The Oxford Martin Programme on Integrating Renewable Energy

Synthesis Report

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INTRODUCTION

1. Welcome to the Integrate Programme

Electricity systems around the world are going through a fundamental transition, as countries seek ways to address climate change, and meet the goals of the Paris Agreement by integrating renewables into energy systems. Never before have the roles of citizens, civil society, businesses, and governance been so important in shaping the energy transition. We must overcome many challenges to achieve our goal of a low carbon energy system. These challenges cover a range of technical, social, economic, and governance issues.

The Oxford Martin Programme on Integrating Renewable Energy, **Integrate**, has delivered a deliberately multidisciplinary programme to examine these challenges and find potential solutions. Our approach looked beyond just the technology, to look at the whole energy system, bringing together people from different perspectives to address these challenges.

The Integrate community is drawn from across the University, and the energy industry. Participants within the University of Oxford were drawn from the Environmental Change Institute, Energy and Power Group, the Department of Materials and the Institute for New Economic Thinking. The community gathered for regular meetings, to discuss active research and collaboration, and new aspects and opportunities. We heard from invited speakers across a range of energy related topics with whom we could exchange and learn from; gaining different perspectives on energy issues. This inter-disciplinary working is a significant factor in the Programme's success.

The Programme has benefited from an engaged Advisory Board which included representatives from Ofgem, the Oxfordshire Low Carbon Hub, Energy Systems Catapult, National Grid ESO and independent energy experts. There were also many external partners from organisations including major players in the energy sector such as Siemens, National Grid, Ofgem, Scottish and Southern Energy, UKERC, RWE, E-on, Scottish Power, Arup, DONG energy, and Mainstream Renewable Power.

This Synthesis Report showcases findings from the Programme with links to where more information and resources can be found. Our key messages are that:

- Solar and wind are becoming the cheapest forms of electricity generation and will be key to a low carbon energy system, together with storage and flexibility;
- Use will depend critically on integrating variable generation into electricity networks;
- Any solution will involve a mix of flexible generation, flexible demand, inter-connection and storage; and
- Changes are urgently needed to energy market design, regulation and governance to accelerate decarbonisation and the ability to meet Net Zero emissions by 2050.

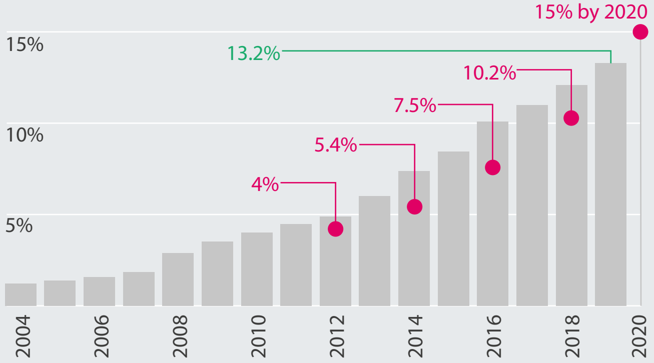
Why renewables?

Energy consumption is a key driver of climate change, as it estimated to generate more than 80% of greenhouse gas emissions in the UK. Replacing our use of fossil fuels with renewable energy is, therefore, critical to tackling climate change.

In order to meet the goals of the Paris Agreement, we must:

- **Decarbonise** electricity supply as quickly as possible, and at the same time:
- **Reduce demand** via efficiency and changes in patterns of energy use, then:
- **Decarbonise** heat and transport by switching fossil fuels for renewable and low carbon sources.

Figure 1: Proportion of UK energy from renewable sources. Blocks show progress to 2019, spots show interim targets. BEIS, 2020. Digest of UK Energy Statistics 2020 (DUKES). Chapter 6 & Table 6.7.



How can we decarbonise our energy supply? What are our options? Our options include:

- Reduced demand for space and water heating through low carbon passive design and construction and increasing energy efficiency;
- Substantial increase in renewable energy electricity generation capacity;
- Long and shorter-term storage of renewable energy via different forms;

- Increase in other forms of renewable energy such as biomass; and
- Flexible generation, demand, storage and interconnection.

The rise of renewables

Renewables are already key components of a low carbon energy system.

The cost of solar and wind have fallen substantially over the past ten years so that renewable electricity without subsidy is now competitive with fossil fuels, and becoming cheaper. This is incredible given that fossil fuels receive major subsidies, and that the full carbon cost of using fossil fuels is not reflected in their pricing (CCC, 2016, p68).

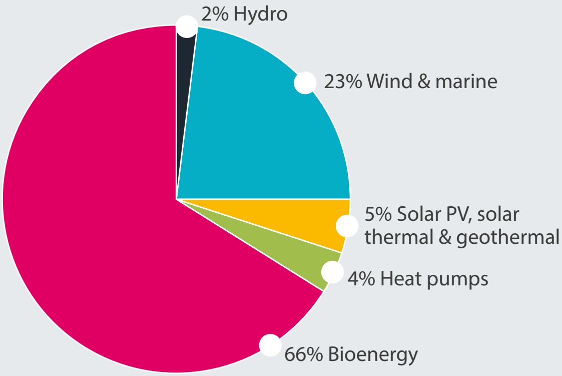


Figure 2: Renewable energy sources in 2019. BEIS, 2020. UK Energy in Brief 2020. Crown Copyright. Page 31.

Over recent years, the number of renewable energy sources has been increasing significantly. Figure 1 shows that at the end of 2019, 13.2% of the UK's total energy consumption was derived from renewable sources, heading towards the target of 15% by 2020 set by the EU 2009 Renewable Energy Directive.

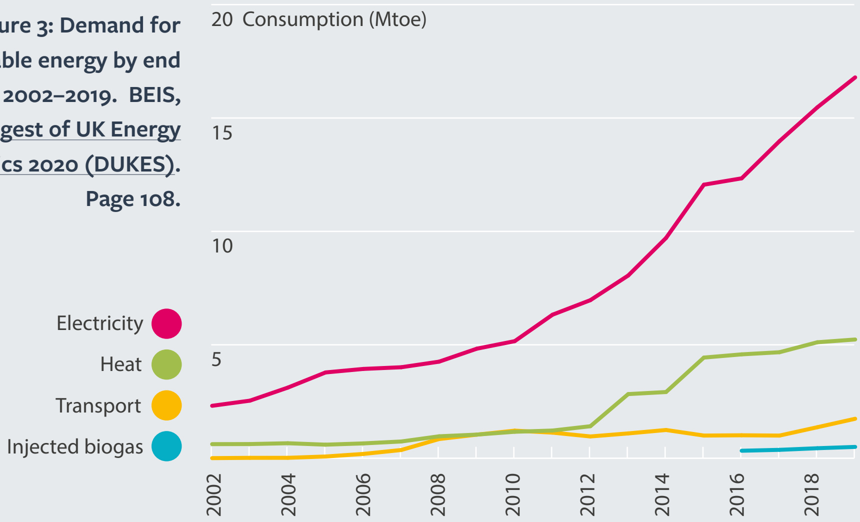
Figure 2 displays what sources of renewable energy were used in 2019 and Figure 3 shows the end use of renewable energy over 2002–2019.

Most of the demand for renewable energy is for electricity production (Figure 3), and renewable energy sources contributed 47% of the electricity generation over January to March 2020 (Figure 4).

But barriers remain

Achieving our Net Zero ambitions requires the co-evolution of technology, society and institutions. Energy systems must now incorporate consideration of multiple factors: physical infrastructure assets, consumers and citizens, business models, as well as governance and policy in the context of the existential threat of climate change.

Figure 3: Demand for renewable energy by end use, 2002–2019. BEIS, 2020. Digest of UK Energy Statistics 2020 (DUKES). Page 108.



Costs are falling for renewable electricity sources and so, on the face of it, costs should not be preventing their wider uptake. However, several existing market failures create major barriers, such as the subsidised use of the atmosphere as a carbon sink, unpriced benefits of technological innovation, and issues related to electricity system balancing.

In comparison to renewables which receive little support, fossil fuels receive several types of ‘regulatory subsidies’. For example, these include the lack of a sufficient carbon or pollution tax which means that the real costs of production are shielded, transferred, or borne by public funds. Fossil fuel projects enjoy favourable policies on certain risks: requirements for upfront insurance costs, guarantees and premiums are proportionately and significantly lower than e.g. for nuclear; export finance supporting oil and gas projects of UK companies overseas positively affects their balance sheets; and UK companies also enjoy Oil & Gas industry practices like ‘cost recovery’ in standardised production sharing agreements or petroleum laws (abroad) while no equivalent is prevalent for renewables.

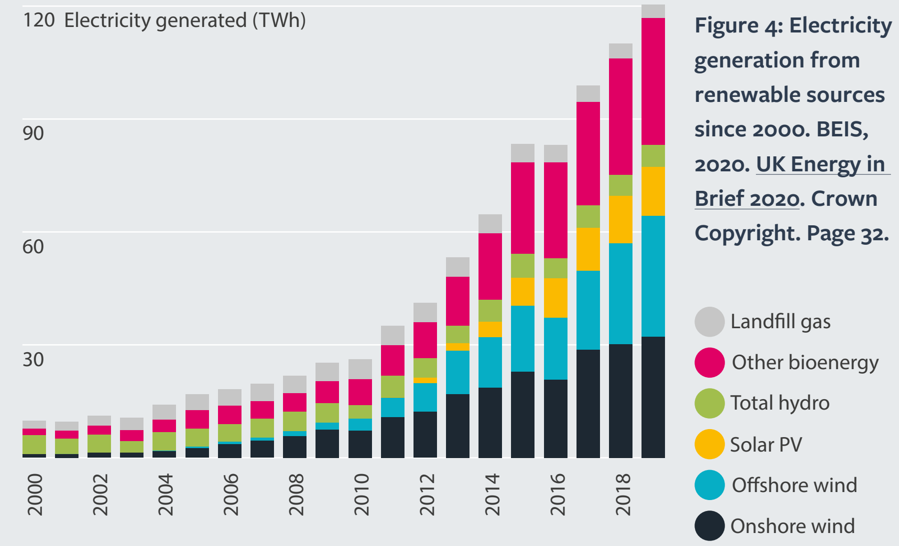


Figure 4: Electricity generation from renewable sources since 2000. BEIS, 2020. UK Energy in Brief 2020. Crown Copyright. Page 32.

Current policies mostly focus on support to develop and install the renewable energy technology, not their integration into networks. So, there are critical unanswered questions like: ‘how might electricity markets need to be reformed?’ and ‘how might new actors be engaged’?

Another key barrier is the variability of renewable energy technologies. Variable generation raises problems for balancing the supply of energy to the demand for energy on different timescales (from seconds to seasons) and different spatial scales. Some technical mitigation measures are known and can be classed as flexible generation, flexible demand, grid interconnection and energy storage. There is much work developing new technological solutions in each of these categories from the use of solar panel inverters for reactive power at night, and using synthetic inertia from energy stored in the rotational mass of a wind turbine wind turbine blades as energy storage. We will need a combination of approaches and further innovation.

Only by understanding, and then dismantling, market failures can we be successful in integrating very high levels of variable generation and ancillary measures (storage, flexibility) into electricity systems. Further, any decarbonisation solution will involve some mix of flexible generation, flexible demand, inter-connection and storage. This will require change in current approaches to electricity market design, regulation and governance, including the role of energy users.

We need to look at the whole system

Taking a whole systems approach, to understand the interdependencies of the transition has been the hallmark of our work.

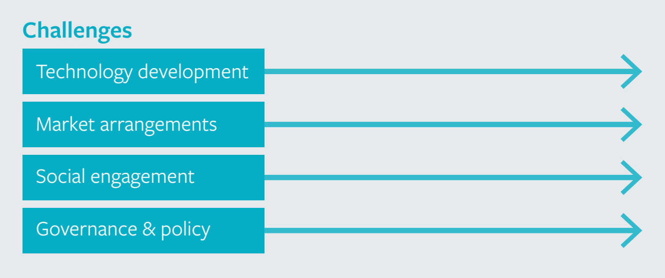
The rapid energy system transition that needs to happen cannot rely on technological fixes alone. Insights into the social and economic dimensions are also required, and such a complex transition must consider markets and business models, citizens and societal engagement with energy, and policy, governance and regulation alongside electricity infrastructure and technology development.

Technical and social aspects of energy systems are not always considered together, but they are inseparable. While significant progress has been made with ‘stand-alone’ technologies both in terms of cost and deployment, our work has shown that the potential positive impact of new, smart tech and ideas could be wasted if there are no accompanying structural changes to the power system, or if they are not adopted by the public. For example, our work on peer-to-peer energy trading highlighted the need for any new marketplace or business model development to align not only with the engineering realities of the energy system, but also the needs of the people who will use the system. If this is not done, the system will fail.

Further, in our route to achieving net zero emissions, taking a whole system approach means looking at sectors that have not been traditionally linked with electricity. Space heating and transport are areas where a major transition away from fossil fuels is needed quickly and where electrification will play a key role.

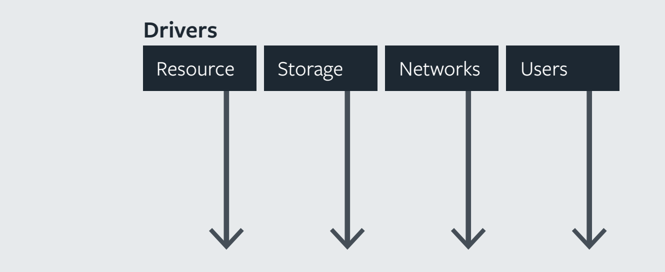
Challenges and drivers

In order to provide critical insights that span technology, market, society and institutions, we started off by identifying the **challenges**:



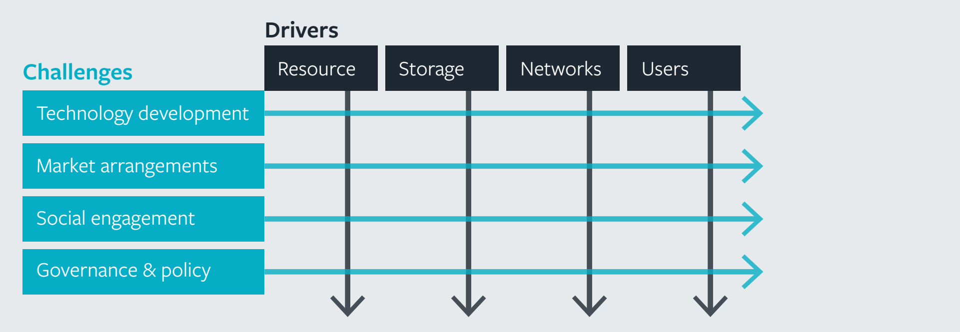
- **What are the promising technologies in development?** What hurdles need to be overcome to further integrate renewable energy? How can innovation be supported?
- **How should the power market reform?** New approaches are needed in situations where renewable energy causes short run marginal costs to fall close to zero, and where flexibility is under-valued.
- **How to engage people with distributed energy resources?** Social change and system design will influence the willingness of businesses and households to engage with, distributed energy and smart technologies.
- **What's the role for policy and governance?** Investment in renewable and clean energy faces political, planning and regulatory barriers that need to be dismantled.

From this we set out the **drivers**:



- **The best resource mix**. The balance of solar, wind, biomass and other sources will be critical.
- **Long-term storage economics**. Batteries are viable for intra-day storage, but less so for inter-seasonal storage so what are the low-cost alternatives that enable the decarbonisation of heating?
- **Impact on networks**. Renewable energy technologies disrupt the current network funding and pricing, equitable allocation and capacity but also offer many opportunities.
- **Users**. People are a critical element of the energy system yet often overlooked. The energy revolution has the potential to bring the benefits of clean energy to everyone.

Combining the challenges and drivers shows the interdependences of these different aspects which has framed our approach.



In our different research projects we have tried to focus on at least one challenge and address it against drivers in the system.

Let’s find out more.

CHALLENGES

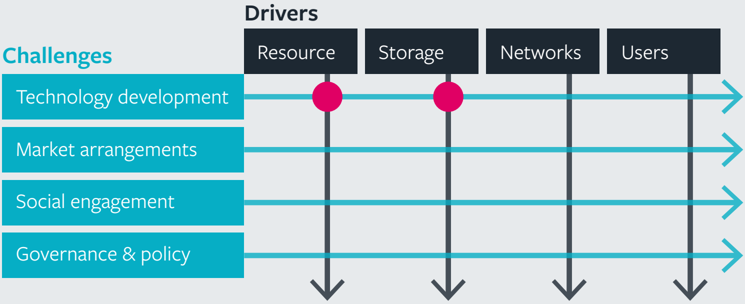
2 The challenges: Technology

Around the world, renewable energy resources are being installed to add to, and replace, existing non-renewable power stations. In many countries wind and solar dominate, but these technologies bring challenges as they cannot provide system balancing without the use of other sources of flexibility. In some countries grid scale battery storage and interconnected local storage systems are being trialled. These systems are relatively costly but costs are continuing to fall.

Because of the variability of renewable power generation, there is uncertainty over whether the actual generated power will match the predicted demand in any given time. Electricity grid operators need to schedule adequate flexible resources to cope with the increased uncertainty and variability in the system. If they fail to do so, and the demand and generation do not match, this may lead to power cuts and outages, or the overloading of network assets.

We have conducted work in three areas to explore how technological solutions can help grid management.

Using different renewable resources together in a complementary way



One way is to use different energy resources together, in a complementary way. This allows operators to smooth the output of renewable resources, providing certainty over power production for a defined period of time.

Using Kenya as a case study, we investigated the possibility of operating hydropower and solar energy as a single dispatchable unit, taking uncertainty into account.

To explore opportunities for hybridising renewable resources to deliver efficient and dispatchable generation, an optimisation framework was built to determine how each unit, i.e., hydro and solar, would be used. The findings show that hydro and solar resources may be used together to smooth the output of solar generation and may be used to meet the increasing electricity demand in some countries.

So based on these findings, it seems that there is much potential for using different renewable energy inputs together.

Apostolopoulou & McCulloch, 2017. Cascade hydroelectric power system model and its application to an optimal dispatch design

Apostolopoulou et al, 2018. Robust optimization for hydroelectric system operation under uncertainty. doi: 10.1109/TPWRS.2018.2807794

Apostolopoulou & McCulloch, 2018. Optimal short-term operation of a cascaded hydro-solar hybrid system: a case study in Kenya. doi: 10.1109/TSTE.2018.2874810

How can this be implemented on the ground? Firstly, there would be a need to update existing ways of scheduling hydroelectric resources so that they can be used in conjunction with other energy sources. Secondly, it would be best to install solar generation close to hydroelectric systems so the same network infrastructure may be used.

These two factors mean that much work is still needed in terms of governance and the use of scheduling technology before combined deployment of renewables can become the norm.

Cao et al, 2019. Optimal design and operation of a low carbon community based multi-energy systems considering EV integration. doi: 10.1109/TSTE.2018.2864123

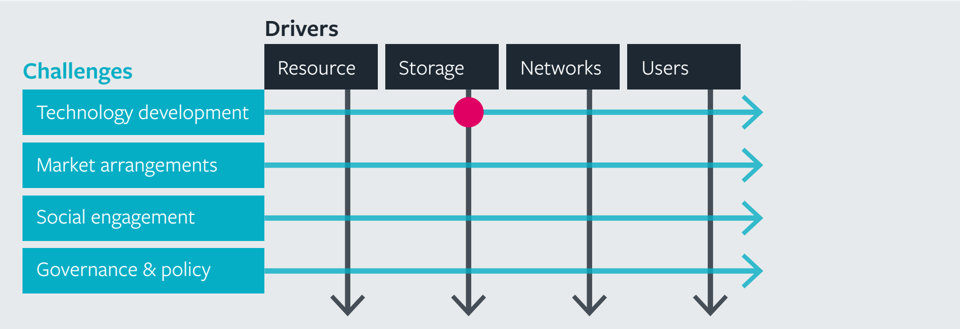
In another study, we explored the hybridisation of electricity, heat power, and transportation energy so that their advantages could be combined in a multi-energy source system.

Our conceptual Eco-town, a low carbon, community based multi-energy system, used a fuel cell, combined heat and power units (CHP), hot water tank storage, gas boiler and photovoltaic (PV) generators to meet the electrical, thermal and transportation electrification energy demands in an eco-friendly multi-energy microgrid.

We explored different possible designs and operational modes and found that it is possible to achieve the triple goals of reliability, cost-effectiveness, and minimal emissions. Our results show that by using different technologies it is possible to reduce carbon emissions dramatically, while maintaining cost effectiveness, and that smart charging of EVs helps to reduce costs and meet system reliability requirements.

We hope our work and methodology can be used by planners to create multi-energy systems and determine the best combination and capacities of different low carbon technologies to meet energy demands for both heat and electricity.

Next generation lithium ion chemical batteries



The second area we explored was how to improve battery technology. We have explored the chemistry of anodes, cathodes, and atomic structures.

We have investigated lithium (Li) rich materials that can potentially unlock a higher energy density than current state-of-the-art Li based batteries. This could revolutionise the battery and electric vehicle industries and accelerate the sustainable energy transitions.

Our work examined oxygen-redox in Li-rich materials for next-generation Li-ion batteries. We explored the crystal structure rearrangement in these materials, caused by oxygen-redox, which is a cause of battery capacity fading over the long term.

To explore the crystal structure rearrangement, we characterised the materials at different charging and discharging states, using multiple advanced techniques. The findings showed significant crystal structure reconstruction (from monoclinic to rock salt) happening on both the surface and bulk of the cathode particles associated with oxygen redox.

House et al, 2018. Lithium manganese oxyfluoride as a new cathode material exhibiting oxygen redox. doi: 10.1039/C7EE03195E

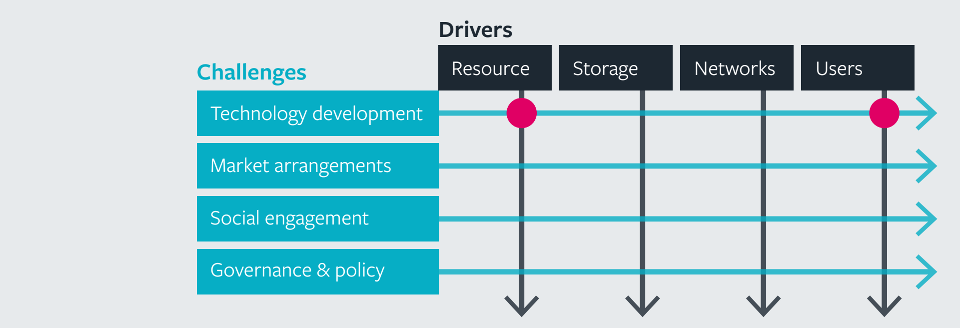
House et al, 2019. What triggers oxygen loss in oxygen redox cathode materials? doi: 10.1021/acs.chemmater.9b0

Lozano et al, 2018. Low-dose aberration-free imaging of Li-rich cathode materials at various states of charge using electron ptychography. doi: 10.1021/acs.nanolett.8b02718

Wang et al, 2018. Plating and stripping calcium in an organic electrolyte. doi: 10.1038/nmat5036

Our results contribute to the search for a potential solution to the capacity decay issue of chemical batteries. This sits alongside other work in the industry examining battery capacity, and their combined use with supercapacitors.

Hot water batteries



Vijay et al, 2020. Potential for domestic thermal storage to absorb excess renewable energy in a low carbon future. doi: 10.1109/ISGT45199.2020.9087704

Another way to store and use excess renewable energy is through the use of domestic hot water tanks. This approach provides an economical option to store energy by heating hot water and negate potential emissions arising from fossil fuels.

We examined how the feasibility of this approach by determining the capacity of hot water tanks required and the potential savings in a low carbon future, using a power dispatch model.

With our model, we looked at the effect of different scenarios generated by industry practitioners to represent different potential energy mixes in the year 2040, for the UK and Europe, that have. These scenarios reflected the need to meet different emission reduction targets, different levels of investment in renewables, uptake of distributed energy technology and use of gas. All scenarios feature interconnectors that pass electricity between the UK and mainland Europe.

The scenario featuring large amounts of renewables encounters the largest scale curtailment, but all scenarios feature some curtailment, with higher curtailment in summer than other seasons. Curtailment is the reduction or cessation of (here) renewable energy production below what could have been produced. For the UK, our results show curtailment could range between 1 TWh and 10 TWh of energy in the year 2040. This is equivalent to the average annual energy use of 345,000 to 3,450,000 typical households.

We looked at the expected demand for hot water across the year to understand the potential capacity for storing hot water, and also the percentage of households that would need to have a smart hot water tank to absorb all of this potentially wasted energy. The results show that 50% of UK households would need a tank to do so. However, if only 20% of all houses in the UK had tanks, we found that up to 80% of this otherwise wasted energy could be captured and used productively.

For consumers, we estimated the potential savings using electricity tariff projections and assuming that the energy would be provided at half of the retail price. With these assumptions, each smart tank household could save up to £53 per year.

3 Market arrangements

The shift toward renewable energy has altered the fundamental economics of wholesale energy markets, which historically were often purely based on the economics of short run marginal costs. The wholesale market is where energy suppliers purchase energy from generators, and then sell it on to their retail customers (domestic and commercial). Prices on the energy market are volatile and rise and fall regularly.

Short run marginal costs relate to the costs of producing a unit of electricity, such as fuel and operational expenditure. Long-run marginal costs cover the cost of meeting demand indefinitely i.e. the construction of a new generating unit and the generation, transmission and distribution costs to meet the highest demand.

The shift toward renewable energy has also led to decentralisation and democratisation of energy, as traditionally passive consumers become ‘prosumers’ i.e. proactive consumers with distributed energy resources (DERs) such as domestic PV and home batteries, actively managing their consumption, production and storage of energy.

This raises questions about the future of markets to drive further decarbonisation, as well as the ability to co-ordinate small-scale flexible energy resources to balance networks on local scales, which could reduce the costs of renewable integration and improve energy security. Changes are needed to existing market arrangements to facilitate or incentivise this coordination.

In addition to analysing market structures to support the uptake and management of renewables, research has focused on how the application of subsidies and other financial levers through different business models can drive the adoption of small scale solar systems.

However, much electricity system analysis is based on old system characteristics (e.g. large centralised plants, national systems, kWh energy markets). Given power infrastructure lasts for a long time (~50 years and more), this is a dangerous approach to take as old system characteristics are rapidly changing. Many aspects of a decarbonised energy systems are radically different. For example, they feature:

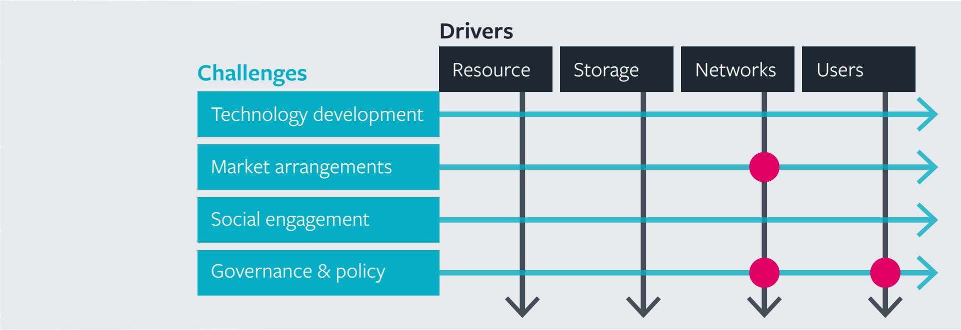
- Smaller scale of energy generation;
- Zero short run marginal costs;
- A new role for demand side actors; and
- The possibility of peer to peer sharing.

So how do we avoid “mental lock-in”?

Decarbonising the energy sector will play a fundamental role in combating climate change but doing so at low cost will require substantial innovation. Hundreds of billions of public money are spent subsidising R&D globally each year. Is this enough? Are these resources spent wisely? How can policy help drive clean energy innovation at speed and scale?

Fundamentals have shifted. How to deal with zero marginal cost energy

Reform of energy tariff pricing



Rhys, J. 2018. Cost reflective pricing in energy networks. The nature of future tariffs, and implications for households and their technology choices.

The findings of a study carried out by Dr John Rhys and the Energy Systems Catapult could encourage the switch from gas boilers to low carbon heat pumps.

The study investigated whether or not the fixed charges components of energy bills – for network, environmental and social costs – are efficiently distributed between the standing charge and the unit price of electricity and gas tariffs (is the charge per unit of consumed energy).

These largely fixed costs pay for maintaining and upgrading transmission grids and distribution networks, balancing demand on the system, and supporting social and environmental policies.

The study found different consumers pay different contributions for the same fixed costs of making energy supply available, such as transmission and distribution charges, because costs are recovered through the unit price. This approach means:

- Consumers installing generation assets on their own premises, such as solar PV or diesel generation, under-paid their correct share of fixed costs. This is because they avoid many of the costs recovered in unit pricing by generating their own electricity;
- An artificial incentive has been created to build small ‘on-site’ generation vs large generation; and
- Consumers installing low-carbon demand technologies, such as heat pumps, over-paid their correct share of fixed costs recovered in the unit price because they used more electricity.

This means that overall consumers are under-charged for the fixed costs of making energy supply available and over-charged for the units of energy they consume. The fixed costs avoided by those with generation on their own premises have to be recovered in the bills of other consumers, including those in fuel poverty, increasing their energy bills.

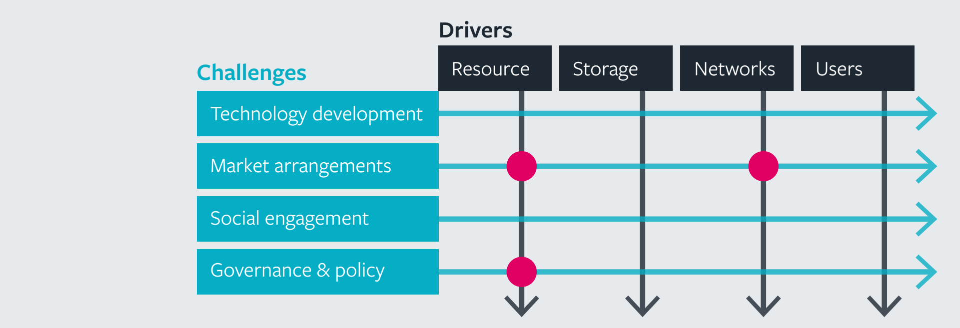
The study also found:

- Rebalancing fixed and volumetric charges, into the standing and unit prices respectively, would enable fixed costs to be more equitably recouped from bill-payers;
- Spreading the environmental and social costs more evenly between gas and electricity would lead to a more efficient allocation of costs, however removed such costs from bills and placing them onto general taxation would be a much more progressive approach; and

- “Time of use tariffs” that reflect the variable cost of delivering electricity at different times, would encourage the charging of electric vehicles (and other non-time critical demand) to off-peak periods and create a more efficient electricity system.

The study also found that the gas network may have a valuable role in the future to help meet peaks of energy demand that are short lived via the use of hybrid heat pump/gas boilers. This would take advantage of the existing gas network asset, rather than investing in additional capacity in electricity generation/networks that will only be used rarely.

Rethinking market design



Farrell et al, 2019. An auction framework to integrate dynamic transmission expansion planning and pay-as-bid wind connection auctions. doi: 10.1016/j.apenergy.2018.06.073

This work explored how market and policy instruments can work to incentivise a decarbonisation agenda. Variability associated with renewables can increase price volatility on wholesale energy and balancing markets, which increases investment risk. We looked to see if wholesale markets alone can sufficiently hedge the increased investment risk associated with renewables.

We found that market instruments may require a radical redesign if they are to support continued investment in renewable resources alongside effective grid management. Policy levers must respond to increased spatial, temporal, and social variability associated with renewables.

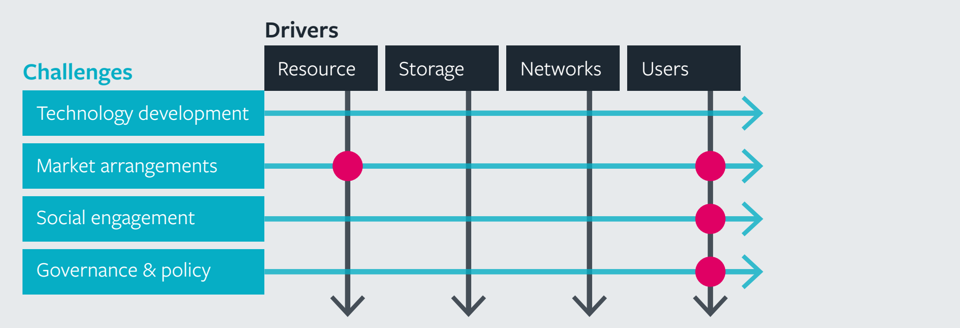
For example, capacity payments and/or long-term contracts are required to overcome the exposure of investors to risk. New additional services (e.g. storage, flexibility) could supplement revenue but will not be sufficient by themselves in the short to medium term.

Farrell, 2018. The increasing cost of ignoring coase: inefficient electricity tariffs, welfare loss and distributed energy resources. doi: 10.2139/ssrn.3291506

Capacity markets should guide investment decisions, and energy markets should guide operational efficiency by allocating electricity use to periods where it is valued most. Capacity payments must be carefully designed to: (1) ensure generators respond to operational signals, (2) incentivise an appropriate technology portfolio and (3) procure the correct balance of ancillary services.

Policy shifts will be needed to implement and ensure this market redesign happens, so that total decarbonisation of energy production can be incentivised.

New and flexible market actors



We explored how to integrate flexibility into the power system by incentivising coordination between prosumers i.e. owners of small-scale distributed energy resources such as electric vehicles and home batteries.

Boait et al, 2019. The practice and potential of renewable energy localisation: results from a UK field trial. doi: 10.3390/su11010215

We used power system modelling and optimisation with methods from game theory and networked market design to develop and test different local energy trading algorithms.

Morstyn et al, 2018. Bilateral contract networks for peer-to-peer energy trading. doi: 10.1109/TSG.2017.2786668

Han et al, 2018. Incentivizing prosumer coalitions with energy management using cooperative game theory. doi: 10.1109/TPWRS.2018.2858540

Morstyn et al, 2018. Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. doi: 10.1038/s41560-017-0075-y

Morstyn et al, 2018. Designing decentralized markets for distribution system flexibility. doi: 10.1109/TPWRS.2018.2886244

Morstyn et al, 2018. matching markets with contracts for electric vehicle smart charging. doi: 10.1109/PESGM.2018.8586361

Dixon et al, 2018. Flexible cooperative game theory tool for peer-to-peer energy trading analysis. doi 10.1109/PESGM.2018.8586348

In our modelling approach we used the existing retail electricity market structure but created new multiple bilateral contracts to encourage flexibility. These contracts set prices from peer to peer negotiations which not only considered costs but also social, philanthropic and environmental energy preferences.

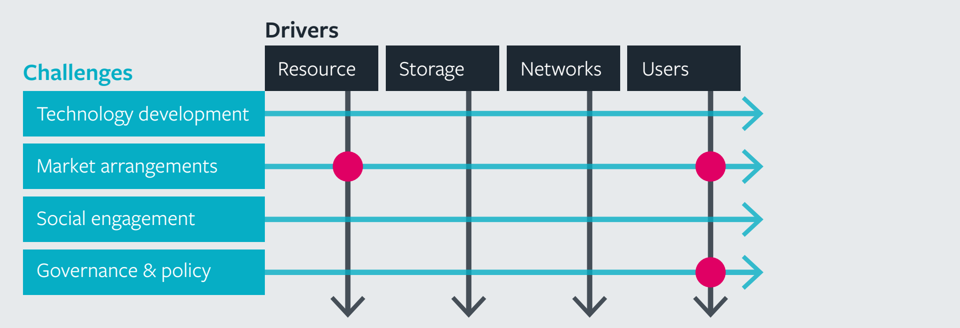
We found that multi-interval trading allowed prosumers to manage their storage systems effectively, and were able to reduce their exposure (risk) to energy price fluctuations by forward trading. Our use of game theory showed that there was a significant incentive for prosumers to cooperatively schedule their storage systems. A federated power plant structure – a virtual power plant formed through peer-to-peer transactions between self-organising prosumers – was an ideal way in which prosumers could cooperate and also address social, institutional and economic issues in a way that top-down approaches for prosumer coordination are not able to.

This means that if properly coordinated, prosumer owned distributed energy resources could help markets deliver secure, affordable and clean electricity.

However, before these benefits to be realised, regulatory arrangements need to be updated to allow these new business models and systems. Further, changes to regulations applying to distribution system operators (DSOs) are also needed. The situation at the moment is that the rate of return is linked to network capacity investments, and so DSOs are not incentivised to support distributed energy resource adoption and procure local flexibility services. If the regulation was changed by associating DSO rate of return with network efficiency then this would incentive small scale distributed energy and flexibility services from prosumers. DSOs would be able to use structures such as federated power plants to organise impartial markets for prosumers.

How do financial incentives drive the adoption of small-scale solar systems?

Solar subsidies in the US



There is an assumption that subsidies that are made available from governments are passed-through to consumers in the form of lower prices in order to incentive or encourage e.g. the uptake of solar systems. Measuring this ‘pass-through’ is an important tool in economic analysis and policy evaluation.

Pless & van Benthem, 2019. Pass-through as a test for market power: an application to solar subsidies. doi: 10.1257/app.20170611

We looked at solar subsidies and how they are passed-through to solar system prices.

Pass-through is an important tool of economic analysis as it can reveal important characteristics about supply, demand, or market power. Market or monopoly power refers to the ability of a company to raise and maintain price above the level that would prevail under competition.

Our data came from the California Solar Initiative created in 2006: the largest state solar rebate programme to date in the United States. We looked at situations where consumer would either buy or lease a solar system for their building, using proprietary solar leasing data and combined it with public data capturing solar subsidies and prices for those who purchase systems.

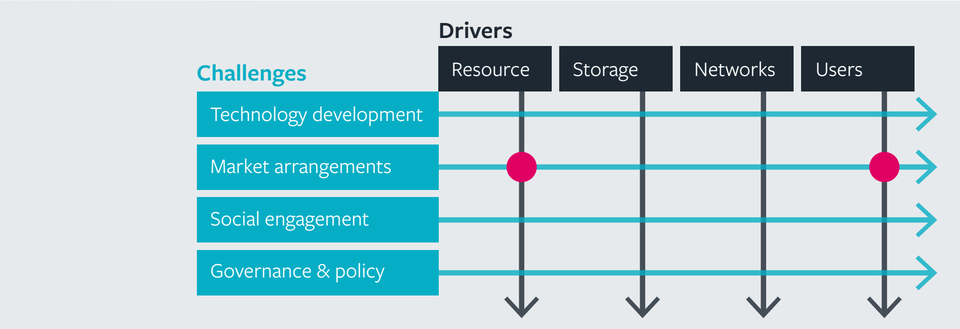
We used econometric methods were used to estimate the pass-through of subsidies to solar system prices for buyers vs. lessees.

We found that pass-through of the subsidy is remarkably high: the pass through is 78 cents for every dollar increase in subsidies for purchasers of solar systems. For those who lease, a $1 increase in subsidies translates to a decrease in solar system prices of $1.53. These estimates show that in the setting of the Californian solar market, solar companies pass on most of the subsidies to customers.

However, at the same time, we provide evidence that solar markets in the US is imperfectly competitive, that is, companies have market power. This implies that the value of the subsidies to consumers is lower than it would be in a competitive market.

These findings have relevance for competition authorities who may be interested in addressing this imbalance of power in order to improve the efficiency of solar markets and increase uptake.

Third party solar ownership models



We also considered the implications on the structure of solar markets and explored the relationships between residential solar prices and market structure. In particular, we looked at third party ownership (TPO) models.

The market for residential solar photovoltaic (PV) systems has experienced tremendous growth over the past decade. As the market continues to grow, it prompts new questions about the nature of competition between solar installers and how this competition, or lack thereof, affects prices consumers pay.

Pless et al, 2017. The price-concentration relationship in early residential solar third-party markets. NREL/TP-6A20-66784

It is often assumed that more competition leads to lower prices, but this is not universally true. For example, some studies have shown that factors such as brand loyalty could lead to a negative relationship between concentration and price in imperfectly competitive markets. As such, the relationship between prices and market concentration is an open empirical question because theory could predict either a positive or negative relationship.

We found that market structures remain a relevant policy issue affecting the potential for rooftop solar to contribute to decarbonisation efforts or other policy objectives. Imperfect competition has implications for potential market growth.

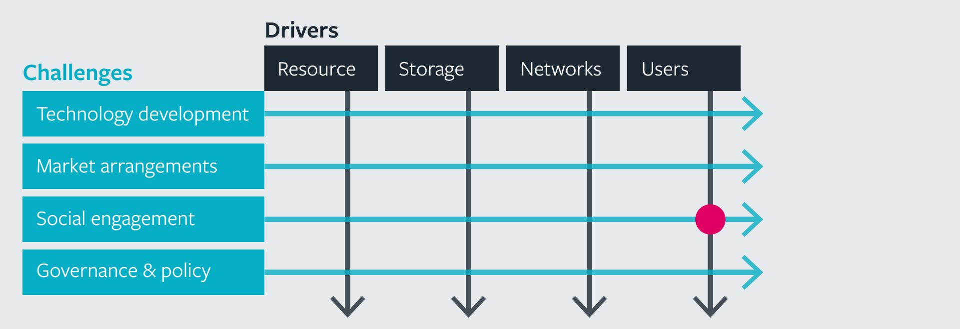
Our findings suggest that there is a negative relationship between market concentration and solar system pricing in early TPO markets; however, this could change as the structure of residential solar markets continues to evolve.

4 Social engagement

Climate change, environmental degradation and the provision of energy services are all complex processes that have to be addressed with material, cognitive, moral, social, and political resources. We benefit from more research on the benefit of energy from the perspective of people, and greater insights into the "demand" side of energy. Too much emphasis on either a technological, structural, or cognitive 'fix' will be insufficient to achieve the fundamental shifts in energy consumption needed to meet emission reduction targets.

We have undertaken a variety of research into the "demand" side, including exploring (1) how people can be persuaded to change their energy related behaviours, (2) how households with solar systems use the energy they are producing, (3) the impact that smart appliances could have, and (4) how end user behaviour is accounted for when considering models of power system scenarios.

It's not just about the tech



Our work explores the best ways to engage energy users – people! – in discussions related to energy consumption, energy demand, and environmental issues

Purely technical fixes to reduce or manage demand are rare or non-existent. Too much emphasis on either a technological, structural, or cognitive 'fix' will not be sufficient to achieve the shifts in consumption needed to meet target for emission reduction.

Energy innovation involves far more than simply inventing and rolling out a new technology: it involves many people or 'actors' and organisations who are responsible for building, operating and adapting systems and end-uses, and who learn and change at varying speeds. Good communication between these actors, in terms relevant to their experience and knowledge, is therefore essential in order to achieve useful outcomes.

The role of 'middle actors' in energy systems, people who act as bridges or guides between producers and consumers, experts and non-experts, technicians and lay people, owners and tenants, is important for effective communication.

Abrahamseet al, 2018. Communication is key: how to discuss energy and environmental issues with consumers. doi: 10.1109/MPE.2017.2759882

Boait et al, 2019. The practice and potential of renewable energy localisation: results from a UK field trial. doi: 10.3390/su11010215

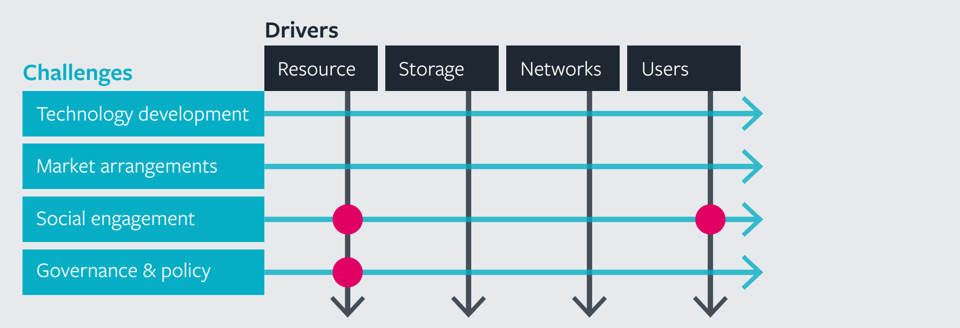
Darby, 2019. Smart and sustainable, fast and slow.

Effective communication may involve several channels: technology itself, direct communication through messaging, and indirect communication via middle actors and informal networks. Good communication is also needed in: design, investment, construction and maintenance for buildings, mobility, appliances, and infrastructure; development of operational standards; development of distributed generation and storage, where network operators, vehicle fleet operators, energy service companies and tariff designers all need to communicate with each other and with their customers; appraisal of possibilities, risks, and uncertainties in highly-connected systems.

Our work has shown that the inclusion of people in decisions, and understanding likely behaviour is critical to deliver successful initiatives on energy conservation and demand response. It is also critical to inform interventions and policy instruments that seek to change the scale and patterns of energy use in the short and long term.

Demand response can be defined as a change in the usual pattern of energy consumption undertaken for a range of reasons such as to avoid peal loads on the grid system; in response to price signals (avoid high costs or take advantage of low costs) or minimise emissions or when the carbon intensity of the grid is relatively high. Example of demand response vary from individuals using appliances at a different time than usual or turning down room thermostats, to companies or industries reducing or stopping activities for short periods.

How much do households with solar systems actually use the energy they are producing?



How much of their generated electricity do owners of rooftop PV consume?

Estimating self-consumption and predicting the resulting electricity bill savings are critical for policymakers, as potential electricity bill reductions are often used to calculate appropriate incentives to deployment targets for low or zero carbon energy generating technologies. This is particularly relevant given the need for regulatory changes that will expedite Net Zero emissions and implement local energy systems.

Despite mass adoption of solar PV, there are few studies on solar self-consumption and they are limited to small-scale trials with unknown representativeness. Self-consumption refers to using the electricity generated from e.g. rooftop generated PV within the home rather than exporting it to the national grid.

Part of the reason for the low number of studies is due to the decision that export meters did not need to be fitted to households when the solar panels were installed.

McKenna et al, 2018. Solar photovoltaic self-consumption in the UK residential sector: New estimates from a smart grid demonstration project. doi: 10.1016/j.enpol.2018.04.006

Alas, this lack of data has resulted in a lack of evidence to determine payback times for PV investments, leading to inaccuracies which can hamper consumer adoption and prevent good policy. For example, in 2015, the UK government reviewed the PV Feed-in Tariff (FiT) scheme but found that there was little usable evidence to assess the scheme.

In order to provide some insights, we explored how UK residential households used the energy generated by their solar panels. For our study, we managed to obtain one-minute electricity monitoring data for 302 households that participated in a UK smart grid demonstration project and performed analyses to determine self- consumption levels and payback times. This data helped us to build a model to explore what would be the findings for a typical UK household with electricity demand of 4,000 kWh/year and a 2.9 kW PV system.

We found that annual self-consumption levels were between 37–45% of generation – a level of self-consumption greater than the estimates used by Energy Saving Trust. As a result, householders would save £138 per year from electricity bills alone (i.e. not including FiT payments): this is approximately twice the Government estimate. Also, on average, PV households export 55–63% of generated electricity, compared to the 50% assumed by the FiT.

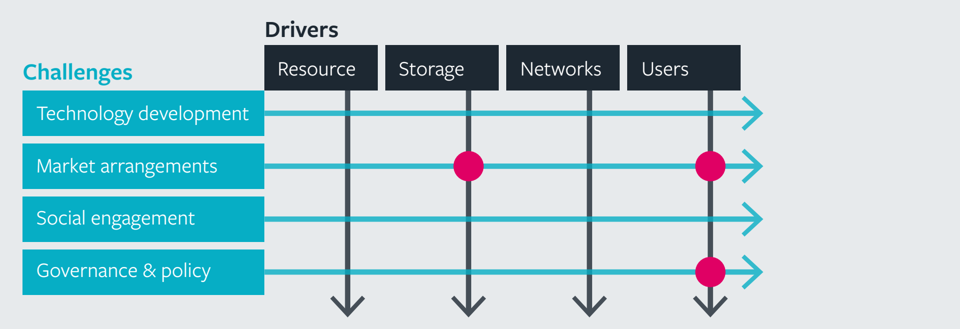
This self-consumption is equivalent to a 24% reduction in average annual electricity demand from the national grid which is a significant amount. If more households had solar panels, and home batteries, the need for new large scale electricity generating assets would be greatly reduced.

We are now in a post-subsidy era for residential solar PV in the UK. The Smart Export Guarantee (SEG) has filled the place of the FiT, whereby energy suppliers must offer to purchase domestic solar generated energy at a given price they can set, which must be higher than zero.

One of the drivers behind self-consumption is because the cost of electricity imports is ~15p per kilowatt, compared to the ~4p per kW under the FiT and >0p per kW under the SEG. That, coupled with the greater availability of home battery storage is a great incentive to store and use as much self-generated energy as possible.

Export meters are required for the SEG which means that in the future, more data will be available on the generation and self-usage of households with solar panels, and the effect of home batteries, leading to much better estimates not only of energy bill savings and payback times, but also explore the potential of new financial incentives or time based rules, for example for electric vehicle charging.

The potential impact of smart appliances



A key expectation of energy efficiency policies is the reduction in greenhouse gas emissions.

Many studies have looked at the efficiency of individual efficiency measures, so we decided to look at the potential of system efficiency. We explored the potential of smart appliances to act as energy demand responders and reduce emissions by shifting the time when power was needed by appliances, and by storing renewable energy to use it later.

McKenna & Darby, 2017. How much do smart appliances reduce CO2 emissions? Assessing the environmental impact of domestic demand response technologies.

After having reviewed literature on the potential for greenhouse gas savings from such demand response technologies, we created a conceptual model of the potential for demand response. Using this, we estimated the reduction in greenhouse gas emissions from the use of domestic battery systems in the Irish power system.

Our findings indicate that the benefit of the smart appliances in reducing greenhouse gas emissions may be negligible unless there is also structural change in the power system, e.g. replacements of old polluting power stations by cleaner forms of generation. This means that unless there are more sources of renewable and low carbon electricity feeding the national grid, few emissions will be saved from shifting power timing.

Also, the potential environmental gains from greater system efficiency may be reduced or even offset by additional overall energy consumption from e.g. sensors and monitoring equipment, and from the impacts from mining and processing materials used in the smart components.

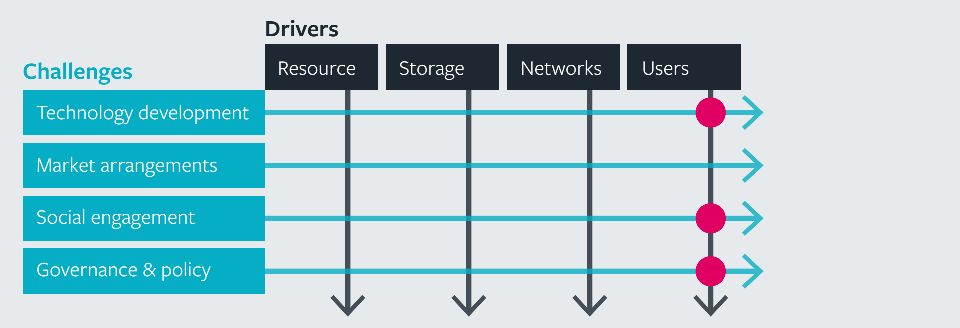
If demand response can be aggregated to be large and reliable enough as a resource to system operators, then this will affect plant commissioning and decommissioning. This is because the use of smart appliances can lead to a reduction in the peak power demand, which may otherwise have necessitated a new power generation station, with all the embodied emissions that entails, as well as operational emissions if it is not a renewable energy plant.

Carbon pricing and emissions trading can complement the impact of demand response in bringing about change in the preferred priority of generation sources, which should be based on their carbon intensity.

We recommend that smart appliance specifications and standards should include the requirement to be usable for demand response aggregation.

Further, the components of smart appliances should be assessed for environmental impact, including the expected efficiency losses in batteries that will occur over time and with use. Wherever possible, recycled materials should be used in these technologies.

The need to account for end user behaviour



We explored how activity-based energy demand models can be enhanced to provide more useful tools to assess the potential of demand response.

McKenna et al, 2018. Simulating residential demand response: Improving socio-technical assumptions in activity-based models of energy demand. doi: 10.1007/s12053-017-9525-4

Energy models are an important tool to assess different net zero futures. However, it is very important that they include aspects of human behaviour. We won't gain a realistic understanding of how our energy system will work in real life without insights on (a) the extent to which people and organisations may be willing, and able, to engage in changing their demand for energy; (b) the public acceptability of different tariffs and technologies and likely uptake; and (c) the potential flexibility of everyday practices.

This is particularly acute as the need for behaviour change and ability to be flexible when we use energy becomes an ever more pressing need in low carbon electricity systems.

We need to move away from purely technical and economic-based models and their underlying assumptions, towards more grounded and integrated socio-technical models.

In our studies we reviewed current models and found that some assumptions are not robust, for example, that time-use diaries (typically for one person and one day) are reliable guides to energy use, that activities are randomly related to one another, and that all dwellings are occupied on a permanent basis by average adults who own standards sets of appliances and use them in the same way.

We recommend that future energy models incorporate links between appliance usage and activities using evidence-based information. Service expectations i.e. how users expect to use appliances or receive a service, are important influences on the amount and timing of potential energy demand flexibility. Such influences should be more widely included in energy models as doing so would improve modelling predictions. Also, flexibility spans over a range of time scales, from immediate responses, to longer term trends. These timescales are not always represented, but should be.

Darby, 2020. Demand response and smart technology in theory and practice: customer experiences and system actors. doi: 10.1016/j.enpol.2020.111573

Demand response from 'smart' i.e. internet connected devices in homes and businesses is becoming a reality. It brings issues of trust, data ownership and access rights to previously inanimate or 'dumb' appliances. For example, smart fridges can turn themselves off for a few minutes, without any change to their internal temperature (and thus no food spoilage), at time of peak demand on the electricity grid. If all the smart firdges were turned off in this way, the aggregated reduction in demand would be significant, and the fridge owner may not even notice. Would you be happy to have a fridge that can be remotely turned off for this reason? Would you have trust in the mechanism to the fridge off and on without any hiccups? What if something went wrong: who would be liable? Might it affect your privacy, or warranty?

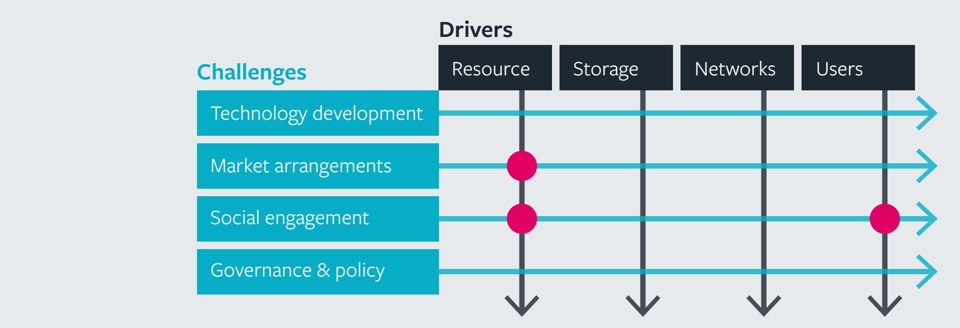
How about hot water? Would you be happy to benefit from a smart hot water tank that could automatically be powered when there is surplus power on the grid, such as periods of high renewable energy generation and low demand? Or a washing machine that, when filled with items to be cleaned, would turn itself on when the carbon intensity of the grid is at its lowest, even though it may result in the wet clothes not being removed for a while? Do the benefits outweigh the potential disadvantages?

We examined results from a three-year project that installed smart electric storage heaters and electric hot water cylinders in ~800 premises, mainly homes, in three European countries (Germany, Ireland and Latvia). The potential for demand response for storage is significant. It is estimated that the storage potential in the EU from smart-enabled replacements of residential storage heaters and hot water cylinders could, in aggregate, be four times that in dedicated storage capacity (e.g. pumped hydro). Such smart devices could provide a substantial decentralised way to store excess or cheap electricity, via remote control by grid or network operators.

The findings from the project emphasise the importance of the user experience, and that people and interactions needed to make demand response approaches successful. Without good experiences, people will have little appetite for smart enabled technology, and we won't be able to realise its full benefits for demand response. Success is achieved when the smartness is distributed between technologies and people. Demand response cannot always be a wholly technological, self-regulating, wholly automated, fit-and-forget process; there is a critical role for humans. Participating in demand response involves people's (customers') judgements on energy services and activities, ability to control equipment, a good customer-utility relationship and carefully judged, agreed rules.

The design of demand response services must ensure three key aspects are in place: reliable connectivity between devices, intelligible human-technology interfaces and controls, and, very importantly, constructive person-to-person conversations (care). Procedures are needed to agree consent to adopt technologies and tariffs and allow for remote control, as well as for providing customer support and taking responsibility for failures in service provision.

New energy business models to enable peer to peer trading



A critical challenge facing us is: how best to incentivise coordination between vast numbers of distributed energy resources, each with different owners and characteristics, for mutual benefit? Concomitant with the changes in energy production, and smart appliances, is the need for new business models.

We have seen the rise of the 'sharing economy', which involves interactions between individuals, without a third party, to give access to goods and services facilitated by a trading platform: think Uber or Airbnb. These peer to peer (P2P) interactions allow small suppliers to compete with traditional providers of goods and services.

Morstyn et al, 2018. Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. doi: 10.1038/s41560-017-0075-y

Gavin & Morstyn, 2019. Chapter 2 in Gall & Stanley (Eds). 2019. Trading sunlight: prospects for peer to peer energy trading in the UK solar industry. Solar Trading Association: London, UK. ISBN 978-1-5272-5273-8

We explored how peer to peer trading platforms help coordination and integrate these resources into existing power system operations and markets. We've seen that small-scale energy generators, i.e. prosumers, are currently incentivised to maximise the use of their own self-generated energy. However if we could coordinate prosumers, and managing their assets together, this would give rise to significant advantages, such as:

- Increased network efficiency;
- The ability to match supply and demand on a local level, which could alleviate the need for investments in generation and transmission infrastructure, and could reduce transmission losses;
- Better management of local power flow and voltage constraints; and
- Accelerated progress to low-cost electrification of heat and transport, which are key steps towards decarbonisation and achieving net zero by 2050; and
- Reduced pollution.

Grouping prosumer assets in this way is commonly termed a **Virtual Power Plant** (VPP). It's virtual because while it doesn't exist as a traditional large centralised power plant, but a network of small distributed energy providers.

Different models

Existing coordination strategies are characterised by a top-down design and centrally controlled by a single entity, which defines the terms. Such top-down strategies may work against the preference of prosumers to manage their resources according to the preferences with regard to risk, environment or equity issues. For example, some prosumers may wish their surplus energy to be subsidised for community hall users or people in fuel poverty.

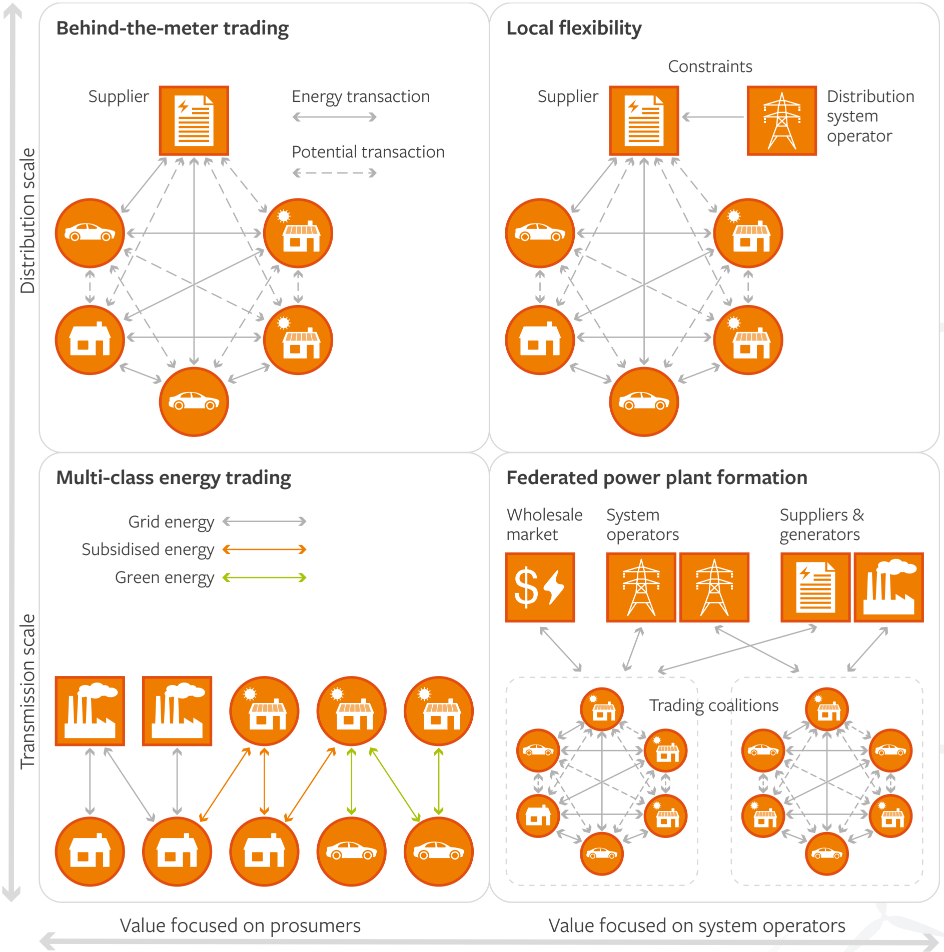
We devised different peer to peer trading models to give more choice to those prosumers who are willing to provide some flexibility, but who are reluctant to give total control to the central intermediary of a Virtual Power Plant and wish to set or negotiate mutually beneficial rules for transactions.

These different P2P energy trading models can be tailed to best suit the energy being transacted, the physical scale of the potential energy trade, and the value offered to the participants. The different business models are

- **Behind-the-meter trading**: Prosumers are incentivised to sell excess generation to other prosumers with flexible loads and storage systems, rather than export it to the wholesale market.
- **Local flexibility**: A single supplier managing energy import and export can organise a local P2P energy market, and buy/sell energy Good for local situations with network constraints.
- **Multi-class energy trading**: Prosumers express additional preferences other than cost e.g. to sell their energy e.g. environmental or philanthropic reasons.
- **Federated power plant**: A bottom up approach which groups prosumers into traditional coalitions, in which the prosumers retain control and define the transactions in which they are willing to take part. The software platform would align the interests, preferences and requirements of electricity consumers, prosumers and power system operators.

A number of pilot schemes and demonstrator projects are currently underway across the world to test and assess different energy trading platforms operating in parallel at different physical and temporal scales.

We look forward to the future opportunities for peer to peer trading for prosumers!


Behind-the-meter trading
Supplier
Energy transaction
Potential transaction
Local flexibility
Constraints
Supplier
Distribution system operator
Multi-class energy trading
Grid energy
Subsidised energy
Green energy
Federated power plant formation
Wholesale market
System operators
Suppliers & generators
Trading coalitions
Distribution scale
Transmission scale
Value focused on prosumers
Value focused on system operators

5 Policy/regulation

Much of the research undertaken in other parts of our research programme has highlighted the need to take a whole systems approach whilst increasing the granularity with which electricity systems are modelled, managed and assessed. This means scaling up from peer-to-peer local energy markets right up to national scale interventions.

How can society design a policy and regulation framework that can and will support the innovation, investment and management of renewable energy resources?

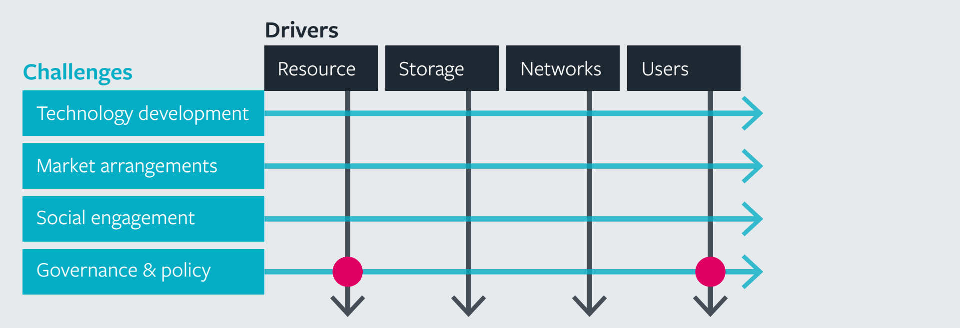
Clean energy innovation is pivotal for meeting future energy needs and eliminating harmful emissions. While there have been great advances forwards in terms of technological development, there remain gaps in knowledge on the support mechanisms that actually generate innovation.

To address this knowledge gap, we looked at policy and regulation in a number of areas:

- Support for clean energy innovation;
- Electricity infrastructure charging; and
- Decarbonising domestic heating.

What are effective ways to support clean energy innovation?

R&D subsidies



Fostering innovation and economic growth is one of the most pressing economic challenges; with most advanced countries offering subsidies for research and development (R&D) comprising hundreds of billions of dollars in public expenditures each year. The economic case is straight-forward: competitive markets undersupply innovative activity as firms cannot realise exclusively, the benefits of their innovations.

Pless, 2019. Are 'complementary policies' substitutes? Evidence from R&D subsidies in the UK. doi: 10.2139/ssrn.3379256

As a result, governments subsidise research and development (R&D) activities general through a mix of different mechanisms, including direct grants and tax credits. But are these effective in encouraging new areas of research that wouldn't have happened before? Do they complement other policies and incentives? Accounting for subsidy interactions could substantially improve the effectiveness of public spending on R&D.

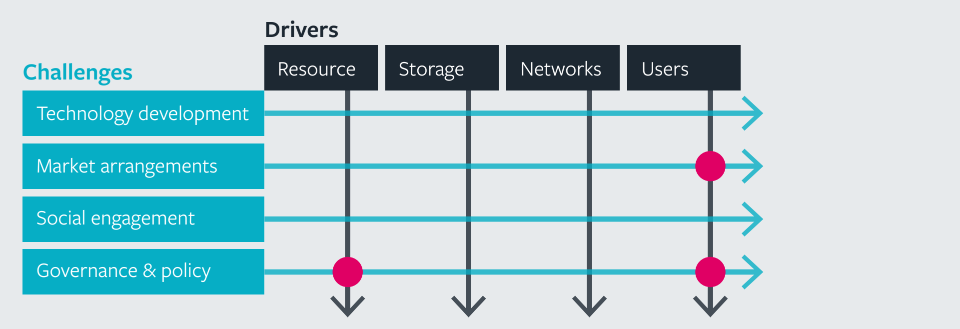
We looked at funding rules, policy changes and the interaction of direct grants and tax credits to explore how they impact commercial activities or behaviour in the UK, and to determine if they are complements or substitutes. These two types of subsidy are among the most popular tools used by policymakers to subsidise clean energy R&D.

The results showed that, for small firms, direct grants and tax credits for R&D are complements. The effect of an increase in tax credit rates is to substantially enhance R&D expenditures, as the subsidy assists with overcoming high fixed costs and eases financial constraints. Subsidy interactions also affect the types of innovation efforts that emerge: with increases in both these types of subsidies, small firms steer efforts toward developing new goods as opposed to improving existing goods. The complementarity of subsidies for small firms suggests that they are under-subsidised.

For larger firms the subsidy acts as a substitute. The higher tax credit rates given to these firms are supporting spending that they would have invested in anyway, without additional subsidy. We find that companies receiving public subsidy tend to reduce R&D investments that are financed internally and through private external finance. This indicates that public funds are crowding out private spending.

These findings have important policy implications, particularly as many countries continue introducing and increasing the generosity of R&D tax credits, with direct grants and tax credits being the most popular tools that policymakers use to support business innovation. We have shown that these subsidies are interdependent, and so these interactions (and scale of enterprises) need to be accounted for when designing policies in order to substantially increase the effectiveness of public spending on R&D.

Innovating for the Environment



Finding solutions and adaptation measures to climate change and need to transition to clean energy systems need significant innovation in many areas, from technology, services, business models, and more. Policy plays an important role in shaping and encouraging innovation systems.

Many governments globally are currently reconsidering their industrial policies to reduce their greenhouse gas emissions. Without cheaper forms of zero-carbon energy, transport, and agriculture, it will likely be impossible to meet the climate targets of the 2015 Paris Climate Agreement; and more innovation in high-carbon technologies may make matters worse.

How can we create policy to ensure that it steers innovation efforts in a direction that helps to protect environmental systems? It is critical to be able to distinguish between innovations that enhance global environmental systems and those that undermine them.

We generated five policy proposals that would support more innovation of the environmentally beneficial kind and less innovation of the environmentally harmful kind.

Hepburn et al, 2018. Policy Brief – Encouraging innovation that protects environmental systems: five policy proposals. doi: 10.1093/reep/rex024

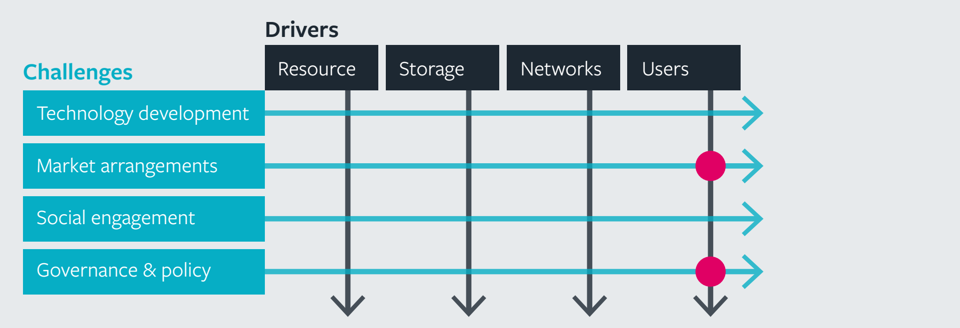
Pless, J., Hepburn, C. & Farrell, N et al, 2020. Bringing rigour to energy innovation policy evaluation. doi: 10.1038/s41560-020-0557-1

- **Policy 1**: Price natural capital properly: This includes implementing more stringent environmental regulations and policies that address environmental externalities and interventions that increase the prices of dirty products, processes, and services.
- **Policy 2**: Support environmentally friendly R&D and innovation and discourage environmentally harmful innovation: This includes providing R&D tax credits and grants in order to reduce the cost to private sector firms of investing in R&D that promotes sustainability. Government laboratories and research institutes can also be supported to complement private sector R&D, particularly for large capital-intensive research projects. Similarly, removing unnecessary subsidies on fossil fuels will discourage innovation that is environmentally harmful.
- **Policy 3**: Support early-stage deployment of clean technologies: This is especially important when there are additional market failures (e.g. learning spill overs, first-of-a-kind costs) or when the economically optimal interventions under policies 1 and 2 are not possible or will not address the urgency implied by planetary boundaries.
- **Policy 4**: Support collaborative R&D: This entails targeting financial support for R&D activities that specifically bring together multiple entities—such as private sector firms, universities, and national laboratories—to capitalise on complementary skills and resources.
- **Policy 5**: Reduce barriers to external financing: This includes policies such as corporate tax relief that rewards investments in clean innovation activities and helps high-risk companies raise funds not only for early-stage R&D but also for companies engaged in the later stages of innovation.

This list of policy recommendations is not intended to be exhaustive. Ultimately the appropriate mix of policies for driving innovation depends on the policy, economic, and social context.

However, we recommend that these policies should be considered in any portfolio of innovation policies aimed at protecting global environmental systems, especially given the urgency of addressing additional pressures on sustainability from climate change risks.

Mission Innovation



Clean energy innovation is pivotal for meeting future energy needs and eliminating harmful emissions. Government funding is needed to support substantial public research and development (R&D) funding to the level required will not be reached by private investor due to market failures and other barriers to innovation. The amount of funding needed is significant, but small compared to the cost of meeting the impacts of unabated climate change.

Pless, J., Hepburn, C. & Farrell, N et al, 2020. Bringing rigour to energy innovation policy evaluation. doi: 10.1038/s41560-020-0557-1

While the amount of funding needed is important, so is the design of support mechanisms and policy portfolios; increases in R&D spending alone do not guarantee successful innovation outcomes. Resources must be spent wisely if they are to achieve the desired innovations, and this is especially so if the R&D spending pledges are not met. Policy design should be based on the best evidence of what works, and why, so that scarce resources are not wasted.

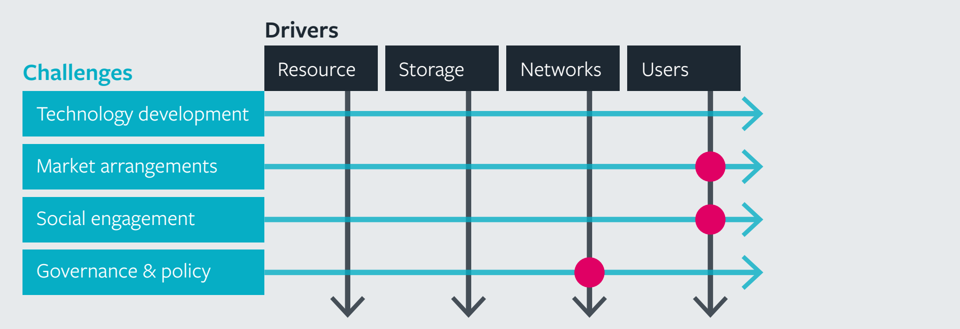
Surprisingly, ways to most effectively drive innovation with public spending is still not well understood. So, we explored how policymakers and grant-making agencies can more effectively spend public funds on clean energy R&D.

We identified four key methodological challenges that must be addressed so that a wider body of robust evidence on innovation policy effectiveness can be created. Removing barriers that contribute to these challenges is critically urgent for understanding the effectiveness of different innovation outcomes that can help deliver a net-zero-carbon energy system. Establishing a causal link between policy and innovation outcomes can be achieved by:

1. **Heterogeneity**: measuring innovation outcomes in new and consistent ways;
2. **Quality and direction of innovation**: identifying the causal effects of R&D public support mechanisms on innovation outcomes;
3. **Mechanism interaction**: examining how policies work together as well as the interaction of actors; and
4. **Persistence**: accounting for time lags between receiving research support and commercial success.

Our most important recommendation is that governments and grant-making agencies should work with innovators and researchers to remove barriers by implementing the above approaches. A disconnect between innovators, legislators, and policymakers leads to regulatory lags or a framework that's not fit for purpose. At the very least, impact evaluations should be conducted. Another recommendation is to develop improved measures of innovation outcomes and consistently track them over time, as well as finding appropriate ways to manage legal restrictions.

Network charging



How does the shift to a power system with distributed energy resources, affect the way in which we pay for electricity – not just what we consume, but all of the required infrastructure from pylons to the cables connecting our homes.

Frerk, 2018. Integrating renewables – the future of network charging.

Historically, there has been broad consensus around the principles to be applied in setting charges. While the key issue of recovering costs is important, there are other criteria such as simplicity, predictability and fairness.

With fossil fuel energy generation, short run costs were known and formed a predictable basis on which to base costing structures and power markets.

The increase in renewable energy has changed this predictable costing basis. While both the short and long run marginal costs for renewable energy is reducing, with short run costs nearly zero, and long run costs following a trend that will see them dropping below fossil fuels, the variable nature of renewable energy, and the need for storage and other technology needed to meet demand causes increased complexity and the need for risk management.

How should this be factored into network pricing? What is the basis or way in which we can balance the need to recover costs, ensure supply, while incorporating social desires such as simplicity, predictability and fairness, as well as decarbonising our energy supply? How can the regulators create and steer a broad framework of principles to a desired direction that is fair and agreed by all? The need to move to meet net Zero and create wholly flexible energy network means that the need to agree these trade-offs has become urgent.

To explore these trade-offs, we examined options for network charging from economic and engineering perspectives to derive a framework for considering trade-offs that will account for spare capacity, wider policy, user choices, visibility of charges, and vulnerable customers.

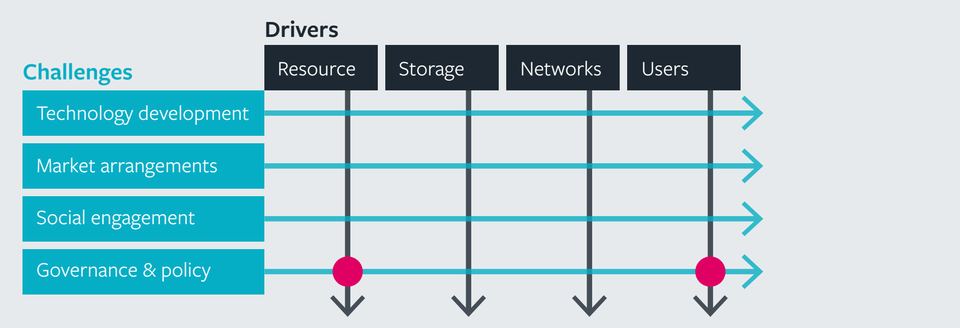
While we have set out a range of different possible tariff structures, we recommend that the "right answer" will depend on many factors. These include the wider industry structure, the mix of distributed energy resources in any particular area (which is dependent on geographical and economic factors amongst others) and the broader policy goals to be addressed.

In summary, we believe that:

1. A greater emphasis should be put on capacity-based charges;
2. Use of capacity charges based on property value as a proxy should be given serious consideration;
3. Charges should ideally be linked to the customer's peak capacity;
4. A charge should also be levied for peak export capacity;
5. Granular charges may be appropriate for large users, but the regime should be kept simple for residential customers;
6. The recovery of costs should be done through charges that mirror what is considered appropriate for cost reflective charges; and
7. It is important to reflect on both long run and short run cost signals, for example through a fixed charge to recover long run costs, and though usage charges to reflect short run costs.

We also recommend that a consumer perspective is brought into what is a highly technical issue. If radical changes are to be made to charges there will be winners and losers. Consumers – and in particular vulnerable consumers – need a stronger voice in this debate.

Domestic heating



Decarbonising domestic space and water heating is a massive challenge for meeting national climate targets, often neglected in current discourse. In Europe, space and water heating account for approximately 80% of final energy use in the domestic sector. To meet the legally binding targets of reducing emissions to below 80% of 1990 levels by 2050, we need to critically reduce the emissions associated with this heating demand.

Barnes & Bhagavathy, 2020. The economics of heat pumps and the (un) intended consequences of government policy. doi: 10.1016/j.enpol.2019.111198

These are the ways in which we can do it:

- Improving the energy efficiency of buildings, so less fuel is needed to achieve comfort, especially for low income households;
- Reducing the carbon intensity of gas by changing to or blending with hydrogen; and
- Using electricity for heating in place of gas, given that the carbon intensity of electricity is now close to, and will be lower than, that of gas before 2025.

One way to use electricity to generate heat in our homes is to use heat pumps, but in the UK they are not commonly used, despite incentives such as the Renewable Heat Incentive.

Why not?

One of the reasons is because **taxes and levies** are applied more heavily on electricity bills than gas bills. While the net effect of these policies on energy has been to lower domestic bills, it is true that current taxes and levies are applied more heavily to electricity than gas bills. This exacerbates the unit price differential between gas and electricity, resulting in electrified forms of heating (such as heat pumps) being unattractive to consumers from a cost perspective.

These are the reasons why taxes and levies are higher on electricity than gas:

- **Taxes**: The EU Emissions Trading Scheme (EU ETS) and carbon floor price in the UK, impose a carbon price on electricity but not on gas. These taxes are passed through to consumers within the wholesale market price of electricity.
- **Levies**: Levies are placed on UK energy suppliers to pay for a range of environmental and social objectives, such as the winter fuel payment. The cost of these levies is passed through to households via domestic energy bills.

We also found that the **upfront cost** of heat pumps is important. The low affordability of low-carbon technologies is probably the most important barrier facing many households that wish to decarbonise their heating. The impact of taxes and levies is relatively small when considered against the very large upfront costs of heat pumps, compared to gas boilers. These large upfront costs will be a major obstacle. This is especially so when occupants think they will not live in the property for a long time. This is despite the fact that efficient heat pumps would cost less to run than gas boilers, if it were not for the taxes and levies on electricity.

In order to remove these barriers, we recommend the following policy interventions to supporting the deployment of heat pumps and help us get to net zero by 2050:

1. Place environmental and social taxes onto general taxation rather than on electricity bills.
2. Increase awareness, training and installation of heat pumps in order to reduce the upfront costs through economies of scale, competition, and lower labour costs.
3. Continue to improve the performance of heat pumps, setting and upholding a minimum efficiency standard that will help minimise running cost.

6 Conclusion

Moving to a renewable and low carbon energy future is an immense challenge but one that is accepted by society across the world as urgently needed to combat climate change.

Our work in the Integrate Programme has helped uncover some of the challenges facing the further integration of renewable energy, across technical, social, economic, and governance issues. We have highlighted the need for a whole system approach to changing energy systems and multidisciplinary solutions for maximise success. Passionate people across the world are developing ways to overcome barriers, find new technological solutions, dismantle economic and regulatory obstacles, and ensure that people are at the heart of equitable change.

Here's to a Net Zero future for everyone, powered by renewable energy!

RESOURCES

Resources

Briefing notes

We have created briefing notes to summarise the key policy implications from specific aspects of our work. You can find the briefings on our website.

Blog posts

A number of written pieces are published on the blog page of the website of the Programme on Integrating Renewable Energy, based on research published in academic journals by researchers.

As the range of work undertaken by the Programme is diverse, so are the blog pieces. We hope you enjoy reading them.

Videos

Bespoke videos made by the Programme are shown on its website and stored on its YouTube channel. The video topics range from explaining research on Vehicle-to-Grid to moving to zero carbon smart electricity systems. The channel also includes the recordings of the webinars the Programme has run covering topics from energy efficiency, moral dilemmas, the issue of electricity access versus reliability, and hydrocarbon taxation.

Publications

Integrate has delivered many academic publications. The multi-disciplinary nature of the Programme can be seen from the range of topics and author collaborations.

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About Integrate

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