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Blueprint for a post-carbon society:

How residential flexibility is key to decarbonising power, heat and transport

OVO energy

Imperial College London

Contents

Executive Summary

OVO and Imperial College London have examined a range of energy system scenarios and analysed the effect of adding flexibility from residential demand onto the energy system.

A time of transformative change

The UK is on the brink of the next industrial revolution. We're electrifying transport and heat and at the same time integrating more cheap, abundant renewable energy onto the system. The benefits of a post-carbon society delivered via the electrification of heat, power and transport are profound: less money spent on fuel for cars, gas for homes, and cleaner air for everyone.

Investment in our energy network infrastructure is critical to this transformation, but innovation and advancements in technology and energy storage have created new ways to manage demand. They're enabling us to shift as much consumption as possible away from peak times, when demand is highest and the grid is most congested. And they're enabling us to store cheap renewable energy when its available.

Flexible storage, located near consumption and found in electric vehicles, smart electric heating and home energy storage devices offer a perfect solution to ease grid capacity issues, and will limit the need for expensive grid upgrades and reinforcements. The energy storage found in these behind-the-meter (BTM) devices can act like an energy reservoir, soaking up cheaper renewable power that can then be used when required or released back into the grid at times of peak demand.

OVO continues to call for the Government, regulators and the industry to work together and adapt to this new energy system where supply no longer has to match demand and flexibility makes energy cheaper for everyone. For the first time ever, Imperial College London have undertaken extensive modelling to demonstrate the value that residential flexibility will bring to a post-carbon society.

Analysis by Imperial College London and OVO

This report models three energy system scenarios:

1. Burning Platform: a steady state system that sees a grid carbon intensity of 200g per kWh

2. Stepping Stone: progress made on decarbonisation and a grid carbon density of 50g per kWh

3. Future Survival: one of the most ambitious low-carbon system scenarios for the UK ever conceived and a grid carbon density of 25g per kWh

All three scenarios consider increasing levels of electrification in transport and heat. The final, and most ambitious scenario "Future Survival" envisages near complete decarbonisation across the power, residential heat and road transport sectors.

Future Survival envisages 25 million electric vehicles on the road, 21 million homes with electric heating and 93% of electricity coming from renewable energy sources. This would result in a total carbon emissions reduction of 65%. Although ambitious, it is achievable and in line with a 2°C scenario if achieved by around 2040, though we argue this could be achieved much sooner, representing a significant step towards achieving a post-carbon society.

Critically, we examine the impact on the cost of electrification if we are able to utilise the flexible energy found within electric vehicles (controlled by smart charging and vehicle-to-grid charging), home energy storage batteries, and smart electric heating. We envisage these devices being controlled and coordinated by a distributed energy management platform capable of providing grid balancing services.

Key findings

1. Residential flexibility will create whole system cost savings of £6.9bn

Adding residential flexibility to the Future Survival scenario can save whole system costs of up to £6.9bn, or 21% of total electricity system costs. These savings come from reducing the investment requirements in network infrastructure, and from using cheaper renewables like wind and solar instead of more expensive low carbon generation like nuclear and carbon capture and storage (CCS).

2. Electrification and decarbonisation will save £206 per household per year

To power the demand for electric vehicles and electric heating, the cost of the electricity sector increases by up to 40% in the most ambitious Future Survival scenario. In this scenario however, this cost increase is more than offset by displacement of the cost of fuel for transport and heat and their associated carbon emissions, resulting in potential overall savings of £5.6bn per year compared to the Burning Platform scenario. This is equivalent to approximately £206 per household whilst undergoing radical decarbonisation.

3. Intelligent charging of electric vehicles will save up to £3.5bn

Enabling smart charging using electric vehicles could save £1.1bn/ year compared to dumb, inflexible charging. Incorporating bidirectional, vehicle-to-grid charging could save £3.5bn, a nearly 4x increase.

4. Smart electric heat alone will create a £3.9bn saving

Adding the flexibility from thermal storage to electric heating can save £3.9bn in total system costs, and represents one of the lowest cost pathways to heat decarbonisation.

5. Residential flexibility and low cost renewables are the perfect partnership in a post-carbon society

In low carbon scenarios, residential flexibility can be used to balance the variability of low cost renewables, almost entirely displacing the need for higher cost low carbon generation such as CCS and nuclear.

Results of cost savings by residential flexibility

Cost savings (£bn) of residential flexibility in:

	Burning Platform	Stepping Stone	Future Survival
Smart charging	0.1	0.52	1.13
V2G	0.14	1.39	3.47
Smart heating	0.51	2.70	3.9
Residential battery storage	0.35	1.37	2.93
All BTM options	0.80	4.36	6.87

What's next?

The modelling shows that unleashing flexible energy at a residential level will be critical to reducing the cost of decarbonisation in the UK. With new technologies like electric vehicles, smart electric heat and home energy storage, consumers can actively participate and engage in the energy transition, whilst saving themselves and others, billions of pounds.

The biggest challenge to extracting the value of these technologies is the lack of route to market and revenue streams for residential flexibility.
To achieve decarbonisation at least cost, regulatory and market changes are required in order to facilitate the adoption of these technologies, in line with OVO Energy's Flexibility First proposals[1].

[1]Flexibility First blog - https://www.ovoenergy.com/ovo-newsroom/press-releases/2018/july/industry-calls-for-changes-to-energy-networks-regulations-to-unleash-flexibility-revolution.html

Context and objectives

A time of transformative change

The UK energy system is undergoing a fundamental transformation in response to a range of drivers;

Government decarbonisation commitments

- In order to meet climate change goals set out in the 2015 Paris Agreement and remain within the emissions envelope of a 2°C warming scenario, UK carbon emissions must peak within the very near future and reach near zero levels

Electrification of everything

- The shift to EVs will have a profound impact not only on transport but on the energy system as a whole. Energy currently delivered by petrol will be shifted to the power sector
- Many other sectors that use fossil fuels will shift to electricity, including heating and cooling

Exponentially falling renewable energy and storage costs

- The cost of distributed renewable energy like wind, solar and energy storage has fallen to the point where they now compete on cost with fossil fuels for new build plant
- Greater renewables will increase the system flexibility requirements to ensure the system can efficiently maintain secure and stable operations in a lower carbon system

IoT and intelligence

- Smart metering is already creating massive increases in data volumes
- Everything will be internet connected and smart, enabling new business models such as demand-side response

What do we mean by flexibility?

System flexibility

System flexibility is the ability to adjust generation or consumption in order to maintain the secure operation of the energy system. It will be the key enabler of the energy system's, cost effective, low carbon transformation.

A recent study undertaken by Imperial College into flexible resources, demonstrated the system wide benefits of integrating new sources of flexibility relative to the use of conventional thermal generation-based sources. Cost savings achievable by accessing these new sources of flexibility include:

- Reduced investment in low-carbon generation, as the available renewable resource and nuclear generation can be utilised more efficiently, enabling the system to reach its carbon target with less low carbon generation capacity;
- Reduced system operation cost, as various reserve services are provided by new, cheaper, flexibility sources rather than by conventional generation; and
- Reduced requirement for distribution network reinforcement and backup capacity.

Why is OVO looking at residential flexibility?

OVO believes that most flexibility will be found at a residential level via behind-the-meter (BTM) technologies. This includes battery storage or DSR associated with smart EV charging or smart residential appliances. These will be an integral part of the customers' home energy systems.

The way these resources are utilised could be very different from the dedicated flexible assets with separate metering, connected at higher voltages in the distribution network. In addition to system needs, BTM flexibility will also be driven by the incentives and tariff structures the customers are exposed to.

Previous work from Imperial College London on behalf of the National Infrastructure Commission indicates that flexibility provided by smart technologies such as demand response and batteries can lead to savings of up to £8bn a year in scenarios with high renewables penetration[2]. National Grid's Future Energy Scenarios 2018 also analyse two credible pathways to achieving our 2°C commitments, both of which envisage increased battery storage, demand response and other forms of system flexibility.

[2] https://www.theccc.org.uk/wp-content/uploads/2017/06/Roadmap-for-flexibility-services-to-2030-Poyry-and-Imperial-College-London.pdf

What makes this report different?

Our modelling builds on this previous work in two directions;

Firstly, we examine a scenario with particularly high uptake of both electric vehicles and electric heat, in addition to a high penetration of renewable power generation, resulting in ultra-low total system emissions, representing the most ambitious scenario ever modelled in detail for the UK.

Secondly, whereas previous studies have looked at commercial scale flexibility, we assess the impact of incorporating intelligence and flexibility at the residential level. We compare energy system costs depending on whether the inherent flexibility of electric vehicles, smart electric heating and home energy storage is used to provide grid balancing services or not.

Objectives

The study evaluates the potential system benefit of large-scale deployment of BTM flexible resources, including battery storage, smart appliances, smart EV charging and flexible heating demand. The evaluation will contrast the benefits to those of large-scale flexible solutions, and includes a range of plausible scenarios for future decarbonised UK energy systems.

Key objectives of the study include:

- Establish the viability or otherwise of ultra-low emission scenarios with high electrification.
- Understand the relative importance of small scale but high volume BTM flexibility at the residential level, compared with more centralised, typically 'front-of-meter' flexibility.
- Understand the system benefits of smart electric vehicle charging and understand the relative importance of V2G versus one directional smart charging.
- Understand the benefit of incorporating low-cost thermal storage with electric heating.

This study will also consider whether the full potential value of BTM flexibility can be captured through the current market mechanisms and whether the current regulatory and market arrangements represent a barrier for full utilisation of BTM flexibility.

The results are used to highlight the feasibility of ultra-low carbon energy scenarios, the potential role for consumers in the energy system, and the ongoing regulatory barriers to achieving low-cost decarbonisation that need to be addressed.

A note on modelling

The central means of analysis used in this study is the "WeSIM" whole energy system model developed by Imperial College. Whole energy system modelling has recently emerged as a beneficial means for policy makers, investors and industry to compare energy technology choices based on their engineering feasibility and economics. Multiple energy system modelling studies for the UK have been conducted by various groups including National Grid's Future Energy Scenarios, the ENA's Open Networks Project, and Imperial College London's previous reports.

Scope of the report

The study models the technical and economic viability of different scenarios for the power, heating and road transportation sectors. Removing greenhouse gasses from other parts of the energy system such as aviation, shipping, agriculture and industrial processes whilst discussed briefly, are out of the scope of this project and will be the subject of future work.

Scenarios, key assumptions and methodology

Selection of baseline scenarios

Credible future development scenarios have been selected for analysis. The starting assumptions in these scenarios are largely taken from National Grid's Future Energy Scenarios (FES 2017) for the UK power system. In total, 3 main scenarios have been explored.

For each of these 3 scenarios, the starting conditions were adjusted for increasing levels of electrification and and the levels of nuclear and CCS were allowed to vary from a baseline of zero.

Summary of starting assumptions for the baseline assumptions:	Burning Platform	Stepping Stone	Future Survival
	200g / kWh	50g / kWh	25g / kWh
	3m EVs	17m EVs	25m EVs
	4m electrically heated homes	12m electrically heated homes	21m electrically heated homes

Grid carbon intensity	**200g / kWh**	**50g / kWh**	**25g / kWh**
FES 2017 scenario (starting point)	**SS 2030**	**TD 2032**	**TD 2040 for gen**
Starting generation capacity (GW):			
Nuclear:	**1.2**	**11.3**	**15.8**
Wind:	**29.3**	**42.9**	**49.6**
PV:	**15.4**	**29.5**	**35.2**
CCS:	**-**	**2.7**	**8.3**
Interconnection (GW)	**9.8**	**18.5**	**19.7**
Storage (GW)	**5.8**	**8.8**	**9.5**
Electricity demand (gross, TWh), of which (m, homes):	**339.0**	**372.3**	**411.1**
EVs:	**4.6 (3.1)m**	**25.3 (16.9)m**	**37.4 (24.9)m**
Heat pumps:	**3.3 (1.1)m**	**29.0 (9.3)m**	**61.8 (19.8)m**
Resistive heating:	**33.7 (3.4)m**	**31.4 (3.1)m**	**15.1 (1.5)m**

Residential flexible technology

Having established these baselines, we apply our whole-system modelling approach to run detailed quantitative studies on whole-system benefits of BTM flexibility for the scenarios and sensitivities[3] selected. This analysis quantifies and breaks down into components the cost savings available in the future UK electricity system from the deployment of various flexible BTM solutions. For each type of behind the meter flexibility, we run cost optimisation routines on the following options allowing the generation mix and level of interconnection to vary within the constraint of the level of grid carbon, and compare with the baseline scenario.

	Option	Assumption
1.	**Baseline**	None of the below options are included
2.	**Smart EV Charging**	50% of EVs allow their charging demand to be shifted (80% in FS scenario)
3.	**Vehicle-to-grid (V2G)**	Same as #2 + EVs can also support V2G services (incl. frequency response)
4.	**Smart heating**	50% of electrically heated homes have ~3 hours worth of thermal energy storage (4 hrs in FS scenario)
5.	**Residential batteries**	1m households install 5 kW Li-ion battery totalling 5GW (2m and 10GW in FS scenario)
6.	**All BTM options**	Options 3-5 combined together

This allows us to assess the value of BTM flexibility and identify the sources of savings such as operating costs or avoided infrastructure investment costs. It also allows for a comparison between relative merits of these solutions from the whole-system perspective, and provides an insight into how the value of these solutions change as a function of the assumed system evolution scenario (for instance, to which extent the penetration of variable RES or electrification of heat and transport boost the system value of behind-the-meter flexibility).

The key results of the cost optimisations for each of the 3 scenarios are set out in the following section.

[3] A scenario is a defined set of input assumptions; a sensitivity is a change to one or more of the assumptions within a scenario to determine the impact on outputs.

Key findings

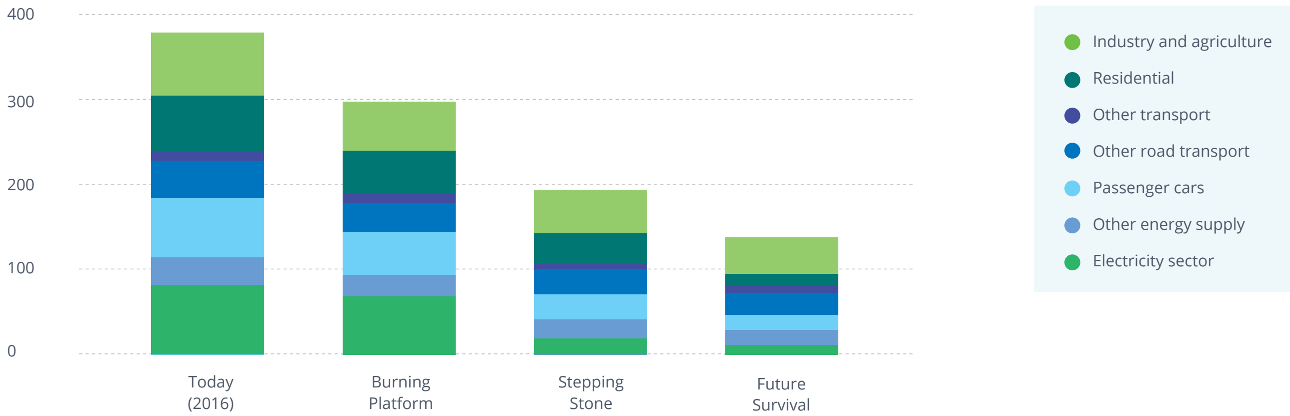
Carbon emissions

We have estimated the carbon emissions by sector for each scenario[4].

Our most ambitious scenario, sees carbon emissions of 138 $MtCO_2e$ compared to today's level of 379 Mt CO_2e, a reduction of 64%

These reductions are as a result of highly significant reductions across the power, heat and transport sectors. In particular we have forecast a high uptake of electric vehicles and residential electric heating. This scenario represents near complete decarbonisation of the power, residential heating and road transport (cars) sectors. As we discuss in conclusions, achieving this scenario would be a strong platform for further, complete decarbonisation of the energy system through electrification.

Total carbon emissions ($MtCO_2e$)



Benefits of residential flexibility

To establish baseline scenarios, the model ran optimisations on the level of generation capacity within the constraints of achieving the 3 different levels of grid carbon intensity (200, 50 and 25 gCO_2/kWh) whilst accommodating the level of EV, electric heat and battery uptake as defined in the assumptions.

From the 3 baseline scenarios described above we examine the 5 variations outlined above incorporating different types of residential BTM flexibility connected to the low voltage distribution network. The generation stack has been varied in each scenario to achieve the lowest cost scenario.

[4] See Appendix 3 for assumptions

Scenario 1

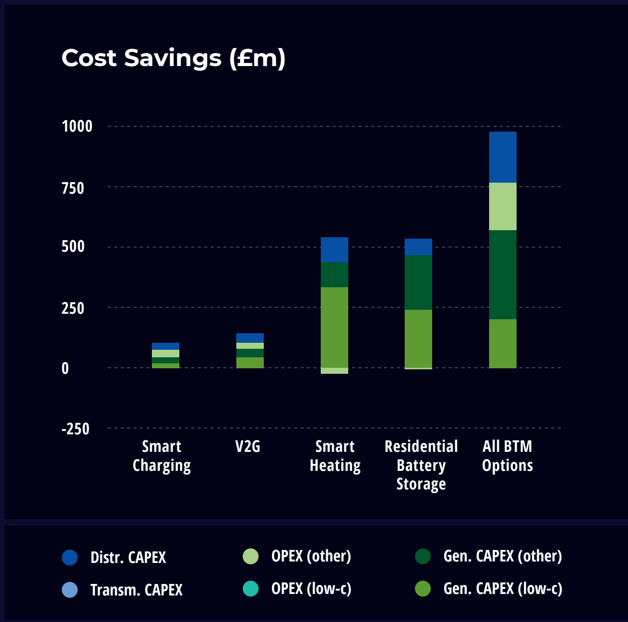
Burning platform

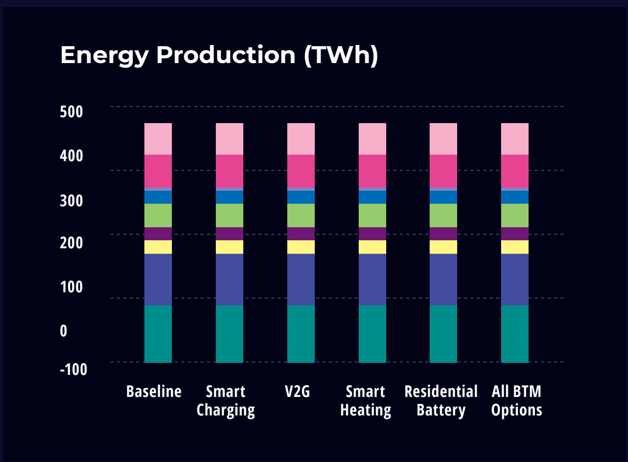
£500m savings in smart heat

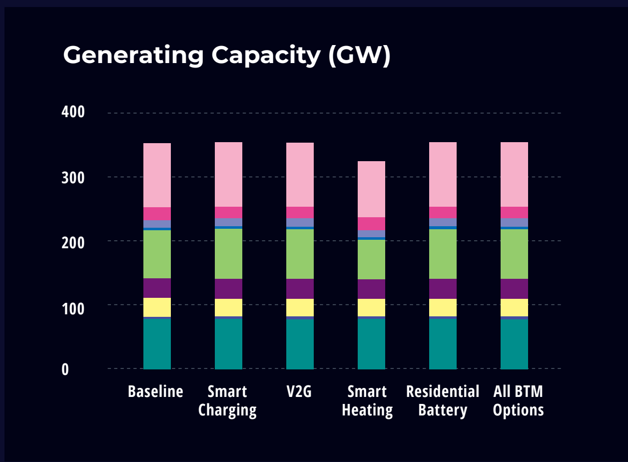
‹£1bn close to £1bn saved in total

As has been shown in previous work by the National Infrastructure Commission[5], the impact of flexibility is less pronounced in scenarios with lower quantities of renewable generation. Still however, there is a significant impact even on the 200g/kWh Burning Platform scenario.

Smart charging and V2G lead to annual savings of £100m and £150m respectively resulting from reduced capex requirements for generation and distribution. The impact of smart heating is more pronounced, resulting in £500m of savings, the largest share of which comes from improved utilisation of solar energy, meaning a reduced amount of solar PV capacity is required to reach the same grid carbon level. Adding residential batteries also saves £500m, and combining all options would save close to £1bn annually.







[5] https://www.nic.org.uk/news/ministers-must-seize-the-golden-opportunity-to-switch-to-low-cost-energy/

Interconnection OCGT Storage Hydro Other RES Biomass PV Offshore wind Onshore wind Nuclear Gas CCS CCGT

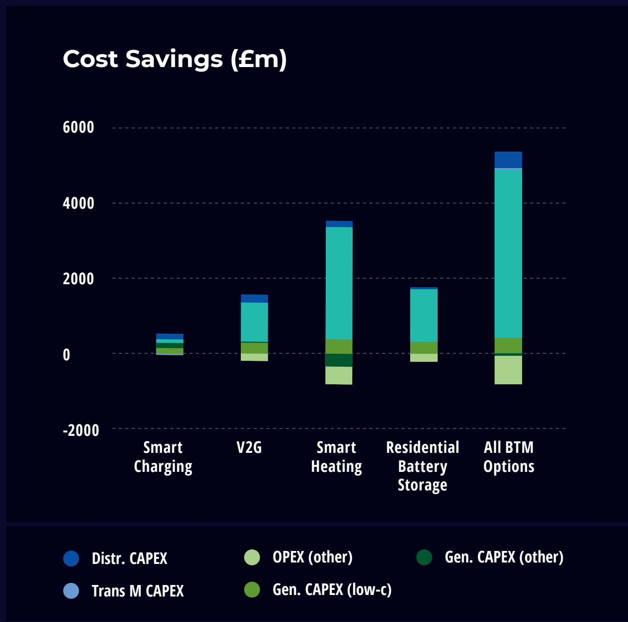
Scenario 2
Stepping stone

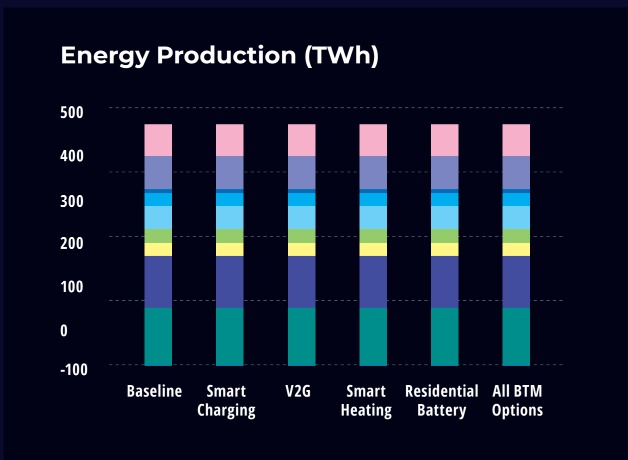
£1.4bn
saved by V2G charging

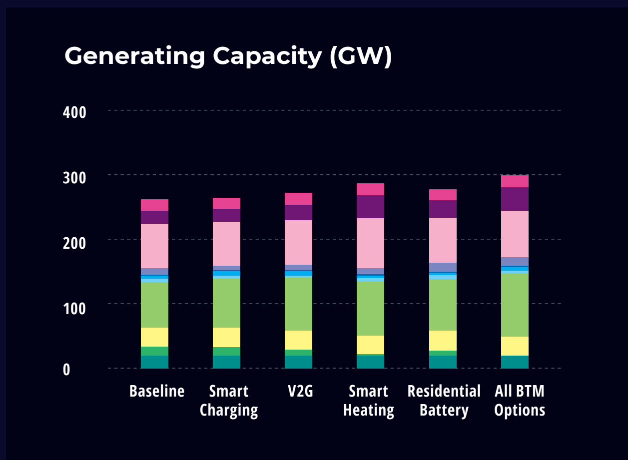
£4.4bn
saved in total

In the Stepping Stone scenario, which has a much larger proportion of low carbon generation, the impact of flexibility is more significant because flexibility enables higher cost, low carbon generation such as nuclear and CCS to be displaced by lower-cost renewables. In this scenario, residential flexibility leads to cost savings from a combination of reduced generation CAPEX requirements, reduced distribution network CAPEX and reduced operating costs of low carbon generation (nuclear and CCS).

Relative to the baseline, smart charging and V2G lead to system savings of £0.5bn and £1.4bn respectively as a result of the greater flexibility provided by V2G. Smart heating provides £2.7bn of savings, which is due to the flexibility enabling low cost renewables (primarily offshore wind and solar) to displace CCS and nuclear. Combining all options leads to highly significant savings of £4.4bn annually.
This figure can be compared to a previous Committee on Climate Change report[6] where similar analysis demonstrated savings of up to £7.8bn in a high renewables (50gCO2/kWh) scenario by incorporating commercial front-of meter batteries. This analysis indicates that a very significant portion of the benefit of flexibility can in fact be delivered at the residential, low-voltage level.







[6] https://www.theccc.org.uk/wp-content/uploads/2017/06/Roadmap-for-flexibility-services-to-2030-Poyry-and-Imperial-College-London.pdf

Interconnection · OCGT · Storage · Hydro · Other RES · Biomass · PV · Offshore wind · Onshore wind · Nuclear · Gas CCS · CCGT

Scenario 3

Future survival

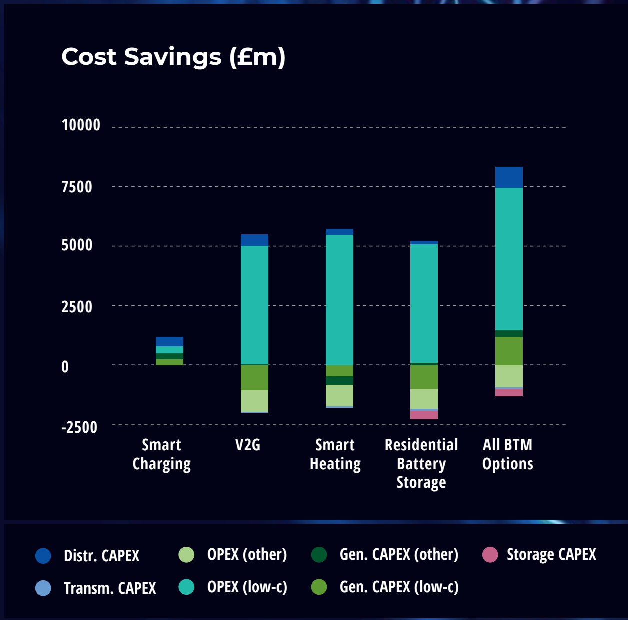
cheaper renewables

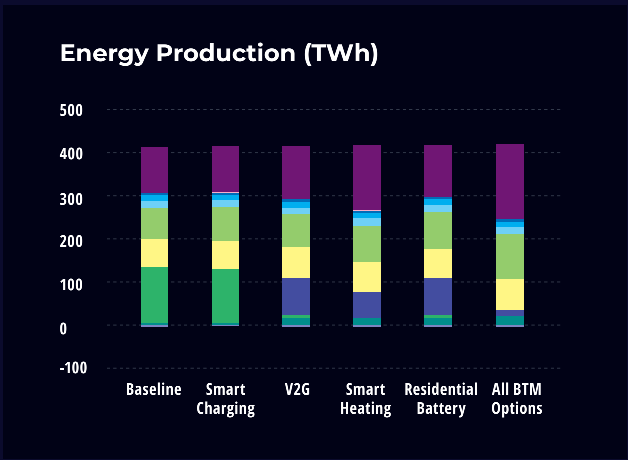
£6.9bn
saved in total

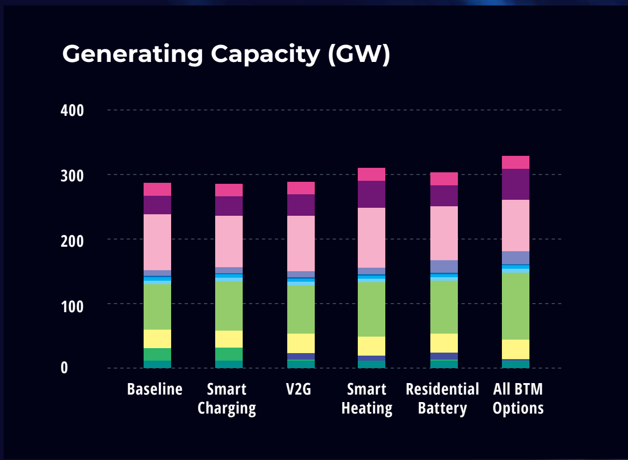
The future survival scenario which has near complete electrification of residential heat and transport demonstrates the greatest value of residential system flexibility. V2G leads to savings of £3.5bn/year, compared to smart charging at £1.1bn. Smart heating leads to savings of £3.9bn/year resulting from the displacement of CCS with other low-carbon generation. Residential battery storage can contribute savings of £2bn from displacing Open Cycle Gas Turbines (OCGTs) and CCS.

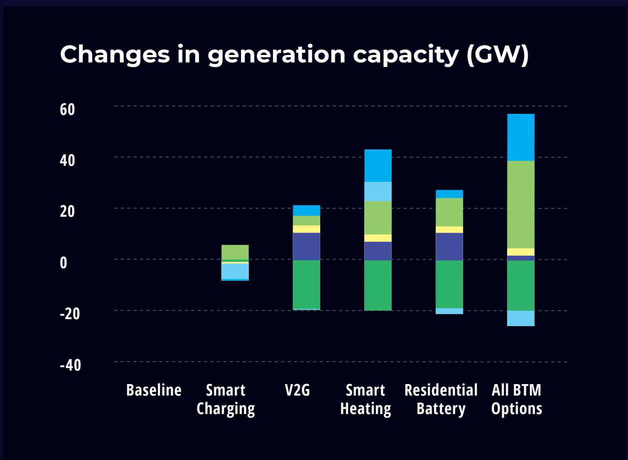
Combining all options contributes savings of £6.9bn, relative to the Future Survival scenario baseline with no flexibility, which represents approximately 21% of total electricity system costs. Distributed equally across all households in the UK, this saving equates to £256 per household.

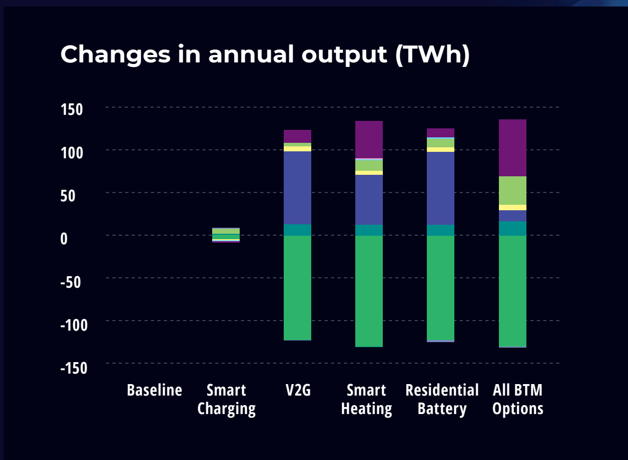
The figures below show the changes in generation capacity and annual output vs the baseline 25g/kWh scenario. This shows that where all the behind the meter options are included, generation from nuclear and CCS are displaced by increased capacity and output from wind and PV.











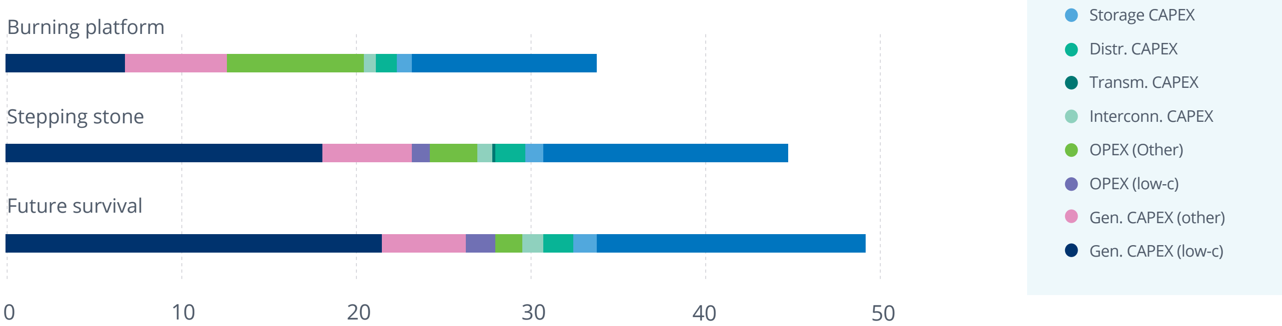
Interconnection · OCGT · Storage · Hydro · Other RES · Biomass · PV · Offshore wind · Onshore wind · Nuclear · Gas CCS · CCGT

Total System Cost Comparison

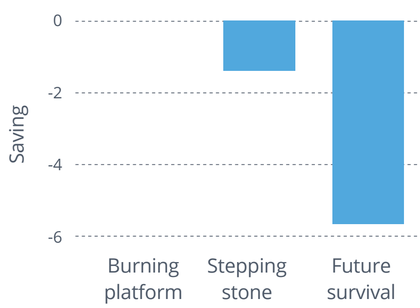
Total system costs have been estimated in order to analyse the relative cost of each scenario[7]. As expected, as the size of the electricity sector grows to meet the increased demand from electrification and decarbonisation, the cost of the electricity system increases significantly. Comparing the scenarios incorporating 'All the BTM' solutions shows that the total electricity system costs increase from an estimated £33bn under the Burning Platform scenario to £48bn in the Future Survival case (see Appendix 3 for assumptions). At the same time however, the transition to electrification leads to savings in fuel and carbon costs. In the Future Survival scenario, fuels savings are £14.1bn for road fuel and £9.6bn for gas for heating. Carbon cost savings are also significant at a total of £5.6bn for both road fuel and gas. We have also incorporated an estimate for the additional CAPEX and OPEX of replacing gas boilers with heat pumps in their regular replacement cycle.

Evaluating all of these costs reveals overall savings of 5.6bn in the Future Survival scenario relative to the Burning Platform. This reflects the improved cost efficiency and costs of electric vehicles and heat pumps and clearly highlights the benefits to consumers, representing overall potential savings per household of approximately £206 by switching to the Future Survival scenario incorporating high levels of low carbon, electric technologies.

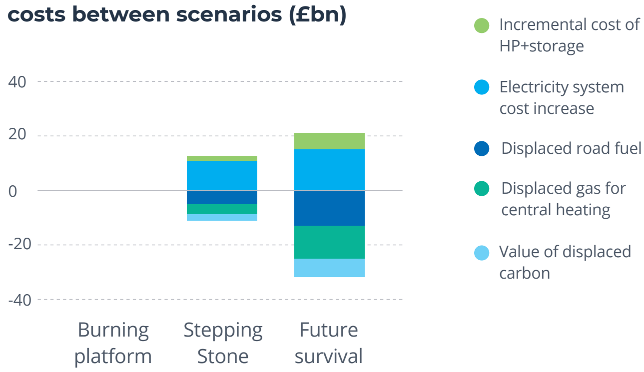
Electricity system cost breakdown (£bn)



Relative system costs (total) (£bn)



Relative change in total system costs between scenarios (£bn)



[7] See Appendix 3 for assumptions

Implications

Power

The analysis presented here demonstrates that it is possible to design an enlarged and decarbonised power system capable of supporting an electrified heating and transport sector. In a low-carbon scenario, adding flexibility enables lower cost low carbon generation such as solar and wind to displace higher cost low carbon generation such as nuclear and carbon capture and storage. In the Future Survival scenario, we demonstrate that ultra-high penetrations of renewable energy are possible if residential flexibility from smart EV charging and smart heating is incorporated. This shows that the electrification of transport and heat can play an important role in the decarbonisation of the power sector.

Road Transport

There are several implications of this analysis for the transport sector. The results demonstrate that the power sector is capable of cost effectively supporting electrification of road transport on a massive scale, whilst undergoing near complete decarbonisation. Furthermore, both smart charging and V2G technologies lower the cost of decarbonising the power sector. In relative high-carbon scenarios, smart charging and V2G can be used to offset distribution network upgrade costs and gas peaking plant. In low carbon grids, the benefit of flexibility shifts to enabling the replacement of expensive low carbon generation with lower cost renewables like wind and solar.

Interestingly, the analysis shows the relative value of bi-directional, vehicle-to-grid charging compared to single directional smart charging. In all scenarios, V2G is worth more to the energy system than smart charging for the same number of participating vehicles due to the greater amount flexibility provided. This difference in value increases as the proportion of renewables and number of EVs increases as shown in the table below;

		Energy system benefit (£bn/yr)		Benefit per participating vehicle (£/yr)	
Scenario		Smart Charger	V2G	Smart Charger	V2G
Burning platform	(assumes 50% participating vehicles)	0.1	0.15	65	97
Stepping stone	(assumes 50% participating vehicles)	0.5	1.4	59	166
Future survival	(assumes 80% participating vehicles)	1.1	3.5	55	176

Heat

Heating represents 30% of total UK carbon emissions and is often cited as the most challenging aspect of decarbonisation given the prevalence of fossil-fuel based heating in UK buildings. A recent study by the Committee on Climate Change[8] reviewed multiple pathways and concluded that electrification of heating was the lowest cost option to decarbonising this sector compared to hydrogen based options. This study builds on previous work by examining the interaction of electric heating with other residential demand side flexibility from EVs and batteries, and by examining a scenario of ultra-high penetration of electric heat with thermal storage. This study incorporates 20 kWh of thermal storage per property (4hrs), a total of 0.20 GWh and power capacity of 49 GW in the Future Survival model. The flexibility provided by the thermal storage saves system costs of £3.9bn, largely coming from replacing high cost CCS with wind and solar PV in the generation strack. This value equates to approximately £394 per participating household per year.

Residential batteries

We have modelled a small proportion (2m, 7%) of UK homes with residential battery storage. This small number results in significant savings for the energy grid of £2.9bn in the Future Survival scenario. This represents a value of £1450 per participating household.

Other sources of emissions

The scope of the analysis conducted here was limited to the power sector, residential heating and road transport. Other sources of carbon and non-carbon greenhouse gas emissions such as aviation, shipping, agriculture and industrial processes will be the subject of future works.

What the study shows is that the power system is capable of growing to meet increased demand from electrification of fossil-fuel based processes whilst at the same time decarbonising through a major expansion in renewable energy. This transition is greatly supported by flexible demand.

Therefore, this analysis should provide incentive for further research and development into electrification of all processes that use fossil fuels as their primary source of energy. Whilst still at an early stage, efforts to develop electrification in shipping, aviation and agriculture are already underway, pointing towards an all-electric post carbon future.

[8] https://www.theccc.org.uk/publication/analysis-of-alternative-uk-heat-decarbonisation-pathways/

Current barriers and policy recommendations

It is hoped that this analysis may be beneficial to policy makers by providing evidence of the value of residential flexibility and the role that it can play in the decarbonisation of heat and transport. By quantifying the inherent value to the energy system of residential flexibility, this sets a benchmark for the value from these devices that should be realisable through markets for flexibility services.

The biggest challenge to propagation of residential flexibility is the lack of route to market to grid balancing revenue streams from these devices. It is currently not possible to access the full system value identified by this study via existing flexibility markets, indicating a failing. Regulatory and market changes are required in order to facilitate the adoption of these technologies.

In the UK's current market structure revenue for flexibility services comes from three primary routes; (i) the (Electricity System Operator) ESO, responsible balancing on short timescales, (ii) arbitrage in wholesale energy markets and (iii) newly formed Distribution System Operator (DSO) services. All of these areas are currently undergoing significant review and reform, and several recent consultations such as RIIO-2 consultation, charging futures Significant Code Review and the Capacity Market 5-year review, directly influence flexibility services.

At present, various market rules prevent aggregators from accessing national grid ESO ancillary services. DSO services are nascent and limited, and wholesale energy market structures could be improved to enable participation of residential flexibility.

We are calling for policy makers and regulators to adopt a 'flexibility first' approach to prioritizing flexibility. It is therefore hoped that the evidence presented here will help inform policy makers about the need to support the growth of residential flexibility.

Conclusions

By modelling the technical and economic aspects of a variety of energy system scenarios, this study provides a range of insights into the potential role of small scale, BTM flexibility in a near complete decarbonised society. A summary of key findings;

This study shows that the electricity system is capable of growing to meet increased demand from complete electrification of residential heating and road transport, powered by high penetrations of renewable energy. Furthermore, this decarbonised, all-electric scenario results in significant cost savings compared to higher carbon scenarios.

In all scenarios, the use of residential flexibility is shown to significantly reduce the cost of the electricity system.

In higher carbon energy systems, residential flexibility leads to cost savings by displacing distribution network infrastructure costs and the need for traditional sources of flexibility i.e. thermal generation.

In lower carbon energy systems, residential flexibility leads to significantly greater savings by enabling the greater utilisation of lower cost low carbon generation sources such as solar and wind, displacing the need for high cost low carbon generation such as nuclear and CCS.

Both smart electric vehicle charging and V2G charging can provide significant system savings, but in some scenarios, V2G can provide up to x4 times the value per vehicle versus single directional smart charging.

Smart electric heat can provide enough flexibility to enable renewable generation from wind and solar displace the need for both nuclear and CCS, whilst providing savings of up to £3.9bn / year

In the lowest carbon and highest flexibility scenario analysed, the greatest saving achieved from residential flexibility was £6.9bn / year. This represents a very significant portion of the total benefit that can be gained from flexibility on any scale, demonstrating that residential flexibility can have a major impact on our energy system. This highlights that consumers can play a critical role in shaping our energy system, and ultimately in our fight against climate change.

Appendix

A1 Assumptions on generation technologies

The assumptions on the levelised costs of energy (LCOE) for low-carbon generation technologies used in the study are specified in the second column of Table 1. For the three renewable technologies (offshore wind, onshore wind and solar PV) the LCOEs were based on recent evidence provided by Aurora Energy Research[1] and Bloomberg New Energy Finance[2], and were also informed by discussions with the CCC and BEIS. For nuclear and CCS generators the costs were taken from the most recent BEIS Electricity Generation Costs estimate[3]. The costs of variable renewables were assumed so as to reflect the significant recent cost reductions seen in the CfD auctions in the UK and in the costs of renewable projects in continental Europe and internationally.

The maximum capacity factors for different low-carbon technologies assumed in the study are specified in the third column of Table 1, and reflect typical UK utilisation factors for wind and PV generation, as well as 90% annual availability for nuclear and CCS generation to account for planned maintenance.

Table 1. Assumptions on LCOEs for low-carbon generation technologies

Technology	LCOE (£/MWh)	Capacity factor
Offshore wind	57.5	41.9%
Onshore wind	45	27.2%
Solar PV	40	11.9%
Nuclear	94	90.0%
CCS	102	90.0%

[1] Aurora Energy Research, "Prospects for subsidy-free wind and solar in GB", March 2018. https://www.auroraer.com/insight/prospects-subsidy-free-wind-solar-gb/

[2] Bloomberg New Energy Finance, "Flexibility gaps in future high-renewable energy systems in the UK, Germany and Nordics", report for Eaton and Renewable Energy Association, November 2017. https://uk.eaton.com/content/content-beacon/RE-study/GB/home.html

[3] BEIS Electricity Generation Costs (November 2016), https://www.gov.uk/government/publications/beis-electricity-generation-costs-november-2016.

A2 Description of WeSIM modelling

In order to carry out this study, we use the Whole-electricity System Investment Model (WeSIM) developed by Imperial College, which is specifically designed to perform this type of analysis. WeSIM has been extensively tested in previous projects studying the interconnected electricity systems of the UK and the rest of Europe.

WeSIM simultaneously optimises system operation decisions and capacity additions to the system, while taking account of the trade-offs of using alternative measures, such as DSR and storage, for real-time balancing and transmission and distribution network and/or generation reinforcement. For example, the model captures potential conflicts and synergies between different applications of distributed storage in supporting intermittency management at the national level and reducing necessary reinforcements in the local distribution network.

The optimal decisions for investing into generation, network and/or storage capacity (both in terms of volume and location) are based on modelling the real-time supply-demand balance in an economically optimal way while ensuring security of supply. Capturing the interactions across different time scales and across different asset types is essential for the analysis of future low-carbon electricity systems that include alternative balancing technologies such as storage and demand side response.

A3 Description of total system carbon and cost assumptions

Carbon assumptions

- Today's carbon emissions by sector are taken from UK Government statistics for 2016[9]
- For industry sectors outside the scope of this report, we have assumed general efficiency improvements in emissions of 20, 30 and 40% for BP, SS and FS scenarios respectively relative to today's levels.

Cost assumptions

- Total system cost consists of investment cost (CAPEX) of generation, storage, interconnection, transmission and distribution infrastructure plus the operating cost (OPEX) for power generation.
- Total system cost refers to the annual CAPEX and OPEX required to deliver electricity at the lowest cost, where all investment costs are annualised using appropriate lifetime and discount rate assumptions.[1]
- Within the total annual system cost the CAPEX values for generation, storage and interconnection assets apply to their entire capacities (i.e. both existing and those added by the model), while transmission and distribution CAPEX only include incremental or reinforcement cost above the current situation. In other words, the total system cost does not include the investment costs associated with the existing transmission and distribution infrastructure.[2]
- Generation CAPEX and OPEX is separated into low-carbon technologies (wind, PV, nuclear and CCS) and conventional or other technologies (CCGT and OCGT).

[1] The approach with minimising the annualised system cost is equivalent to assuming the year in question will repeat itself in perpetuity.

[2] Although this slightly diminishes the completeness of reported total system cost figures, it allows for an identification of key drivers for changes in total system cost across scenarios, also enabling the quantification of system benefits of flexibility by looking at differences between scenarios, where the cost associated with fixed (i.e. existing) infrastructure is not relevant.

[9] https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-2016

A4 - Intraday system balancing

The below figures illustrate the impact of residential flexibility on the energy system over a period of several days. The below figures are from the Future Survival scenario showing behaviour of the energy system in a high-wind, winter week and a high-solar, summer week. Comparing the demand (black dotted line) with demand + DSR (dark solid red line) illustrates how all the behind the meter flexibility options respond to grid requirements.

Winter week (22-28 January)

Baseline

All BTM options

Use of CCS as baseload

CCGT and OCGT meeting peak demand

Interconnection predominantly used for imports

Energy storage performing daily arbitrage

Small amount of nuclear used as baseload

No CCS

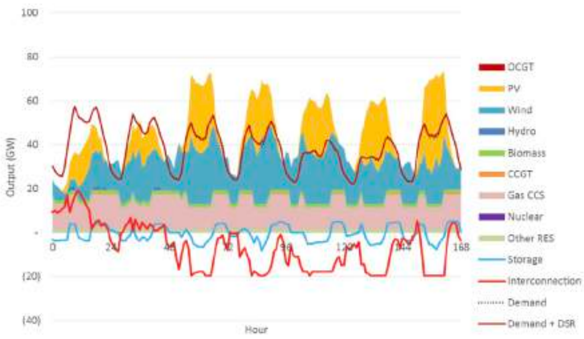
CCGT operating more continuously and OCGT running less

DSR actions (smart heating and smart charging) substantially reduce peak demand

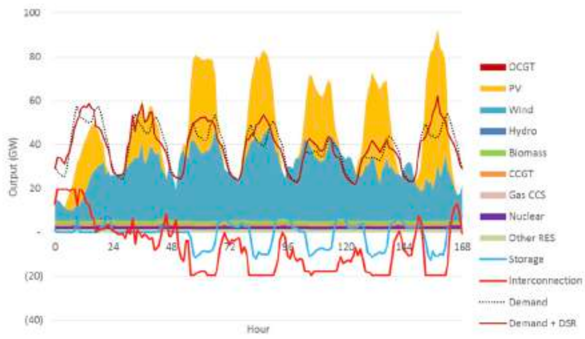
For further information on the methodologies and assumptions please see previous research papers (such as the Roadmap for flexibility services compiled by Imperial College London for the Committee on Climate Change[10]) or contact us directly.

Summer week (25 June – 1 July)

Baseline



All BTM options



Use of CCS for cycling

Interconnection and storage capturing peak PV output

More PV on the system, but also more storage to absorb fluctuations

DSR actions also shifting load towards periods of peak PV output

[10] https://www.theccc.org.uk/wp-content/uploads/2017/06/Roadmap-for-flexibility-services-to-2030-Poyry-and-Imperial-College-London.pdf

Glossary

Terminology	Meaning
Behind-the-meter (BTM)	Refers to technologies or services that reduce the amount of energy being purchased directly. For example, by making energy efficiency upgrades to reduce usage, storing and selling excess energy back to the grid, installing renewable technologies to generate energy onsite and installing energy storage units.
CAPEX	Capital Expenditure
CCGT	Closed Cycle Gas Turbine
CCS	Carbon Capture and Storage
DSO	Distribution System Operator
ESO	Electricity System Operator
Grid balancing	The ability to match the supply of energy to demand
HES	Home Energy Storage
National Grid's Future Energy Scenarios (FES)	FES are a series of pathways projected by the National Grid to help the Government make decisions about energy and environment reform and legislation
OCGT	Open Cycle Gas Turbine
OPEX	Operation Expenditure

Terminology	Meaning
Paris Agreement	The Paris Agreement central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.
Residential batteries	A home energy storage device that has the ability to store electricity for self-consumption, time of use load shifting, backup power, and off-the-grid use.
Residential flexibility	Energy flexibility in the home provided by smart technologies such as demand response and storage batteries
Smart electric heating	Smart electric heat is an electric heating system with storage that is connected to a distributed energy management platform. This enables participation in grid balancing and smart tariffs, and provides improved user control and comfort.
Smart EV charging	Charging that allows Electric Vehicles to interact with the grid to help manage the increased demand for electricity
V2G	'Vehicle to grid' technology, also referred to as 'V2G' enables energy stored in electric vehicles to be fed back into the national electricity network (or 'grid') to help supply energy at times of peak demand.

For further information, please contact **media@ovoenergy.com**