traditionally having lower output flexibility than other generation plant, and the intermittency of renewable energy sources.

These challenges may make it harder to match supply and demand on the electrical grid, while at the same time the demands for electrical energy are expected to increase significantly with the electrification of heating and transport as part of a move to a more energy-efficient and low-carbon future.

To meet these challenges a broad portfolio of technologies will need to be deployed. In this report I will assess the scale and impact upon electricity demand management of: i)the use of plug-in vehicles, ii) the roll-out of smart meters, and iii) the development of electricity storage.

2. Methodology

Having read many sources in order to find out about the technologies, I will include numbers and technical limitations in my report to demonstrate likely trajectories for development of these technologies over the decades leading to 2050. Important factors affecting the projections and limitations, as well as suggested counter-measures to problems arising, will be discussed at the end of each section.

2.1 Department of Energy and Climate Change's 2050 Pathways Tool

Making predictions for how consumers of energy will live their lives in the coming decades is very difficult. In my analysis I have drawn upon DECC's four model scenarios for the penetration of technologies up to 2050. The models have been calculated on the basis of making reasonable assumptions about how different technologies can help the UK meet its 2050 emission reduction targets. There is great uncertainty over which technologies will be adopted by 2050, but these four scenarios are meant to be illustrative of futures in which various technologies succeed and others do not. I will use the scenarios as examples of what level of technology uptake seem reasonable knowing what we do now. More information about these scenarios can be found in Appendix A.1.

3. Plug-in Vehicles

The transport of passengers and freight is currently energy and carbon intensive. An important part of creating a low carbon economy is the decarbonisation of this sector through electrification, but this will mean adding large demands for electrical energy. In this section, I will address the question of how much demand will result from such a transition.

3.1 Current Energy Demand In Transport

Statistics from the Department of Energy and Climate Change(DECC) show the scale of energy usage in transport[1], I have listed the figures in Table 1. Alongside the figures given in mass of oil equivalent I have given the equivalent energy value in terawatt-hours (TWh) which can be compared to the output of electrical energy from UK power generators, given as 381TWh for 2010 [2].

Table 1 Energy consumption figures for transport in 2010 [1]. Unit were converted from kilotonnes of oil equivalent(ktoe) to terawatt-hours(TWh) using the International Energy Agency's Units Converter[10].

Transport Mode	Energy Use (ktoe)	Energy Use (TWh)	Percentage (%)
Road – passenger	28,015	326	50.3
Road – freight	12,940	151	23.2
Air	12,288	143	22.1
Water Transport	1,469	17	2.6
Rail	992	12	1.8
TOTAL	55,704	648	

We see from Table 1 that if electric vehicles used as much energy for passenger transport in 2050 as conventional passenger vehicles do now, then the grid would have to transmit nearly twice as much energy per year. If road freight is to be electrified as well, then this becomes easily more than twice the amount of energy. Thankfully, vehicles with electric motors are significantly more energy-efficient than those with internal combustion engines(ICEs).

The move to low emission vehicles(LEVs) has already begun and the latest generation of vehicles consists of a variety of types, incorporating new technologies to boost their efficiency. For example, some absorb energy during braking to be reused later for acceleration. This does not necessarily require an electric motor as mechanical flywheel-based systems can be used. Hybrid cars are able to achieve high fuel efficiency, compared with pure ICEs, as the electric motor and battery (which can supply or absorb energy) allow the ICE to work closer to its optimal conditions.

The different LEV types require various battery capacities, some can use liquid fuels and some cannot. The future market shares of each type have implications for the resulting electricity demand.

3.2 Low Emission Vehicle Types

I have listed the prominent LEV types, which use electric motors for some or all of their acceleration. Some specific LEV examples are listed in Appendix A.2, along with their battery capacities and energy consumption. In my analysis, I categorise LEVs as follows:

- **Zero Emission Vehicles (ZEVs)**, which get energy from purely electricity or hydrogen and have zero emissions from the exhaust, except for water vapour in the case of Fuel Cells.
    - i) **Battery Electric Vehicles (BEVs, or simply EVs)**, with a battery pack driving an electric motor, sourcing all their energy from the electricity grid. These have the highest electricity storage capacity, typically 15-25kWh.
    - ii) **Hydrogen Fuel Cell Vehicles (FCVs),** which gain electrical energy from carefully reacting hydrogen with oxygen at an electrode. This electrical energy then powers an electric motor. FCVs need to carry a battery as well, to help the fuel cell meet the quickly-changing power demands in vehicles. There are also practical difficulties in storing the hydrogen. It is proposed that hydrogen will come from electrolysis of water using electricity from renewables. I will consider these as using electricity in my analysis.
- **Plug-In Hybrid Electric Vehicles(PHEVs),** which use energy from liquid fuels as well as from the electrical grid. There are various engine configurations that distinguish them:

i)**Extended Range Electric Vehicles(E-REVs),** these carry an electric motor for propulsion and an internal combustion engine attached to a generator to recharge the battery. These are less efficient than EVs as they need to carry that extra weight, but they allow greater range.

ii) **Regular Plug-in Hybrids,** where an ICE engine or an electric motor can provide the propulsion. The vehicle could be used as an electric vehicle for short journeys without liquid fuel, battery capacities typically around 5kWh.

- **Conventional Hybrids**, these do not plug in. They can stop using the ICE when in slow traffic, or on short journeys. The battery is charged from the ICE by reversing the electrical flow in the electric motor. Increasing desire to source energy from lower-carbon electricity means the 2050 projections show movement away from using liquid fuels.

I do not think there will be significant use of FCVs before 2050; it seems to me that it will be difficult for FCVs to catch up with the falling price of EVs, for further explanation of this view see Appendix A.3. The expectation is that most vehicles will be able to plug in and take advantage of low carbon electricity from the grid by 2050.

3.3 DECC 2050 Scenarios for Vehicle Uptake

The DECC scenarios simulate how the proportion of ZEVs and PHEVs will increase by 2050. These projections laid out in Table 2. I will use these figures for penetration in my energy demand analysis.

Table 2 Scenario details from the online 2050 Pathways analysis tool[4]. Listed are the expected percentages for mileage covered by each vehicle type, ZEVs = zero emission vehicles (BEVs and FCVs).

2050 Scenario	% ICEs	% PHEVs	% ZEVs	ZEVs: % BEVs	ZEVs: % FCVs	Public Transport Uptake?
Core MARKAL	20	32	48	100	0	High
HR,MEE	0	0	100	100	0	High
HN,LEE	20	32	48	80	20	Low
HCCS,MB	35	54	11	80	20	Medium

3.4 Low Emission Vehicle Uptake Effect Upon Electricity Demand

To estimate the extra electricity demand while accounting for efficiency improvement, I consider how many miles and how efficient in energy terms these vehicles will be. The scenarios envisage all cars being able to draw energy from the grid, so I divide the vehicles according to whether they can use liquid fuels as well: PHEVs if they can, ZEVs if they cannot. I use the following equation:

$$\text{Transport electric energy demand} = \text{Daily mileage} \times (P_{ZEV} \times E_{ZEV} + P_{PHEV} \times E_{PHEV}),$$

where P_{ZEV} represents the proportion of the nation's mileage driven by zero emission vehicles, which is a fraction between 0 and 1, and E_{ZEV} represents the average electrical energy use per kilometre by these vehicles. For EVs, 15kWh is sufficient for around 100 kilometres (Smart Fortwo ED uses 12kWh/100km and Nissan Leaf 16.5kWh/100km [see Appendix A.2]), for PHEVs a 5kWh battery might cover the first 40 kilometres per day, if in full-EV mode.

For a national daily mileage figure, I found that there were typically around 700bn passenger-kilometres travelled in cars, taxis and vans in the years of the late 2000's [6]. I assume a vehicle occupancy of 1.0(this will be discussed later), then the electrical energy demand from ZEVs if they achieve a market share P_{ZEV}, with an energy use of 15kWh/100km, is given as:

$$\text{ZEV Daily Energy Demand} = \frac{700\,000\,000\,000\ \text{km}}{365\ \text{days}} \times \left(P_{ZEV} \times \frac{15\text{kWh}}{100\text{km}}\right)$$

$$= 288\text{GWh} \times P_{ZEV}, \qquad 0 < P_{ZEV} < 1.$$

Suppose these batteries take 8 hours to recharge overnight, as is recommended; there will be various times at which battery charging switch on and off but when they are all on, this would demand 288GWh/8h×P_{ZEV}=**36GW×P_{ZEV}** from the grid.

The calculation for PHEVs is harder, since they do not technically need to be plugged in at all and can still be used. On the other hand, if users wish to do so, they can use their plug in hybrid as an all-electric vehicle for short journeys up to between 25 and 50 miles typically. This could give significant variation in answers for how much electrical energy they use per mile.

I will label the fraction, *f* of the car's energy use which is supplied from the overnight electrical charging, and assume that the 'electric miles' are as energy efficient as those driven in ZEVs. Hence:

$$\text{PHEV Daily Energy Demand} = \frac{700\,000\,000\,000\ \text{km}}{365\ \text{days}} \times \left(f \times P_{PHEV} \times \frac{15\text{kWh}}{100\text{km}}\right)$$

$$= 288\text{GWh} \times f \times P_{PHEV}, \qquad 0 < P_{PHEV} < 1 \text{ and } 0 < f < 1.$$

This adds **36GW×*f*×P_{PHEV}** to power demand. Remember that the sum of P_{ZEV} and P_{PHEV} will remain less than one and while ICEs and conventional hybrids have a large market share then the sum will be much less than one. So total demand from ZEVs and PHEVs comes to:

$$\text{ZEV and PHEV Daily Energy Demand} = 288\text{GWh} \times (P_{ZEV} + f \times P_{PHEV})$$

Demand Implications of DECC Scenarios

The graphs in Figure 2 show my estimates of how the rising proportion of ZEVs and PHEVs (represented along horizontal and vertical axes respectively) will add to power demand. The effect of PHEVs depends on what proportion of their daily energy use comes from electrical power, charged overnight, and what proportion comes from liquid fuel. I have represented this electric fraction by *f* and shown example cases for if *f*=0.25,0.5 and 0.75.

The DECC trajectories for ZEV and PHEV uptake are represented along the same axes in Figure 1 and this is copied alongside the demand graphs in Figure 2. These scenarios are meant to be illustrative of possible outcomes compatible with current policies, they are outlined in Annex A of the Carbon Plan report[3] and are illustrated on DECC's online 2050 Pathways tool[4]. The DECC scenarios in Figure 1 cover up to 2050, each line tracks the progression from now to 2050 with a point at 2020, 2030, 2040 and 2050; all tracks start now near the bottom left as P_{ZEV} and P_{PHEV} are both very low (sum less than 0.01 in 2010).[1]

[1] The current combined value of P_{EV} and P_{PHEV} is very low; the number of 'alternatively fuelled vehicles' registered, this includes but is not exclusively these categories, was around 23,000 out of a total car market of two million in 2010, giving (P_{EV}+P_{PHEV}+other alternatively fuelled vehicle types < 0.01)[19].

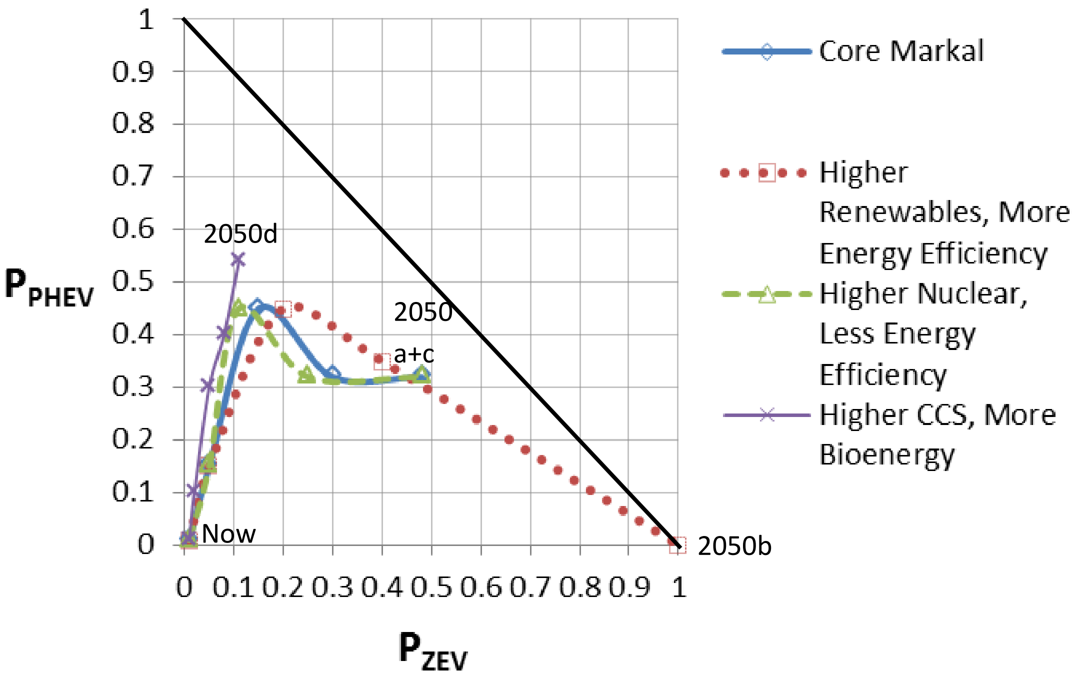


Figure 1: Trajectories for the proportions of each low emission vehicle type in the four DECC scenarios. Each trajectory starts in the lower left corner and each point represents a decade passing. The trajectories are sourced from a Centre for Low Carbon Futures report[11] and the 2050 endpoints are labelled a, b, c, or d in order of scenario.

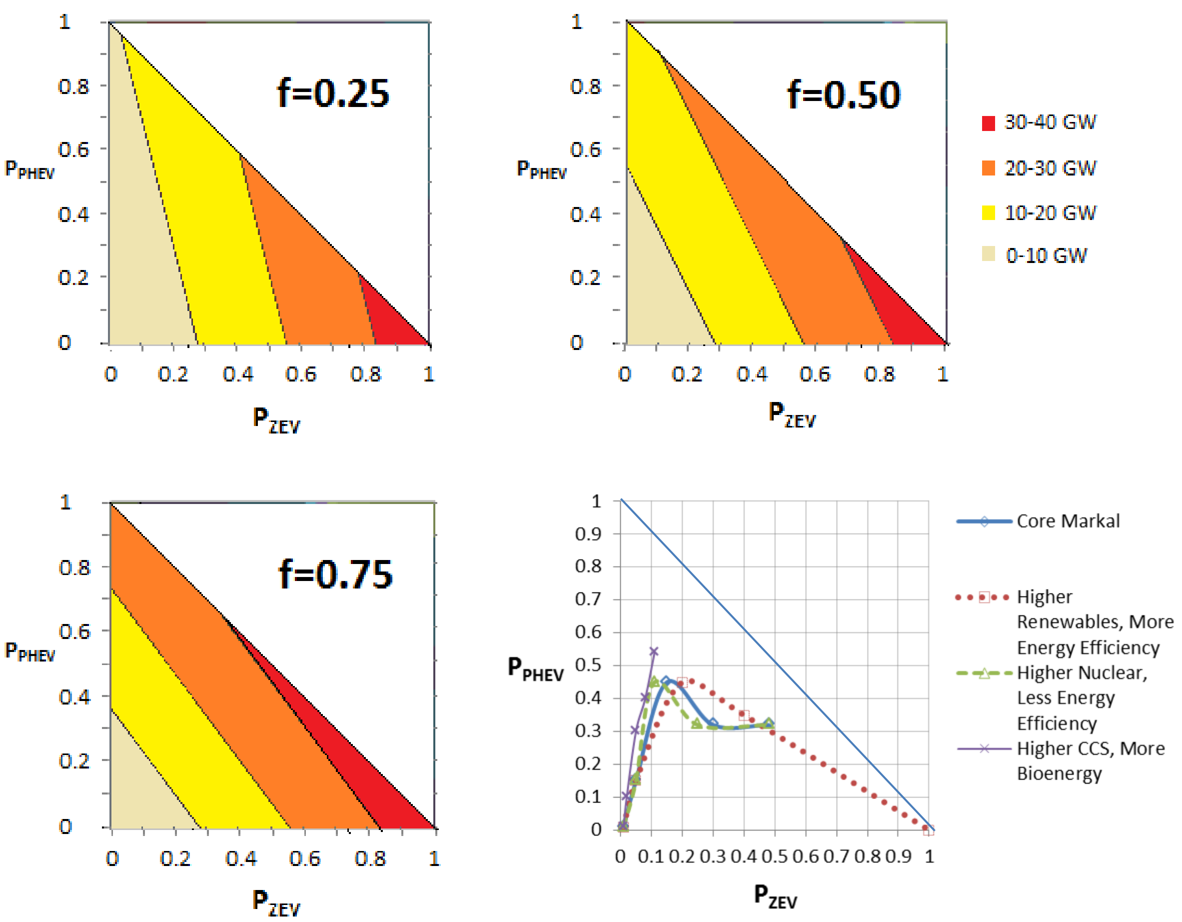


Figure 2: Additional demand, in gigawatts, added during an overnight eight hour charge period. Figures for the uptake of electric and plug-in hybrids in the fourth diagram are based on DECC 2050 Pathway scenarios.

Figure 2 shows a few important aspects, such as that even if hybrids only draw 25% of their power from the grid, then the additional overnight demand, if charging takes eight hours, will approach 20GW. If the 'Higher Renewables, More Energy Efficiency' scenario materialises and we have 100% ZEVs by 2050 then the electrical energy requirement will approach 36GW(288GWh/day) This is not far short of today's peak in demand, however this scenario also includes a significant shift to public transport (effectively a higher vehicle occupancy) to lower energy demand.

3.5 Discussion Points

Vehicle Occupancy I assumed in my analysis a vehicle occupancy of 1.0, this leads to an overestimate of energy consumption since in reality some vehicles are shared, lowering the energy consumption per passenger-km. On the other hand, the figures for energy consumption are figures provided by industry and probably represent ideal operating conditions. In real life energy consumption may be higher than 0.15kWh/km for the vehicles, particularly if they are carrying the weight of extra passengers. So overall, I think working with a vehicle-occupancy of 1.0 is a decent assumption.

Mileage (Strbac et al.,2010)[12] work on an assumption of approximately 1bn kilometres per day by these vehicles and an energy use of 0.15kWh/km leading to a daily requirement of around 150GWh. I assumed nearly twice this amount of miles for passenger vehicles (700/365=1.9bn km/day). Department for Transport Statistics say there were 504bn *vehicle*-km (313bn vehicle-miles) by motor vehicles in 2009 [7]; this is equivalent to 1.38bn km/day. So Strbac et al. may be underestimating mileage and over-estimating energy efficiency. Also, the Department for Transport projects that road traffic levels will grow by 44% from 2010 levels by 2035 [9], so this would mean around 720bn vehicle-km per year.

Values of *f* To recap, the values of *f* represent what fraction of the plug-in hybrid energy use is sourced from the electrical grid rather than liquid fuel. What values of *f* are reasonable? Well, by 2050 the Committee on Climate Change(CCC) expects a high level of electrification in transport and possibly use of biofuels in plug-in hybrids if sustainable sources, that do not compete with food supplies, can be found (e.g. in the HR,MEE scenario). Biofuels are expected to be 16% cheaper than conventional fuels if oil reaches $120/bbl [13, p 150]. The CCC quote the Gallagher review which does not recommended more than 60TWh of biofuel use by 2030 due to sustainability concerns (high abatement CCC scenario,[13, p 35]). Supposing that 60TWh of biofuel can be found (18% of today's road passenger transport oil consumption), we need to acknowledge that even in DECC's scenarios there are still at least 30-40% conventional ICEs by 2030. So if oil prices are high, then biofuel demand will be high too and there will be pressures from industry, aviation and remaining ICE vehicles to use bioenergy in those applications. Current designs of plug-in hybrids carry around 5kWh which is roughly enough to cover a typical day's driving.

Rural-Urban Distinction In terms of sustainability I think it's interesting that certain cities want to lead the way with electric car development. The average driven distance by people in London is under half the national average and only around 30% of the distance travelled by rural drivers [8]. So perhaps a non-urban charge point network scheme (e.g. at service stations) would have better impact. In cities, money may be better spent on improving cycling facilities. Particularly since high upfront costs for low emission vehicles, particularly in difficult economic times, will probably increase the proportion of journeys by public transport and cycling.

Responsive Demand These high figures for load resulting from electric cars suggest that switching the charging systems on and off to balance supply with demand should be explored vigorously. It also seems that charging the car battery to 100% capacity would rarely be needed, so if customers could specify how many miles they will need the following day then that would give an active network operator more flexibility. Perhaps full battery charging at weekends and partial charging during the week will be a good solution as the whole battery capacity is unlikely to be needed on every day. I have also assumed that only a fraction of a typical battery needs to be charged each night and that takes eight hours. This charge may actually be possible in much less time but would lead to a greater amounts of power being drawn from the grid earlier in the night. Hence it is important to spread the charging loads through the night.

2030 Electricity Generation Gap? For high extra demand to be happening around 2030 would be an unfortunate coincidence with ageing power stations closing. So it will be important to ensure the new generation of nuclear plants do not experience unnecessary delays.

4 Smart Meters

Smart meter roll-out is targeted for completion by 2020. There are numerous benefits for suppliers of gas and electricity, including remote meter reading and easier connection/disconnection of supplies. The financial benefits to consumers are mainly through minimising their use of gas and electricity, which both seem set to rise in price.

It is hoped that smart meters can be used as the central coordinator of 'smart' appliances that alter their operation in order to smooth peaks in demand. The activity of smoothing demand will be particularly important as heating of homes is expected to be largely electrified with occupants moving from gas heating to electrical heat pumps. Smoother demand will reduce the need for electricity network reinforcement if a large load is added from plug-in vehicles and/or heat pumps. Which appliances will be convenient to operate smartly and how much shift in demand is possible?

4.1 Smart Appliances

Researchers at the University of Bonn, working on the *Smart Domestic Appliances in Sustainable Energy Systems (Smart-A)* project have combined household surveys detailing when appliances are used with the typical power consumption profile for the appliances through their working cycle[14]. As a result, they divided the national domestic electricity demand into contributions from each device, as shown in Figure 3 from (Strbac et al.,2010)[12].

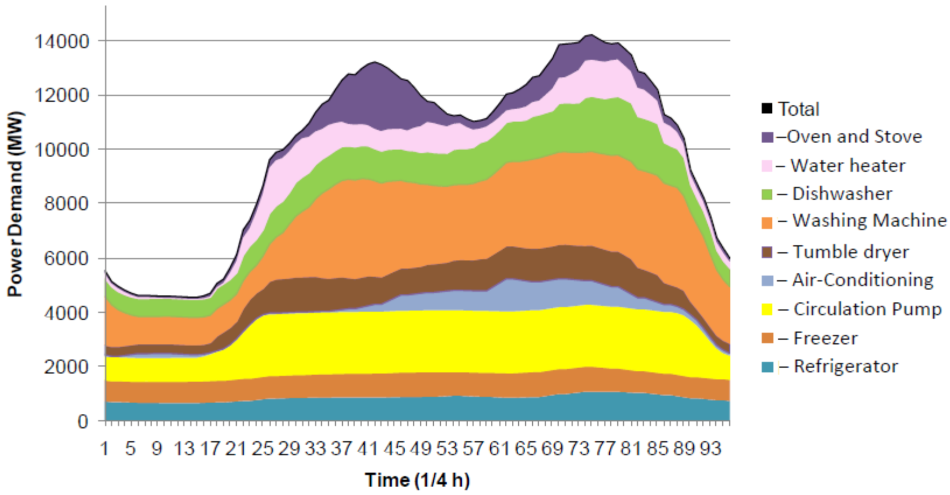


Figure 3: The estimated contributions from domestic appliances to electricity demand, this figure is sourced from (Strbac et al., 2010)[12] based on data from the University of Bonn[14].

Box 1: Explaining Appliances listed in Figure 3
It is probably helpful to explain the role of circulation pumps, air conditioning, water heating and electric heating in the demand curves above. **Circulation Pumps** are electrical devices moving hot water from the heating tank around the heating system. The pump continues to move hot water from the tank and return cooler water for as the property needs warmth. Ground source and air source heat pumps are classed in this category. **Air conditioning** controls temperature and humidity, typically mid to late afternoon use and typically more often used in summer, much more significant for countries like Spain and Italy. 'Water Heaters' covers hot water tapped for washing and other uses but not circulated in the radiators, kettles presumed to be in this category but not specifically mentioned in the University of Bonn report. Electric Heating covers resistive heaters in the household. This includes storage heaters with ceramic cores that draw energy during the night then draw air through the core to heat it on demand.

Sadly, the study had only sporadic indications over household preference for using devices at the weekend or during the week. I think this is important to know as electricity demand is less at the weekend (see Figure 4) so there may be significant benefits in moving appliance use to the weekend where possible; this might be easiest for the case of washing machines, and tumble driers would naturally follow the shift.

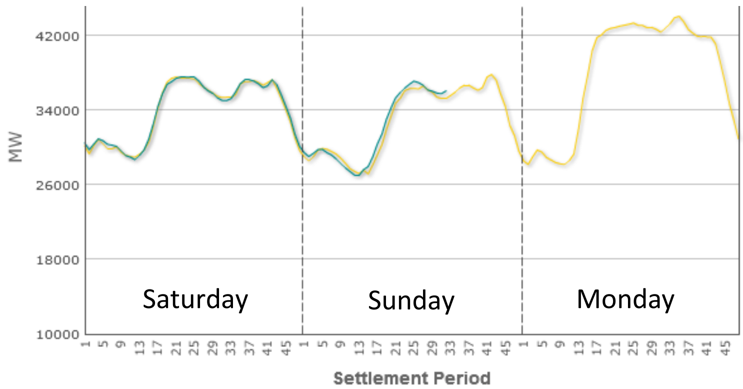


Figure 4: The demand levels seen for electricity during a weekend in April and the demand expectation for Monday. Sourced from the New Electricity Trading Arrangements website[15].

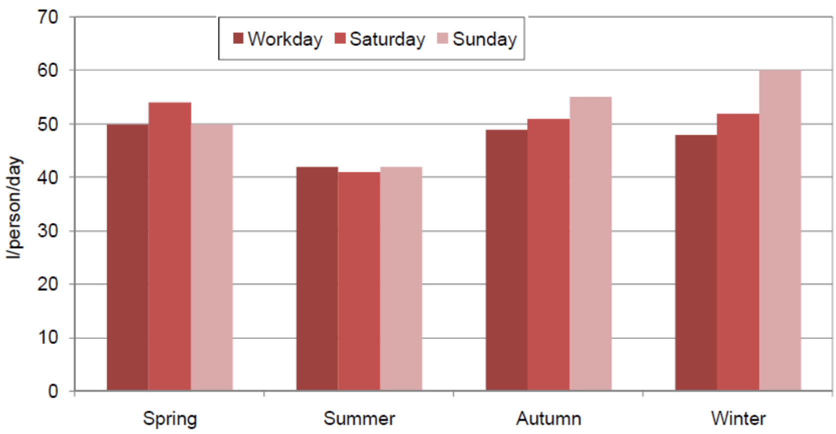
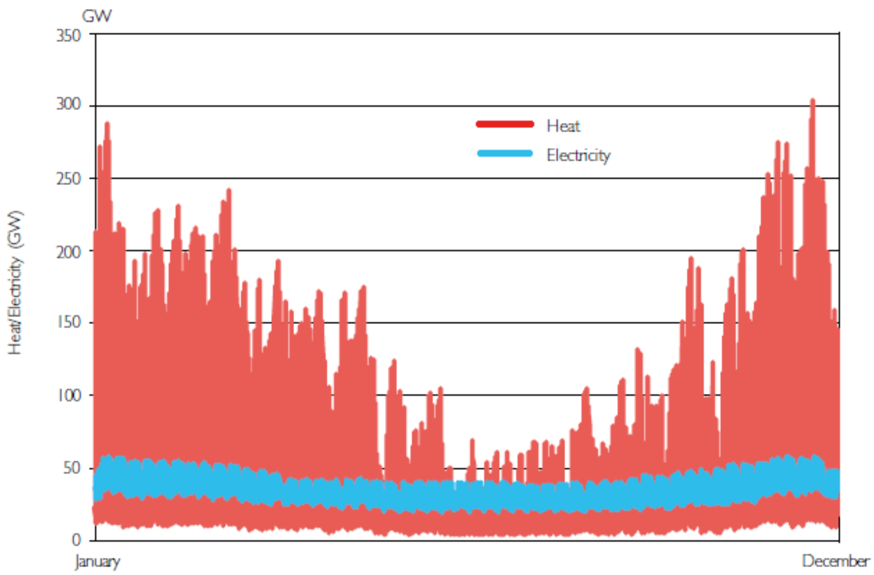


Figure 5: Variation in hot water use from taps, in litres per person per day, from weekdays to weekends and over the seasons. Source: University of Bonn[14] Figure 3.8-9, based on [16].

It is clear from Figure 5 that hot water demand is higher at the weekends in winter. As houses in cold countries become better insulated, the energy demands for water heating are increasingly overtaking the demands from space heating. We can conclude that shifting demand to weekends may be preferable in the summer months, but less so during winter.

4.2 Smart Ground Source and Air Source Heat Pumps

Data from Imperial College in Figure 6 show that heating demand (from commercial and domestic consumers) varies from around 250GW of heat generation during winter down to around 50GW in summer and the demand is highly fluctuating[5, p11].



7 Courtesy of Imperial College. For illustrative purposes only, and based on actual half-hourly electricity demand from the National Grid and an estimate of half-hourly heat demand

Figure 6: Comparison of heat and electricity demand variability through 2010, from [5, p 11].

The future of heating is envisaged to involve a move away from gas boiler-based heating towards heat pump systems that have lower carbon emissions. Government models suggest that natural gas combustion at individual building level should be completely phased out by 2050[5, page 8]. This means a lot more heating demand is expected to move from gas to the electricity grid. The investment cycles in heat pumps are short, and so a large number of heat pumps could be added to the demand in short period if they become fashionable, this is a risk to network operators trying to keep up with demand, particularly if a spike in gas prices causes a speedy transition.
Coefficients of performance are typically 2.2 for air source heat pumps in trials reported by the Committee on Climate Change [13, p 129]. This figure means that if 1 kWh of electricity is used by a heat pump then typically 2.2 kWh of heat are added to the house, the first 1kW of heat is considered as non-renewable, but the other 1.2kWh is classed as renewable. The CCC expects by 2030 provision of 210TWh of renewable heating [13, p 31]. This implies a demand on the grid of 95TWh per year given the coefficient of performance. This extra demand is **roughly a quarter of today's electricity supply**.
Energy efficiency improvements in homes should come before heat pumps as then smaller and less expensive pumps will be needed for the more energy efficient properties. If energy efficiency comes later, then the heat pump may be over-sized and will not be working at its optimum efficiency when the energy performance improves.

If EVs are adding significant loads at night, then heat pumps are probably best used during the day from a grid point of view. With a lower penetration of electric vehicles, heat pump use at night becomes more favourable. On the other hand, heat pumps are more efficient when the outdoor temperature is higher so use at the colder night time might be a bad idea. Control of EVs and HPs in a 'smart' way would provide significant savings by reducing the need for network reinforcement. This remains true even if the penetration of both technologies stays low, as demonstrated by (Strbac et al, 2010)[12].

4.3 Grid Frequency Response

As the balance of supply and demand changes on a minute-to-minute basis, the frequency of oscillations in the electricity in the national grid alters to reflect this. The Distribution Network Operator has the responsibility of matching supply and demand as well as possible and this corresponds to keeping the frequency of the grid within a narrow range around 50Hz. It is proposed that smart appliances could 'listen' to this frequency and respond by delaying their start time. In principle this is a good idea, but the synchronisation of a large number of appliances to this signal could also push the grid balance further from equilibrium as they enter certain parts of their operating cycle at the same time. If smart appliances can help to reduce sharpness of peaks in daily demand by avoiding operation at peak times then this may give the network operator more 'headroom' for stabilising grid frequency on a minute-to-minute basis.

4.4 Discussion Points

Smart Meter Implementation Budget Only around 1% of the smart meters programme budget is set aside for customer support, but the use of smart meters to change demand patterns needs to be consistent otherwise the benefits of a lack of network reinforcement need are lost. If people are confused by their smart meters, they are more likely to become disengaged from monitoring their own energy use and potential benefits could be lost.

Appliances Using Hot Water. The appliances that heat water as part of their working cycle are some of the biggest electricity consumers. There is potential for better use of hot water storage in order to move the electricity demand off-peak. Unfortunately the average amount of hot water stored in homes has been falling and domestic appliances increasingly tend to heat water on demand causing spikes of power and drawing less hot water from the hot water tanks. A report from the Centre for Low carbon Futures points to as much as 80GWh [11, page 9] of heat energy storage in homes. So storing heat energy may be a good strategy for reducing sharpness of peaks in electricity demand.

Tariffs (Strbac et al, 2010)[12] suggest that, since there are local variations in the spare capacity of the electricity low-voltage network, a house-by-house tariff system might be best so that large loads are not correlated in the local networks, but this does sound complicated to introduce.

Strategies Since electricity demand from electric cars and heat pumps is projected to be very large then perhaps having smart technology just on car charging and heat pumps will be sufficient. If these smart systems are applied when charging systems and heat pumps are installed then consumers perhaps will not feel as much grievance over having lost some control of their energy use.

Limitations to altered timings For example, tumble driers have to follow washing machines so timings have to coincide with presence of the householder as they need to switch clothes from one machine to the other. Another issue could be that limiting use of washing machines to the weekend could mean that people panic and do as much washing as they can each weekend and not necessarily less use less power over the entire week. Then this would not reduce energy use and may not save them money. There are a few approaches, maybe if there was a risk of switch off during the week, but no risk at the weekend then that may influence behaviour. Perhaps risk levels could be forecast to associate with renewable energy output.

Smart Circuitry There are issue over how smart circuitry would work in homes. For example: if control is socket specific, then users could override this by plugging into different sockets. This may mean that smart meters will have to limit power being drawn and consumers may not like this.

Adding to Electricity Demand Peaks? (Strbac et al., 2010)[12] expect that Heat Pump function will be optimally during the day and smoothing demand whereas EV charging will predominantly add at night if both systems reach a high penetration. If there is a low EV penetration then more of the heating will happen at night ideally with suitable storage systems in place at a domestic level. They also warn that if electric vehicles and heat pumps are added without smart control and timing then the peak of electricity demand could go as high as 117GW. This would mean a massive need for network reinforcement.

5. Electricity Storage

A new generation of relatively inflexible-output nuclear power stations and increased penetration of renewables that are intermittent means the need for electricity storage will increase. Currently the electricity generation supply lines store fossil fuels with around 30,000GWh of coal and 7,000GWh of gas stored ready for burning [17](Wilson et al, 2010). Although a large part of this store is acting as reserve in case of disruption of the long supply chains.

There is already significant use of pumped hydroelectricity storage as a fast response mechanism to meet peaks in demand, combined cycle gas turbines (CCGTs) make a much larger contribution to meeting daily peaks in electricity demand but pumped hydro can be controlled more closely minute-to-minute. Better storage capacity would mean improved utilisation of existing generation assets as well as reducing the need for investment in the grid and back-up generation.

5.1 Storage Technologies

Listed below are a series of technologies that store electricity, explained in POSTnote 306[18].

- *Pumped Hydroelectricity* - 75-80% electricity recovery, UK has around 2,800MW capacity currently. Difficult to compete with open cycle gas turbines in terms of high capital and maintenance costs. Example: Dinorwig plant can produce 1728MW for 5 hours when reservoir is full.
- *Flywheels* - Limited storage potential due to material constraints. Used in industry to maintain reliability of energy supply. Used in some regenerative braking systems. A large 800 tonne flywheel is used at Culham research centre; this can supply up to 0.4GW and supply 1MWh of energy.
- *Supercapacitors* - Again, energy storage potential is limited, but there are advantages in not converting electrical into mechanical energy then back again. Used by industry for keeping electricity supplies reliable, and also used in regenerative braking systems.
- *Compressed Air Energy Storage* - Using underground caverns to store air at a raised pressure. Electricity is absorbed by the pumps and used to raise pressure in the cavern and, when desired, the electricity can be regenerated by allowing the compressed air to flow into a gas turbine generator. There are limited geological circumstances that are suitable. A more flexible idea is air balloons on the seabed, under research at the University of Nottingham. This is said to have lots of potential however my calculations suggest a balloon at 50 metres depth would need a volume of 6 million cubic metres to store 1 GWh (equivalent volume to around 2500 Olympic swimming pools). Experts think the UK should apparently aim for 200GWh of CAES by 2020. Globally, only two schemes have been commissioned to date, in Germany and the US [11].
- *Battery Storage* - Large installations probably in the range 100kW to 10MW are proposed. Potential to use heavier batteries which are less in demand than the lighter ones favoured in transport applications.

- *Hydrogen* – absorbs electricity to split water into hydrogen and oxygen, then these can be run through a fuel cell to regenerate electricity; but electrolysis, compression of hydrogen, and the fuel cell steps all cause major energy loss, see Appendix A.3.
- *Liquid air* – use energy to cool air and liquefy, then allow expansion upon regaining temperature to drive an electricity generating turbine; but this needs to be very cold, and it's energetically demanding to keep the air cold until you need it.
- *Cryogenic Energy Storage* – storing energy by cooling objects down. Again, takes effort to keep things cold.
- *Superconducting Magnetic Energy storage* – the superconducting materials can store a high current, with small losses over time; but again, it is a lot of effort to keep these things cool.

5.2 Pumped Hydropower Resource Projections

If two major Scottish sites get approved and commissioned, then current pumped hydro could grow from 2.7 GW and 27.6 GWh to 3.9 GW and nearly 90 GWh by around 2020, see Appendix A.4 for more details. I am not aware of any other schemes that are planned, and there are limited opportunities due to UK topology. There are proposals for tidal pools to perform this function too.

5.3 Car Battery Resource Projections

If there is large scale electrification of transport then plug-in vehicle batteries may offer a significant storage resource. To get an idea of scale for this resource, I will assume that there are 26 million vehicles in the whole vehicle fleet (number of cars in use in 2009 that were less than 12 years old, [19]). I assume that a battery in an EV offers 10kWh of battery capacity for electricity storage. I take the growing use of EVs from DECC's 2050 Scenarios mentioned earlier (Appendix A.1 and Table 2) and so I can project how much storage will be available in EVs to 2050.

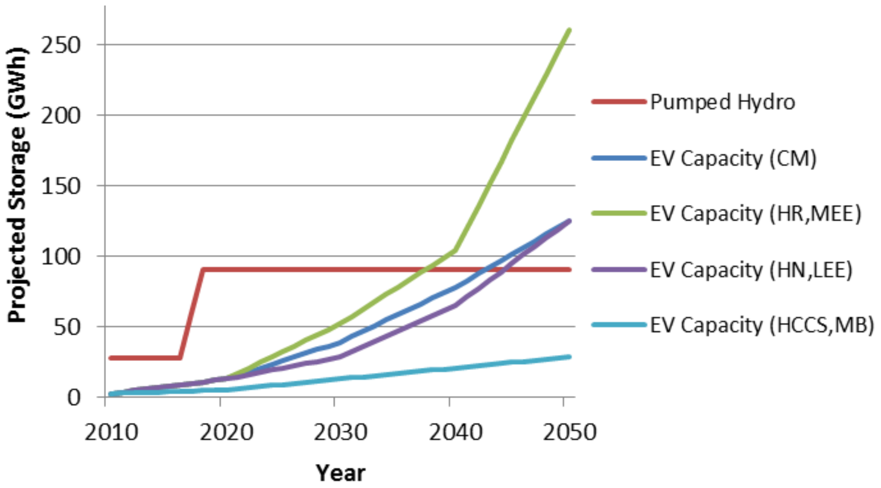


Figure 7: The projected growth of Pumped Hydropower and EV batteries as electricity stores.

Some think that having a lot of EVs connected the network would mean energy from intermittent wind could be better harnessed. To a large extent this is true but there are caveats, for example if wind output is very high at a time when household electricity demand is high: there may be limitations to how much power can be transferred from wind farm to car battery whilst high powers are also being transferred from power stations to households. Having large concurrent flows risks exceeding the rating of the national grid, or local distribution networks, and causing damage. Vehicle to Grid systems for returning power to the grid are possible, but this would need complex metering and electronic controls on board the plug-in vehicles. Also, charging and discharging batteries reduces their lifetimes.

5.4 Hot Water Resource Projections

Nearly all households have capacity to store hot water. This means there is potential for these tanks to move heating demands off-peak. The resource is estimated at 80GWh of hot water energy storage currently[11]. This could be significantly increased, particularly if there are incentives to install hot water tanks alongside heat pumps, but there are space constraints in some houses.

5.5. Discussion Points

Household level storage may be the best way to overcome difficulties in finding centralised sites that are suitable, and centralised sites will have further difficulties with needing new pylon infrastructure. It seems that the storage ability that fossil fuels offer will continue to be needed as few non-fossil alternatives exist as things stand; perhaps this points to an equivalent biomass store as a viable sustainable alternative.

It is interesting to note that when the incentives are in place, people take more notice, for example: post-tsunami power cuts in Japan have really stimulated interest in electricity and energy storage technologies.

6 Overall Conclusions

From my analysis, the uptake of plug-in vehicles looks set to add around 20-30GW of demand overnight (160-240GWh per day). However, the rising costs of motoring, as well as high upfront costs for low emissions vehicles, may cause a shift to public transport, resulting in lower demand.

The electrification of heating looks set to add even more demand for electricity than transport will, even though heat pumps are more energy efficient that conventional heating systems. Domestic energy requirements for heating are massive, but are currently supplied mainly by gas. Electrification of heating needs to be preceded by significant improvements in housing energy efficiency in order for this transition to work well.

The benefits of managing household electricity in a 'smart' manner have been shown in many analyses, although questions remain on the practicality and public acceptability of smart systems. Altered energy-use behaviours need to be long-lasting otherwise the benefits of better-optimised demand patterns will be lost. Shifting appliance use to off-peak times, including weekends, would provide significant benefits in terms of a reduced need for network reinforcements for the electricity grid. Furthermore, a lot of appliances have power surges for heating water so if water is drawn from a hot water tank then this could have peak-smoothing benefits too. Electrification of heating and transport will add high electricity demands, so having these operating in a smart manner from the outset may be sufficient to bring the benefits of smart control without having to interfere with appliance usage to a significant extent. Another important consideration is that the investment cycles in heat pumps are short so a lot of the systems could be added to demand in a short space of time. This could lead to rapid electricity demand increases in scenarios such as a gas price spike.

A range of technologies for electricity storage are possible, but only pumped hydroelectricity has been deployed on a significant scale despite significant demand for storage arising with increased renewable generation. Even the large pumped hydropower stations we have provide much less storage of energy than the stockpiles in the power station supply lines. Much more promising is the range of technologies to store heat, so improving energy efficiency of homes as well as the amount of heat storage in homes should really be a priority.

Limitations on bioenergy resources mean that electrification of transport and heating look set to be significant, even though biofuels are almost cost competitive today with oil-derived fuel. In future, biomass may also be in demand for replacement of the energy stored in stockpiles of coal and gas that exist in the supply chains of variable-output power stations.

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8. Appendix

Appendix A.1 - DECC 2050 Pathways

My analysis draws upon four future scenarios that have emerged from DECC's modelling. The pathways are described in Annex A of *The Carbon Plan* produced by DECC[3]. A MARKet ALlocation(MARKAL) model was used to find the minimal cost route to 2050 endpoints that meet the 80% emissions reductions target. The models factor in many issues but there is no consideration of biodiversity, landscape and noise impacts. The four scenarios are:

- A '*Core MARKAL*' future acts as a benchmark with which to compare other futures;
- A '*Higher Renewables; More Energy Efficiency*' future where cost of renewables falls significantly, innovations in energy storage can manage intermittency, and a large change in energy use behaviour;
- A '*Higher Nuclear; Less Energy Efficiency*' future where energy use behaviour change is only small and carbon capture and storage(CCS) is difficult to deploy.
- A '*Higher CCS; More Bioenergy'* future has successful CCS deployment and also plentiful bioenergy supplies. Bioenergy is used in CCS power stations to generate 'negative emissions'.

In the table below I list some important figures for 2050 in each scenario, sourced from *The Carbon Plan*. For comparison, Electricity Production was 381TWh and Gas Imports around 400TWh in 2010.

Model	Per capita energy saving	Electricity Demand (TWh)	Gas Imports (TWh)	Sustainable Bioenergy (TWh)[a]	Storage
Core MARKAL	50%	470	264	350	Mainly Gas
HR; MEE	54%	530	Near Zero[b]	182	400GWh (20GW) PS
HN; LEE	31%	610	around 90	461	Mainly Gas
HCCS; MB	43%	490	215	471	Mainly Gas

[a] amount of final energy demand met through sustainable bioenergy. [b] 100TWh consumed, but is produced domestically.

There are some inconsistencies between *The Carbon Plan* figures and the latest ones on DECC's *2050 Pathways Calculator* website[4], in particular in the numbers for bioenergy; this may relate to more restrictions on the use of bioenergy becoming apparent since the initial modelling. A lot of the bioenergy numbers fall to 70-100TWh imported in the latest figures.

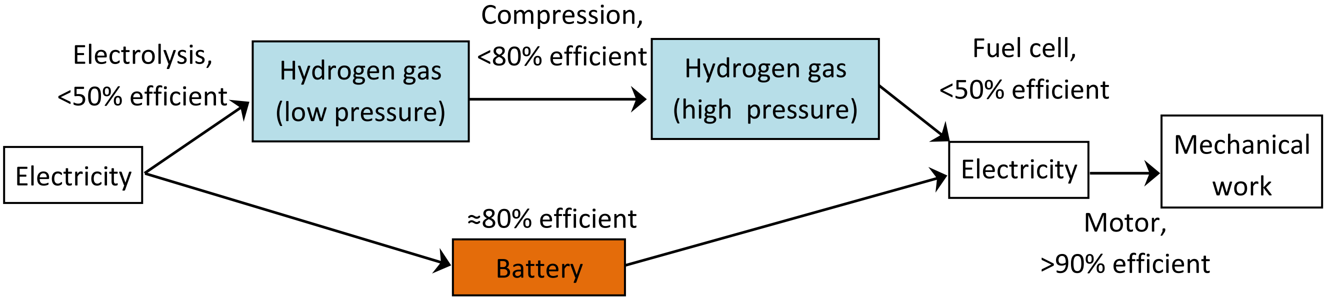
Appendix A.2 - Plug-in Vehicle Technical Specifications

Make and model	Vehicle Type	Starting Price	Battery Capacity (kWh)	Range (miles) or Energy Consumption	Details
Mitsubishi i-MiEV	EV	£23,990	20.25		
Tata Indica	EV		26.5	100	
Nissan Leaf	EV		24		
Renault Fluence	EV	£17,100	22		Battery Lease: £68/month to cover 10,000 km/year for 3 years
Smart fortwo	EV	£13,100	13.2	87 12kWh/100km	Battery Lease: £50/month
Toyota Prius Plug-in Hybrid	PHEV		4.3		
Vauxhall Ampera	E-REV	£37,250	Uses 4-12 kWh of the 16kWh capacity	360 (25-50 purely electric)	N/A
Vauxhall HydroGen 4	FCV demonstrator	TBC[a]	1.8kWh;	'further than an EV'	4.2kg of hydrogen in three carbon-fibre, 700 bar tanks
Honda Clarity	FCV	Around £100,000[b]		70kWh/ 100km	

[a] Expected 2015; [b] Not yet commercialised. Car Specification Sources:
http://www.vauxhall.co.uk/vehicles/vauxhall-range/cars/ampera/equipment_technicaldata
http://www.telegraph.co.uk/motoring/news/8953783/Vauxhall-Ampera-most-eagerly-awaited-car-of-2012.html
toyota.co.uk/Prius
http://www.autocar.co.uk/CarReviews/FirstDrives/Vauxhall-HydroGen-4-Fuel-Cell/261008/

Appendix A.3 – Hydrogen Fuel Cells

Use of hydrogen as a fuel faces challenges, for example hydrogen gas can leak through the walls of metal containers. Hydrogen supply infrastructure will be costly to implement, but there is the advantage that cars with hydrogen tanks can replenish their fuel much quicker than a battery can charge. Fuel cell vehicles also have zero emissions at the exhaust, except for water vapour. My main concern is energy efficiency. If the source of hydrogen is from electrolysis there are large energy losses in the process, as shown in the schematic adapted from [21].



Appendix A.4 – Smart Appliances

Below I list important household devices and estimates of their daily power demand, with figures sourced from (MacKay, 2009)[20]. I have multiplied by 25 million, roughly the number of households predicted for 2030, to indicate a national scale for the energy demands.

Technology	Peak Power (kW)	Average Power (kWh/day)	National Power (GWh/day)
Kettle	3	0.5	12.5
Washing Machine	2.5	0.5	12.5
Tumble Drier	2.5	0.66	16.5
Dish Washer	2.5	0.7	16.5
Oven and Stove	0.8-1.2	1.6	40
Refrigerator	0.09	1.1	27.5
Freezer	0.09	1.1	27.5
Air Conditioning	0.6	0.6	15

Appendix A.5 – Pumped Storage Facilities

Four major sites in the UK with current installed capacity of 2.8 GW, with 27.6 GWh volume[11]. Grey shading indicates anticipated future developments.

Site	Maximum Power (MW)	Energy Stored (GWh)	Operational?
Ffeistiniog	360	≈1.3	Yes
Cruachan	440	≈10	Yes
Foyers	305	≈6.3	Yes
Dinorwig	1728	≈10	Yes
Coire Glas	Up to 600	Up to 30	Submitted to planning March 2012, opens 2017?
Balmacaan	300-600	Up to 30	To be submitted to planning in 2012

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