Imperial College London

Whole-energy system benefits and consumer benefits of large-scale deployment of MADE concept

MADE Project Report

December 2020

Imperial College Project Team:

Dr. Marko Aunedi
m.aunedi@imperial.ac.uk

Mr. Predrag Djapic
p.djapic@imperial.ac.uk

Prof. Goran Strbac
g.strbac@imperial.ac.uk

Contents

1. Introduction 3
1.1. Background 3
1.2. Benefits of flexibility 3
1.3. Previous assessment of benefits of MADE concept 5
1.4. Key objective 5

2. Main features of MADE technical trials 7
2.1. Field trial research questions 7
2.2. Deployment of MADE concept 8
2.2.1. Time-of-use tariffs 8
2.2.2. Seasonality 8
2.2.3. Asset coordination 9
2.3. Field trial interventions 9
2.4. Key findings 10

3. Whole-system benefits of coordinated management of residential flexibility (MADE concept) 11
3.1. Quantifying whole-system benefits of distributed flexible technologies 11
3.2. Scenarios and key assumptions 12
3.2.1. System benefit of MADE concept 12
3.2.2. Assumptions on the number of households 12
3.2.3. Household energy assets 13
3.2.4. Cost assumptions for residential flexibility 13
3.2.5. Electricity system scenario 14
3.3. Quantitative results 14
3.3.1. Impact on system generation mix 17
3.3.2. Distribution network benefits of MADE concept 18
Modelling Approach 18
3.4. Key observations 19

4. Commercial benefits of MADE concept for household consumers 20
4.1. Quantifying consumer benefits of MADE concept 20
4.2. Numerical results for consumer benefits 20
4.3. Key observations 22

5. Conclusions 23

References 24

1. Introduction

1.1. Background

As a critical component of the pathway to achieving net zero greenhouse gas emissions, the GB energy system will need to undergo a fundamental transformation over the next few decades, with particular emphasis on rapid decarbonisation of the electricity sector. Delivering on such targets will require investing in a portfolio of low-carbon generation technologies accompanied by a steep increase in the provision of flexibility services to enable the cost-effective integration of low-carbon technologies.

Decarbonisation of the energy supply is expected to rely on two main pillars: 1) rapid increase in low-carbon generation, primarily delivered through expanding variable renewable energy sources (wind and solar) that have recently seen significant cost reduction, and 2) electrification of large segments of heat and transport sectors. Both of these factors will lead to increased flexibility requirement, delivered among other means by increased uptake of demand-side response (DSR) and energy storage, to ensure the system can efficiently maintain secure and stable operation in a lower carbon system.

System flexibility, referring to the ability to adjust generation or consumption in the presence of constraints or contingencies in order to maintain a secure system operation, will be the key enabler of the necessary transformation to a cost-effective low-carbon electricity system. There are several flexibility resource options available including highly flexible thermal generation, energy storage, DSR and cross-border interconnection to other systems. Quantitative evidence from recent studies strongly suggests that tapping into residential flexibility sources could unlock significant value for the system to support the decarbonisation of energy supply.

Integration between the heating (and cooling) sector and the electricity system can offer an additional source of flexibility and help unlock further benefits on the pathway to decarbonise both power and heat. A higher degree of integration between electricity and other energy vectors, particularly heat and transport, presents novel and unique opportunities to make use of cross-vector flexibility to support the integration of low-carbon generation technologies and to significantly reduce the cost of decarbonisation. As shown in Imperial College's previous analysis, various alternative heat decarbonisation pathways may be feasible, such as those based on heat networks, hydrogen, biogas, or electrified heating, each with their own cost implications and a rich set of interactions between energy vectors, opening opportunities to utilise the flexibility across multiple vectors.[1]

1.2. Benefits of flexibility

A recent study[2] undertaken by Imperial College to inform the development of the roadmap for flexible resources demonstrated that the system wide benefits of integrating new sources of flexibility relative to the use of conventional thermal generation-based sources of flexibility are potentially very significant – between £3.2bn and £4.7bn per year in a system meeting a carbon emissions target of 100 gCO_2/kWh in 2030. Benefits increase substantially with more

---

1 Imperial College London, "Analysis of alternative UK heat decarbonisation pathways", report for the CCC, 2018.

2 Pöyry Management Consulting and Imperial College London, "Roadmap for flexibility services to 2030", report for the Committee on Climate Change, 2017.

ambitious carbon targets, so that at 50 gCO_2/kWh they are estimated at around £8bn per year.[3] Another study[4] by Imperial College assessed the benefits of flexibility with an even tighter carbon constraint of 25 gCO_2/kWh and found those to be in the region of £10.4-13.6bn per year.

Reaching the 50 gCO_2/kWh by 2030 is broadly in line with achieving net zero greenhouse gas emissions by 2050, although many studies argue that the electricity system should actually aim for net negative emissions in order to support other sectors of the economy that are more difficult to decarbonise (such as industry, agriculture, waste, aviation and shipping). For instance, National Grid's Future Energy Scenarios for the UK, published in July 2020, envisage that in order to achieve net zero greenhouse gas emissions for the whole of the UK's economy, the power sector will need to reach net negative emissions in the early 2030s, dropping to -50 to -100 gCO_2/kWh by 2035.[5] More ambitious carbon reduction targets may drive an even higher requirement for flexibility and the corresponding value than identified in the studies referenced earlier in this section.

Key categories of system 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 the carbon target with less low carbon generation capacity or a cheaper mix of low-carbon technologies.

- 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* due to reduced net peak demand that needs to be met by electricity infrastructure.

More specifically, another recent study based on Imperial's modelling focused on the value of residential behind-the-meter flexibility.[6] One of the key findings is that in a low-carbon electricity system residential flexibility can create whole system cost savings of £6.9bn (or 21% of total system cost), while at the same time delivering savings per household of more than £200 per household per year. A major part of the value comes from intelligent charging of electric vehicles, which can save up to £3.5bn through participating in smart charging, while substantial savings are also identified in the area of smart electric heating.

---

[3] Imperial College London, "Value of flexibility in a decarbonised grid and system externalities of low-carbon generation technologies", report for the Committee on Climate Change, 2015.

[4] Imperial College London, "Value of baseload capacity in low-carbon GB electricity system", report for Ofgem, 2018.

[5] National Grid ESO (2020) *Future Energy Scenarios*. Available at: https://www.nationalgrideso.com/future-energy/future-energy-scenarios

[6] OVO Energy & Imperial College: "Blueprint for a post-carbon society: How residential flexibility is key to decarbonising power, heat and transport", 2018.

1.3. Previous assessment of benefits of MADE concept

In our previous report[7] prepared for the MADE project we quantified high-level system benefits of rolling out the MADE solution at the national level for several future system scenarios. Whole-system case studies presented in that report showed significant opportunities to deliver cost savings by utilising distributed flexibility based on the MADE concept. System benefits were found to increase with the level of penetration of electrified transport and heat as well as with the level of carbon reduction. The benefits in the 2035 horizon were found to potentially exceed £5.6bn per year. The main mechanism for delivering system cost savings is through allowing the system to achieve the system-wide carbon target with a less costly low-carbon generation mix, which also means integrating more low-cost solar PV, while at the same time reducing the requirements for high volumes of peaking generation capacity and distribution network reinforcements.

In addition, our high-granularity distribution network analysis suggested there is also a significant potential for distributed flexibility to deliver distribution network cost savings across different voltage levels and asset types, potentially exceeding £650m per year in avoided reinforcement cost in the 2030 horizon.

This high-level assessment, however, did not take into account the specific features of distributed flexible resources deployed and trialled in MADE project, such as the actual sizes of battery storage, EV characteristics, installed power of solar PV and HP parameters for participating households (it rather used generic high-level assumptions for these parameters). Therefore, the purpose of this report is to provide a more detailed assessment of system-level benefits of large-scale uptake of the MADE concept, as well as put those in the context of likely cost required to enable flexibility from the assets included in MADE portfolio of residential flexibility.

1.4. Key objective

Deploying highly distributed flexible solutions, such as residential flexibility sources, at scale presents significant challenges. Therefore, more evidence from demonstrators and trials is required to fully understand the opportunities for deploying and utilising residential flexibility. Addressing this need is at the core of MADE project, which is looking to develop novel control concepts for efficient management of residential PV resources, smart charging of electric vehicles, smart hybrid heat pumps and residential battery storage. The project is expected to provide insights into what types of solutions are needed to unlock the significant but as yet not fully understood potential of demand-side flexibility.

In this context, the first objective of this report is to estimate *whole-system benefits and consumer benefits of MADE concept* i.e., the system value of smart control of residential low-carbon technologies (LCTs), namely PV generation, EVs, hybrid heat pumps and residential batteries. These benefits are estimated in the report for the 2035 time horizon by scaling up the actual MADE trial data, also estimating the impact of penetration of MADE concept on its system value. System benefit of MADE coordination is quantified both as *gross value* that consists of system cost savings, as well as *net value* that takes into consideration the cost associated with enabling the flexibility through MADE. The cost of enabling MADE is estimated

[7] Imperial College London, "High-level assessment of the benefits of large-scale deployment of the MADE concept", report for MADE project, June 2019.

as the sum of the cost of installing residential battery systems and the cost of installing and maintaining the smart control solution.

The second key objective of the report is to estimate the potential commercial value of the MADE concept for the participating consumers, while assuming efficient market arrangements in the future energy system. This assessment is based on the concept of marginal system benefit of the MADE solution.

2. Main features of MADE technical trials

MADE project focuses on unlocking domestic home flexibility through demand-side response (DSR) and residential battery storage, by aggregating electricity load of EV charging and electric heating. The project builds on previous WPD projects and trials focusing on individual residential technologies, namely EVs (Electric Nation), HHPs (FREEDOM) and solar PV installations (SoLa Bristol). Its objective is to enhance and demonstrate PassivSystems' smart control solutions to manage and coordinate EV charging and domestic electric heating against local solar PV generation, variable rate tariffs and local network conditions.

Going forward, it can be expected that there will be a significant proportion of customers that will want to take advantage of decarbonisation incentives by installing all three LCTs, i.e., purchasing EVs along with the accompanying charging infrastructure, installing solar PV panels as well as fitting their homes with electric or hybrid heat pump heating systems, while also coupling these with residential battery systems. Given the significant intra-day variability in typical PV output profiles and heating demand levels, combined with significant opportunities for flexible EV charging (or discharging), the potential to utilise the flexibility of EV charging concepts and the flexibility provided by battery storage could offer very promising economic and environmental benefits to consumers. Nevertheless, the existing evidence base for understanding these benefits is rather limited, and there is a need for deeper understanding of challenges and opportunities associated with coordination between smart EV charging, home battery management and smart HHP control.

This project therefore aims to investigate the network, consumer and broader energy system implications of high-volume deployment of the combination of domestic vehicle to home (V2H) EV charging with hybrid (domestic gas boiler and air-source heat pump) or heat pump heating systems with solar PV generation. The main device for delivering the benefits of residential flexibility is the application of PassivSystems' smart aggregation and control solution that ensures cost-efficient outcomes for the end customers while meeting their comfort level requirements.

This section provides a summary of MADE field trial and is based on a more detailed technical trial assessment undertaken by PassivSystems, of which only the key elements are included here.

2.1. Field trial research questions

MADE field trial was structured with the objective to carry out the necessary interventions and gather the required monitoring data over the course of the project, and thus facilitate the analysis to answer the following questions:

- How does the overall household demand shape (and balance between the assets) change depending on various scenarios with respect to time-of-use tariffs, level of asset coordination, and over the seasons?
- How does the peak demand change between these scenarios?
- How can the demand shape be influenced by interventions i.e., by controlling the distributed flexible assets?
- What are the drives behind the interactions between smart EV charging and the user of the EV?

2.2. Deployment of MADE concept

The MADE field trial involved five participating homes, each of which had all four types of energy assets installed (PV, EV charger, hybrid heat pump and residential battery). Table 1 summarises the main characteristics of the installations in each of these homes.

Table 1. Characteristics of energy assets installed in MADE field trials

#	*HP type*	*HP manufacturer*	*HP rating (kW_{th})*	*Fossil boiler*	*PV array (kWp)*	*Battery*	*EV Charger*	*EV*
1	ASHP	Samsung	5	LPG Combi	4.41	Sonnen hybrid 5 kWh	New Motion 32 A	Nissan Leaf 30 kWh
2	ASHP	MasterTherm	8	Gas system	3.46	Sonnen hybrid 5 kWh	Alfen 32 A	Hyundai Kona 64 kWh
3	GSHP	MasterTherm	22	Oil system	4.41	Sonnen hybrid 5 kWh	New Motion 32 A	Nissan Leaf 40 kWh
4	ASHP	Samsung	9	LPG system	3.78	Sonnen hybrid 5 kWh	New Motion 32 A	Tesla Model 3 75 kWh
5	ASHP	Samsung	9	Oil system	4.41	Sonnen hybrid 5 kWh	Alfen 32 A	Nissan Leaf 40 kWh

MADE field trial explored the impact of three key drivers on the operation of household energy assets: time-of-use tariffs, seasonality and asset coordination. These are explained in more detail in the following sections.

2.2.1. Time-of-use tariffs

The project used three tariffs in the trial, which were implemented as virtual tariffs:

- **Flat tariff**: This provided a baseline scenario as it represents a great majority of today's homes.
- **Economy 7 tariff**: A tariff with a cheap night-time rate (00:00 – 07:00) provided a straightforward example of a ToU tariff. It is widely deployed today, particularly among EV owners.
- **Octopus Agile tariff**: This is a half-hourly tariff where prices are published day-ahead. It provided a great representation of the needs of the network, combining electricity market prices (national influence) with early evening DUoS charges (local influence).

2.2.2. Seasonality

As the project progresses through the seasons, the balance between the assets changes significantly:

- In winter the PV generation is negligible and electrical load is dominated by the heat pump. The battery is only used for ToU arbitrage.
- Spring and autumn are of great interest as there is more than enough PV generation during the day to power the home and the heat pump, with spare for the EV if plugged in, while domestic battery can provide balancing with PV generation.

- The final phase of the project in summer will be characterised by no heat pump demand and excess PV generation, reaching the limits of the domestic battery capacity to store the generated solar output. It will be significant whether or not the EV is away from home during the day.

The trial is expected to continue until October 2020.

2.2.3. Asset coordination

PassivSystems uses a predictive optimisation algorithm to determine the best strategy for assets under its control. Over the course of the project the number of assets optimised together in a coordinated way has been gradually increased:

- **Independent operation:** Initially assets operated largely independently. The hybrid heating system was optimised against a selected time of use tariff and used the fossil boiler when required to keep the house warm or when it was cheaper to run than the heat pump. The domestic battery automatically self-consumed solar generation and discharged against whole-home demand. The EV charged whenever it was plugged in by the user.

- **Hybrid heating system with solar optimisation:** Enabled the availability of free solar generation to influence the hybrid heat pump operation.

- **Hybrid heating system with solar and battery optimisation:** Optimised the hybrid heating system in combination with the battery and the solar generation. This had significance in ToU tariff scenarios where arbitrage with the battery allowed the heat pump to operate more cost efficiently.

- **Full coordinated operation of hybrid heating system, with solar, battery and smart EV charger:** The needs of the smart EV charger are considered in the optimisation calculation, allowing automatic smart scheduling of EV charging and maximising the capacity of the combined batteries to consume cheap rate electricity.

2.3. Field trial interventions

The project has carried out interventions to explore the flexibility of the system to respond to the needs of the network (beyond the baseline response represented by the ToU tariff). After having identified demand peaks in earlier parts of the technical trial, the trials aimed to reproduce the demand peaks and demonstrate that they can be mitigated by subjecting homes to targeted demand constraints. This illustrated that a multi-asset system need not introduce problems to the network as long as it is controlled by a sufficiently smart system.

The majority of the interventions emulated the mechanisms currently being explored by Western Power Distribution in their Flexible Power offering:

- **Secure:** where an advance commitment is given to reduce power for particular windows in time. In reality the commitment is made week-ahead for specific power reductions against an agreed baseline. The project has instead instructed systems the day-ahead to reduce power by as much as possible during windows the following day, 2-6hrs long in the early evening. A key finding was to identify what the minimum achieved power reduction is over the period.

- **Dynamic:** where an availability window is agreed in advance, and on the day 15 minutes notice is given for a demand reduction. Within the Project a demand constraint was applied with 15 minutes notice. An increased virtual electricity price was also applied during the availability window, priced according to the probability of an intervention and the price per kWh of reducing power, which encouraged the system to store energy in advance of the availability window.

The aim was to understand the flexibility and responsiveness of the multi-asset systems against these mechanisms. The deployment schedule for different interventions is shown in Figure 1.

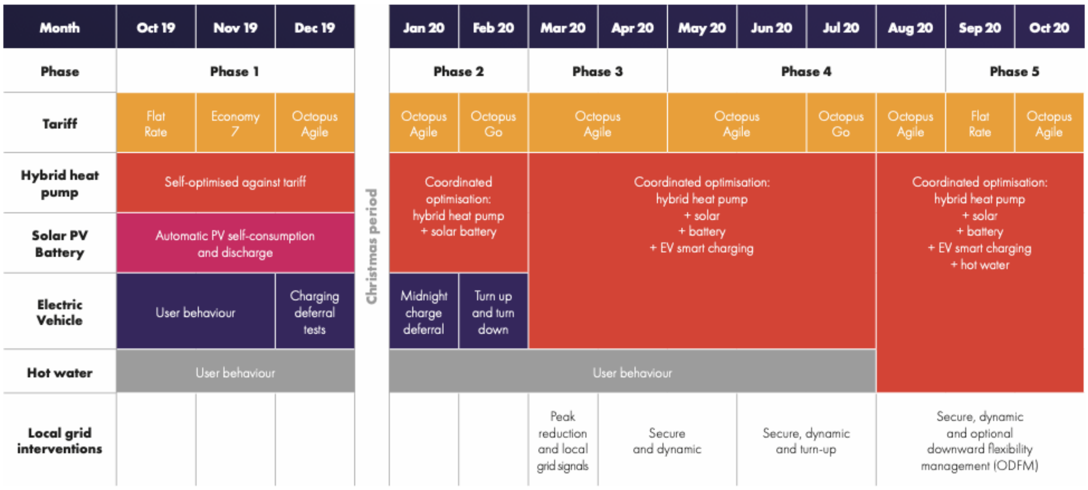


Figure 1. Summary of MADE field trial interventions

2.4. Key findings

Research carried out in the MADE project has shown that there is significant additional value extracted through the coordination of multiple LCTs within a single premise. Both at a system wide level, and at a single property level there are tangible benefits when assets are coordinated rather than operating individually.

With advanced controls it is expected that this flexibility and the associated benefits can be obtained without affecting customer comfort. This is essential if wide scale acceptance of advanced control of LCTs is to be achieved.

The control capabilities have started to be demonstrated within a five-home trial. Further analysis is planned as more advanced control strategies are applied and more data and customer feedback collected. This will highlight the technical control capabilities to implement such coordination as well as initial sample data.

A larger-scale trial would be needed to understand the variance of such response over different geographies and demographics. Nevertheless, the MADE trial is a vital step in developing early understanding in this area.

3. Whole-system benefits of coordinated management of residential flexibility (MADE concept)

This section summarises the approach to quantifying whole-system benefits of a large-scale rollout of the MADE concept, i.e., of coordinated management of residential energy assets. It then proceeds to describe the scenarios included in the quantitative analysis and presents key numerical results.

3.1. Quantifying whole-system benefits of distributed flexible technologies

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 flexible technologies such as energy storage and demand side response. In order to capture trade-offs between different flexible technologies, it is critical that they are all modelled in a single integrated modelling framework. In order to meet this requirement Imperial has developed **Whole-electricity System Investment Model (WeSIM)**, a comprehensive system analysis model that is able to simultaneously balance long-term investment decisions against short-term operation decisions, across generation, transmission and distribution systems, in an integrated fashion.

WeSIM determines optimal decisions for investing into generation, network and/or storage capacity (both in terms of volume and location), in order to satisfy the real-time supply-demand balance in an economically optimal way, while at the same time ensuring efficient levels of security of supply. An advantage of WeSIM over most traditional models is that it is able to simultaneously consider system operation decisions and capacity additions to the system, with the ability to quantify trade-offs of using alternative mitigation measures, such as DSR and storage, for real-time balancing and transmission and distribution network and/or generation reinforcement management. A prominent feature of the model is the ability to capture and quantify the necessary investments in distribution networks in order to meet demand growth and/or distributed generation uptake, based on the concept of statistically representative distribution networks. These statistical archetypes used in the model have been calibrated to actual GB distribution networks to ensure a highly accurate representation of network length, number of transformers and network reinforcement cost.

Analysing future electricity energy at sufficient temporal and spatial granularity is essential for assessing the cost-effectiveness of alternative decarbonisation pathways. In this context, WeSIM based modelling has clearly demonstrated that in order to quantify system operation and investment cost and the carbon performance, quantitative models need to simultaneously consider second-by-second supply-demand balancing issues as well as multi-year investment (e.g., reduced system inertia may trigger investment in flexible technologies). Furthermore, electricity system decarbonisation will also need to adequately consider the synergies and conflicts between local/district level and national (or trans-national) level infrastructure requirements, which is another key feature of WeSIM.

WeSIM carries out an integrated optimisation of electricity system investment and operation and considers two different time horizons: (i) short-term operation with a typical resolution of one hour or half an hour (while also taking into account frequency regulation and short term reserve requirements), which is coupled with (ii) long-term investment i.e., planning decisions with the time horizon of typically one year (the time horizons can be adjusted if needed). All annual investment decisions and 8,760 hourly operation decisions are determined simultaneously in order to achieve an overall optimality of the solution. Key features and constraints considered in WeSIM include: a) power balance, b) reserve and response requirements, c) generator operating limits, d) demand-side response capability; e) distribution network investment, f) carbon emission constraints, g) constraints on electricity imports and exports, and h) security constraints.

3.2. Scenarios and key assumptions

3.2.1. System benefit of MADE concept

Whole-system benefits of MADE concept are quantified for four different levels of uptake of MADE solution: 25%, 50%, 75% and 100% (relative to the number of eligible households). For each of the uptake levels the total system cost is compared to a counterfactual scenario that had a zero uptake of MADE concept but included some flexibility that would likely be provided even without a large-scale rollout of MADE or a similar solution for coordinated control of residential flexibility.

Due to the whole-system nature of Imperial College's modelling approach, the resulting benefits are disaggregated into components of cost savings, distinguishing between generation investment cost (both low-carbon and conventional), operating cost and distribution investment cost. The cost of enabling MADE is also included in total system cost and net benefit figures. Table 2 defines the baseline scenario and MADE scenarios applied:

Asset	Baseline scenario: Optimised assets in silo operation	MADE scenario: Optimised assets with coordinated control (MADE)
Hybrid heat pump: 8 kW	✓	✓
PV generation: 4 kWp	✓	✓
Electric vehicle: 40 kWh battery with charger	✓	✓
Domestic battery with 5 kWh and 2.5 kW diversified peak output	✓	✓
Optimised asset controls	✓	✓
MADE concept: Coordinated control		✓

Table 2: Baseline Vs MADE assets

Imperial College has modelled the costs with and without the MADE concept at a 25%, 50%, 75% and 100% uptake. Any cost reduction achieved by deploying the MADE concept is interpreted as net system benefit of the MADE solution. This is expressed both as aggregate total benefits as well as benefit per participating MADE household, in both scenarios. The benefits are then combined with the estimated cost of enabling MADE to determine the net system benefits, both in aggregate terms and per participating household.

It should also be noted that the analysis is focused on the benefit accrued to the system, rather than the value that can be achieved by participants. Routes to market for many of the value streams do not currently exist.

3.2.2. Assumptions on the number of households

According to the latest data from the Office for National Statistics, there are 28.535 million dwellings in Great Britain, of which 14.748 million are detached, semi-detached houses and bungalows, while the rest are terraced houses and flats. Given that a full deployment of MADE concept will typically require a household with an opportunity to install an EV charger, rooftop PV, a hybrid heat pump system and a residential battery system, it was assumed that only detached houses, semi-detached houses and bungalows will have sufficient space to install a full range of LCTs that are included into the MADE concept. This is a simplifying assumption but is still useful to quantify the system-level benefit of MADE.

3.2.3. Household energy assets

Each MADE-eligible household was assumed to have installed the following LCTs: 1) a hybrid HP system 8kW 2) rooftop PV generation 4kWp, 3) an EV 30kWh and 4) a residential battery system 5kW. If a household had a MADE control system installed (i.e., if it was a part of the MADE rollout), its hybrid HP management, EV charging and battery control were assumed to be carried out with the objective to reduce the overall system cost. This was equivalent to assuming that flexible assets were used to provide services in a fully efficient and cost-reflective market for energy and grid services. If this was not the case, i.e., for non-participating households the utilisation of hybrid HP and EV was assumed to follow less efficient usage patterns, while residential batteries were not available.

3.2.4. Cost assumptions for residential flexibility

The cost of purchasing hybrid HP systems and EVs were not included in the cost estimate of the MADE concept, as it was assumed that these purchasing decisions would be made regardless of whether a household opts to participate in MADE-type control or not.

On the other hand, the cost of installing residential battery storage and the cost of implementing the hardware and software required for smart control were assumed to be in direct correlation with the adoption of MADE concept, i.e., they were considered to represent the direct cost of enabling MADE.

The cost of residential battery storage systems was estimated based on Lazard's levelised cost of storage analysis.[8] The following cost parameters were assumed:

- Capital cost per unit of power: £395/kW
- Capital cost per unit of energy: £197.5/kWh
- Total investment cost for 2.5 kW / 5 kWh battery: £987.5
- Lifetime: 20 years
- Cost of capital: 7%
- Annualised cost per household: £93.2/yr.

The cost of implementing the MADE concept was assumed based on information obtained from PassivSystems, also accounting for the likely cost reductions if this solution is rolled out at scale. The assumed cost of smart control was as follows:

- Upfront cost of hardware, PassivSystems' hub and connectivity: £80 per household
- Service cost: £60 per household per year
- Equipment lifetime: 10 years
- Cost of capital: 7%
- Total annual cost of MADE control: £70.1

---

[8] "Lazard's levelized cost of storage analysis – Version 5.0", November 2019. Available at: https://www.lazard.com/media/451087/lazards-levelized-cost-of-storage-version-50-vf.pdf. Values taken are at the lower range of cost for Residential (PV + Storage), Page 14.

Therefore, the total annual cost per MADE household, consisting of the cost of residential battery storage and the cost of implementing MADE control, is estimated at **£163.3 per year**.

3.2.5. Electricity system scenario

The whole-system benefits of MADE concept in this report are assessed for a GB power system scenario that achieves a carbon intensity of 50 gCO_2/kWh in the 2035 time horizon. This scenario assumed a high uptake of EVs and HHPs in order to be able to assess a broad range of MADE uptake levels. A total of 37 million EVs was assumed on the system, of which 80% was assumed to be connected to MADE-eligible households. The number of hybrid HPs on the system was assumed to be one per MADE-eligible household, or 14.75 million in total.

Initial features of the system were assumed as follows:

- Variable renewables: onshore wind 29.5 GW, offshore wind 28.6 GW, solar PV 68.3 GW (of which 9.3 GW were large-scale PV and the remaining 59 GW were rooftop PV in MADE-eligible households)
- Nuclear: 7.9 GW
- CCS: 2 GW
- CCGT: 20 GW
- Other renewables: biomass 7.1 GW, hydro 1.7 GW, other 1.2 GW
- Interconnection: 20 GW
- Energy storage: pumped-hydro 2.7 GW, large-scale battery storage 5 GW (not including residential battery storage associated with MADE rollout)
- Demand-side response: 20% of DSR uptake was assumed in the baseline scenarios for the I&C sector, and for household appliances, while for the silo asset operation estimate the baseline scenario additionally included smart charging of the entire EV fleet (note that any MADE-enabled flexibility was additional to this)

In order to meet the 50 gCO_2/kWh target, as well as system security, the model was allowed to add more CCS, onshore and offshore wind, CCGT and OCGT capacity, as well as to expand interconnection capacity if cost-efficient.

3.3. Quantitative results

Due to the whole-system nature of our modelling approach, the resulting benefits will be disaggregated into components of cost savings, distinguishing between generation investment cost (both low-carbon and conventional), operating cost and distribution investment cost. The cost of enabling MADE i.e., the cost of residential battery storage and smart control is also included in total system cost and net benefit figures.

Total system cost across the five scenarios (counterfactual plus four MADE uptake scenarios) is shown in Figure 2. Note that the figures for total system cost include the total cost of generation investment and operation cost, but only include the additional cost of reinforcement of distribution and transmission networks (i.e., do not include the cost of existing or fixed network assets). Also, the cost of enabling DSR outside MADE households is not included, although it would be the same across all scenarios and would therefore not affect the estimate of MADE system benefits. The cost of enabling MADE is also included in the charts as a separate category. Total figures are reported using two sets of values, with and without including the cost of MADE.

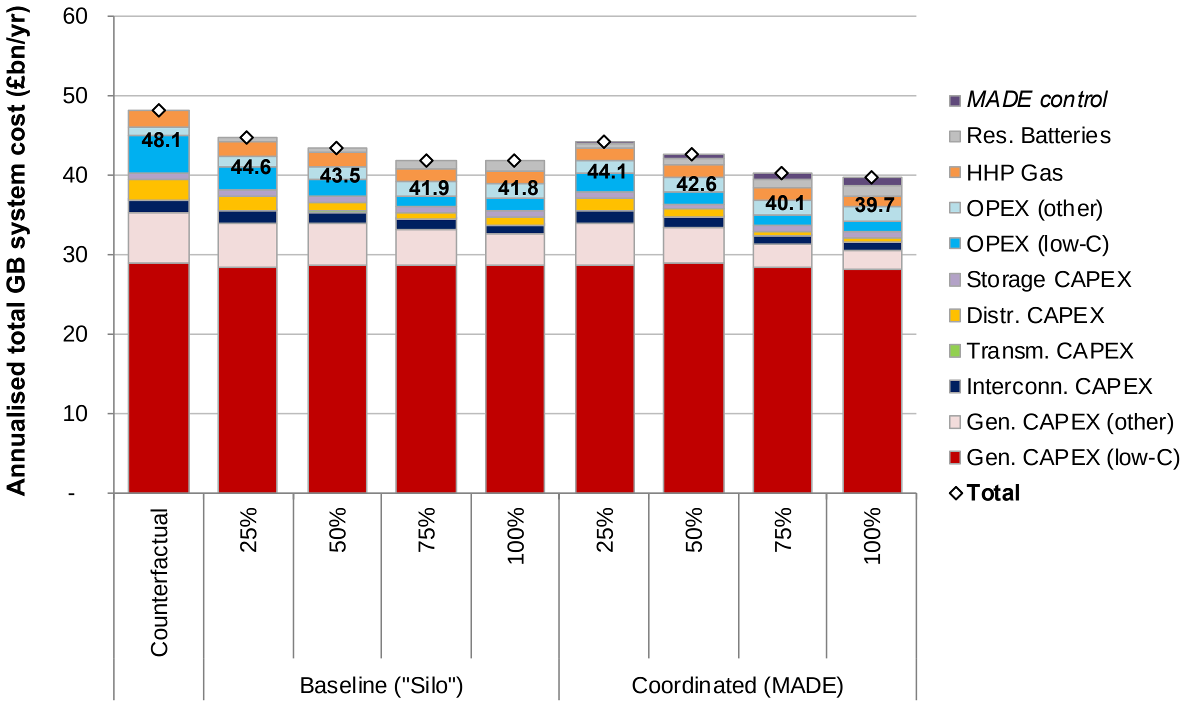
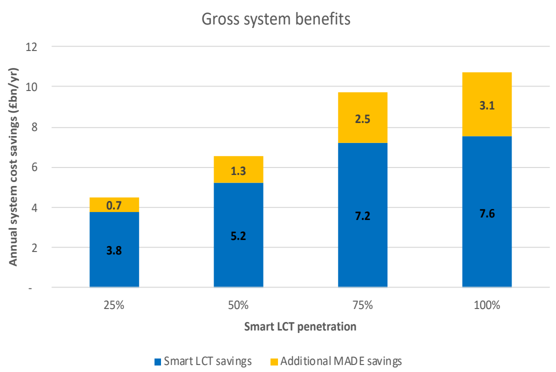


Figure 2: Total system cost across different MADE scenarios

The majority of the system cost is associated with investment in low-carbon generation, with sizeable components associated with conventional generation CAPEX, generation OPEX, interconnection CAPEX and distribution network reinforcement cost. It can be observed that, if the cost of enabling MADE is ignored, the total system cost reduces as the uptake level of MADE concept increases. This cost reduction is the fastest at low MADE uptake levels, whereas at high MADE penetrations there is limited incremental benefit of increasing the number of MADE households. Once the cost of MADE is included in the total system cost, however, the total cost flattens at higher MADE penetrations between 75% and 100%. This suggests that at high levels of uptake the incremental system benefits approximately drop to the level of incremental cost of enabling MADE.

To put the above total cost estimates into context, Imperial College's recent estimate for the total system cost in 2020 was around £27bn/yr. CAPEX of the existing assets base for transmission and distribution, not included in the above figures, has been previously estimated at £2.2bn/yr. and £5.6bn/yr., respectively. Therefore, the system cost in our estimate here for 2035 would be about £9-18bn/yr. higher. Of that increase, about £2.5bn/yr. in the baseline case is the additional distribution CAPEX, dropping to £0.6bn/yr. in the scenario with 100% MADE uptake. However, note that the demand assumed for 2020 was significantly lower due to far lower electrification levels for heat and transport.

System benefits of a large uptake of the MADE concept across the four scenarios can be found as differences between a given MADE uptake scenario and the relevant counterfactual (or baseline) scenarios, as shown in Figure 2 savings are reported as annual values, consisting of annual operating costs and annualised investment costs for different asset types. As in Figure 3, total system cost savings are quantified both as gross benefits (without including the cost of MADE) and as net benefits (reflecting the cost of enabling MADE).



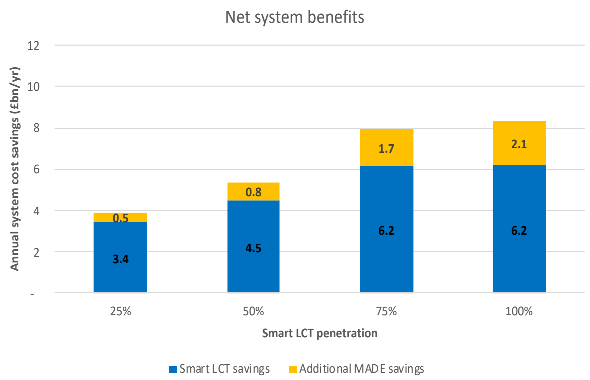


Figure 3: System cost savings by MADE concept: (a) Gross (b) Net

The results in *Figure 3* show that in addition to smart LCT controls, the flexibility delivered via MADE coordinated solutions can achieve substantial system benefits in the order of billions of pounds per year, reaching £3.1bn per year in gross, £2.1bn in net benefits for full MADE penetration. It is also evident that the increase in benefits slows down as the MADE uptake increases, suggesting diminishing benefits of adding new MADE households to an already significant number of MADE-enabled homes. Net benefits of MADE are lower and become saturated at high penetration levels.

Key components of MADE-enabled cost savings include:

- Reduced investment cost of low-carbon generation: distributed flexibility allows cheaper sources of low-carbon electricity (e.g., wind or solar PV) to be integrated more efficiently, and therefore to displace other low-carbon sources (e.g., CCS) while reaching the same carbon target.

- Reduced investment cost of conventional generation: flexible resources can be very effective at reducing peak demand and therefore greatly reduce the need to maintain a high volume of peaking generation capacity to secure a sufficient generation capacity margin and the resulting security of supply.

- Reduced investment cost of distribution networks: highly distributed flexible resources included in the MADE concept can help reduce the loading level of local distribution grids and therefore significantly decrease the requirements to reinforce distribution grids in order to cope with an increase in electricity demand.

- Reduced operating cost of low-carbon generation: as shown later, flexibility can also displace the output of low-carbon generation with relatively higher operating cost, such as CCS or biomass, which is then replaced by lower-cost generation such as wind generation.

3.3.1. Impact on system generation mix

Figures 5a and 5b illustrate how the additional flexibility unlocked through MADE concept affects the cost-optimal generation mix and delivers a more cost-effective portfolio of low-carbon and conventional generation technologies. For the MADE concept (Figure 3a), where the baseline scenario is less flexible, MADE allows for more low-cost wind generation to be connected to the grid, as its integration becomes less challenging, while at the same time displacing the more expensive CCS generation. The capacity of conventional peaking generation (OCGT) is also significantly reduced as the result of enhanced flexibility. In the MADE uptake scenario (5b) we observe smaller changes in the capacities of low-carbon generation technologies, so that the main impact of flexibility delivered through MADE is the reduction in required peaking generation capacity. Note that in the silo operation scenario (5b) the model did not add any CCS generation to meet the carbon target, and therefore no CCS capacity was displaced by deploying residential flexibility.

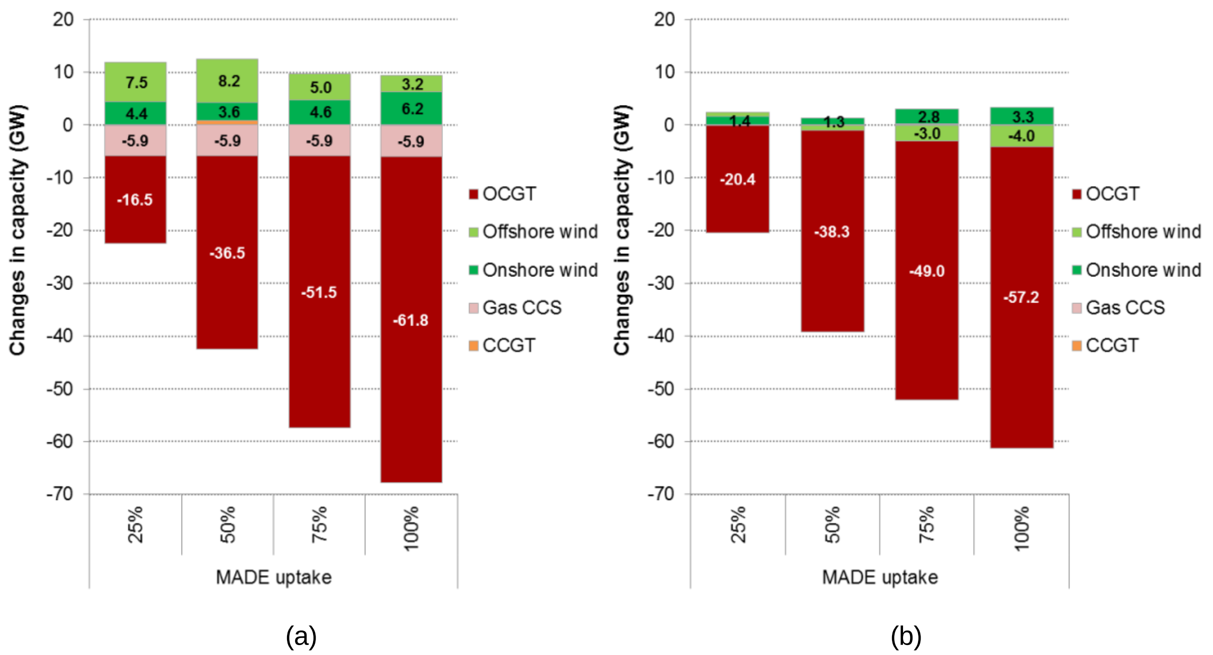
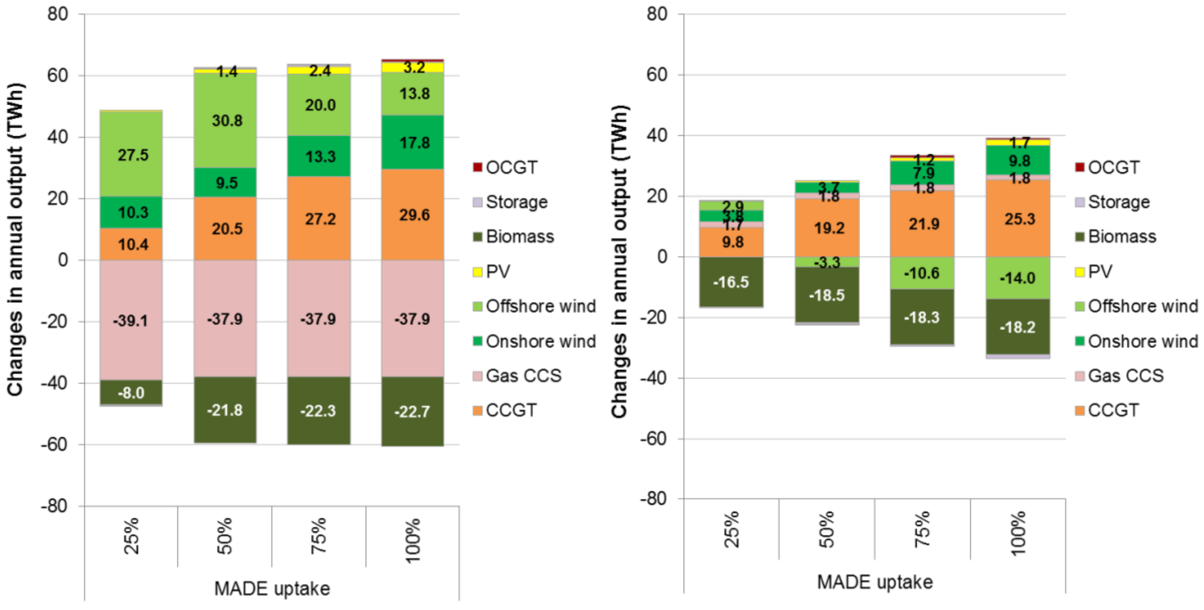


Figure 5. Changes in generation mix driven by MADE concept for (a) coordinated MADE concept (b) silo operation

As well as the generation capacity mix, the distributed flexibility enabled by MADE concept also affects the annual output of different generation technologies. Changes in annual generation output across different scenarios are presented in Figure 6, for coordinated MADE concept (a) and silo operation (b) estimates.



(a) (b)

Figure 6. Changes in annual generation output driven by MADE concept for (a) coordinated MADE concept (b) silo operation

Flexible MADE resources generally allow for more wind output to be integrated and displace the need for higher-marginal cost CCS and biomass output. Also, better utilisation of renewables allows for a higher utilisation of CCGT generation (whose operating cost is also below that of CCS and biomass), despite the same system-level carbon emission target. As with the capacities, in the silo operation scenario there is no CCS output to be displaced, so mostly reflected in displacing biomass generation with higher CCGT output.

3.3.2. Distribution network benefits of MADE concept

Modelling Approach

As shown in Imperial College's earlier studies, significant distribution network reinforcements could be needed to accommodate rapid uptake of EVs and HHPs if these assets are not managed in a network-friendly way. Heat and transport electrification could increase the total cumulative expenditure on distribution networks by up to £50bn by 2035 (or £1.8 billion per year in annualised terms). According to earlier analysis, the total replacement cost of the entire GB distribution network is estimated around £100bn, which makes the £50bn reinforcement cost quite material.

Utilising distributed flexibility, in particular using smart resources such as residential battery storage, EVs and HHPs, could significantly mitigate the impact of electrification of heat and transport on distribution network reinforcement cost. As illustrated in Figure 2 the additional cost of reinforcing GB distribution grids in the baseline scenario (i.e., without any uptake of MADE concept or smart LCT control) is estimated at £2.7bn/yr. It is worth stressing again that these are reinforcement costs that are additional to the CAPEX of the already installed asset base, which in the previous assessments has been estimated at around £5.6bn/yr. With smart LCTs deployed this drops to £1.1bn/yr., a saving of over £1.5bn/year.

When the coordinated control of the MADE concept is rolled out at 100% uptake level, the distribution network reinforcement cost drops to £0.6bn/yr., resulting in a further distribution CAPEX savings of £0.5bn/yr.

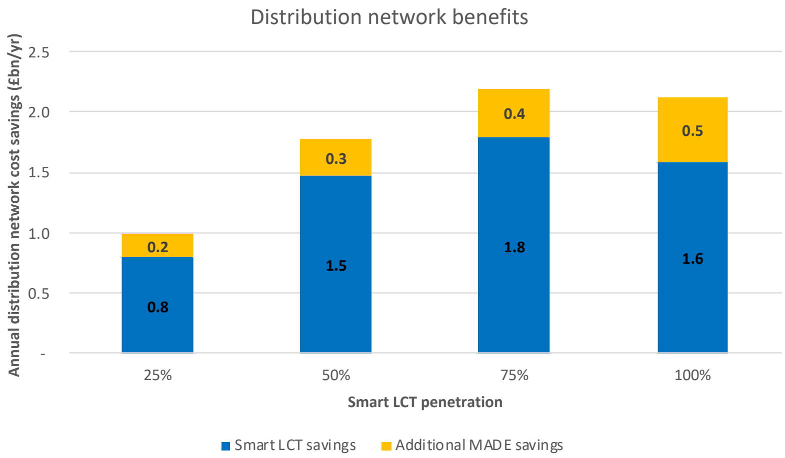


Figure 2. Breakdown of annualised savings in network reinforcement cost driven by MADE concept across voltage levels and network topologies

The results show that the total distribution network benefits of rolling out the MADE concept can reach up to £500m in terms of annualised reinforcement cost, with higher benefits achieved in LV than in HV networks. At higher MADE uptake levels the distribution network benefits tail off, with very limited additional benefits observed when moving from 75% to 100% penetration.

Within both LV and HV levels the predominant savings originate from avoided reinforcement of semiurban networks, which are characterised by a relatively high number of customers, longer network lengths per customer than urban networks, and higher proportion of cables as opposed to overhead lines compared to rural networks. Significant savings also materialise in urban networks, while savings in rural networks are quite low, both due to lower specific network cost and a lower overall demand.

3.4. Key observations

The opportunities to deliver whole-system cost savings by utilising distributed flexibility based on the MADE concept are significant and increase with the level of uptake of the MADE flexible solution. In the 2035 horizon with an ambitious carbon target and high uptake of EVs and HHPs the gross benefits could reach up to £3.1bn per year, through allowing the electricity system to achieve the carbon target more cost-effectively, while at the same time reducing the need for high volumes of peaking generation capacity and distribution network reinforcements. Highest achievable net benefits, after deducing the cost of enabling residential flexibility through MADE, are lower (£0.5 to 2.1bn per year).

The net benefit is still considerable despite moderate levels of flexibility already being present in the system in the form of DSR, large-scale battery storage and interconnectors, as well as smart EVs in the silo asset operation estimates. There is also a significant potential for distributed flexibility to deliver distribution network cost savings across different voltage levels and asset types, which can reach £0.2 to 0.5bn of avoided annualised reinforcement cost in the longer term.

4. Commercial benefits of MADE concept for household consumers

This section extends the analysis presented in the previous section by assessing the commercial benefits that may be available to MADE participating households, assuming efficient market structures are in place for energy, network and ancillary services.

4.1. Quantifying consumer benefits of MADE concept

Previous section quantified the *average benefit* per MADE household, both in terms of gross and net system cost savings. Although it is clear that the average benefit diminishes with increasing MADE uptake, it does not reveal how quickly this benefit reduces for new MADE households added to the already existing portfolio of MADE households, given that the total benefits are averaged out across both early adopters and latecomers.

According to economic theory, *marginal benefits* represent a better approximation for consumer benefits available to participating households if a perfectly efficient market for energy and flexibility is assumed to be in place.

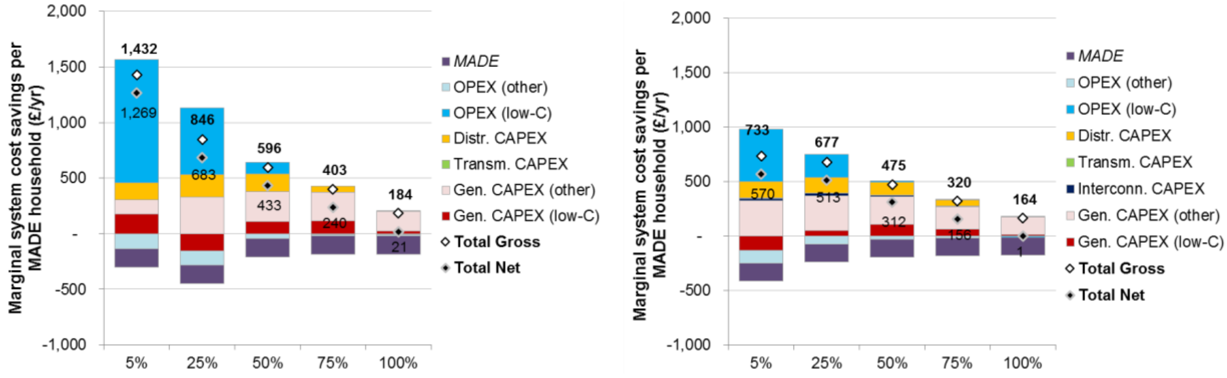
To quantify marginal whole-system benefits of large-scale MADE rollout, we have run an additional set of case studies, where MADE uptake was set to 5%, 20%, 45%, 70% and 95% of the maximum potential number of households. The marginal benefit (MB) at different penetration levels was then found in the following way based on the quantified total system benefit (SB) for a given penetration, divided by the appropriate percentage of total eligible MADE households (MH):

- MB(5%) = [SB(5%) – SB(0%)] / (5% x MH)
- MB(25%) = [SB(25%) – SB(20%)] / (5% x MH)
- MB(50%) = [SB(50%) – SB(45%)] / (5% x MH)
- MB(75%) = [SB(75%) – SB(70%)] / (5% x MH)
- MB(100%) = [SB(100%) – SB(95%)] / (5% x MH)

As before, net marginal benefit is obtained from gross marginal benefit by subtracting the cost of enabling MADE functionality (i.e., the cost necessary hardware and software), as discussed in Section 3.3.

4.2. Numerical results for consumer benefits

Consumer benefits, obtained by quantifying marginal system benefits per participating MADE household, is shown in figure 8 across different MADE penetration levels. The figure shows bot smart silo operational assets and MADE control solution at both gross and net marginal system benefits, and also provides a breakdown of the benefit across key system cost components. Clearly, the consumer benefit approximated by marginal system benefit reduces much faster than the average system benefit per household shown in Figure 8a and 8b, while starting from the same value.



(a) (b)

Figure 8. Marginal system benefits driven by MADE concept (a) and silo asset operation (b) estimates

Early adopters enjoy the highest consumer benefit due to high savings driven by displaced operating cost of low-carbon generation (mostly CCS and biomass), reduced distribution network cost and reduced need for investing in both low-carbon and conventional generation capacity. However, as the penetration increases, most of these benefit components diminish, so that at close to full MADE penetration the only value available to new participants is the displacement of conventional peaking capacity. For the silo asset operation estimate, the gross marginal benefit starts from a value of around £700, which is broadly half the value observed in the coordinated MADE estimate, given that a lot the value has already been captured by smart EVs in the baseline scenario.

Given that any commercial benefits available to consumers will need to justify the cost of deploying smart control and installing residential battery, we also present in figure 2 the net marginal system benefits. This allows us to approximately identify the breakeven point between the incremental cost and incremental benefit of MADE solution. It can be observed that a positive marginal net system benefit for the coordinated MADE estimate is observed at all MADE penetration, although it drops to only £21 annually per household at 100% uptake, while for the silo asset operation estimate the net value effectively becomes zero at 100% uptake. This means that the cost of enabling MADE in households at a very high penetration would cancel the resulting incremental system benefits. Nevertheless, benefits for early adopters appear highly attractive, provided that appropriate market structure are in place to reward them for the benefits they provide to the system.

Note, however, that the high benefits of early adopters may not be available in the long-term as any further increase in MADE penetration would erode the marginal benefits of MADE. According to fundamental economic principles, with a cost-efficient deployment of MADE the marginal gains for MADE participants will erode up to the point where the marginal benefit of MADE broadly equals the marginal cost of enabling MADE, beyond which there would be no further incentive to deploy MADE.

Comparison of average and marginal benefit per household is shown in Figure 9. as function of the number of participating households, for the coordinated MADE estimate and silo asset operation estimates. The functional relationship with the number of MADE households is shown for both gross and net benefits.

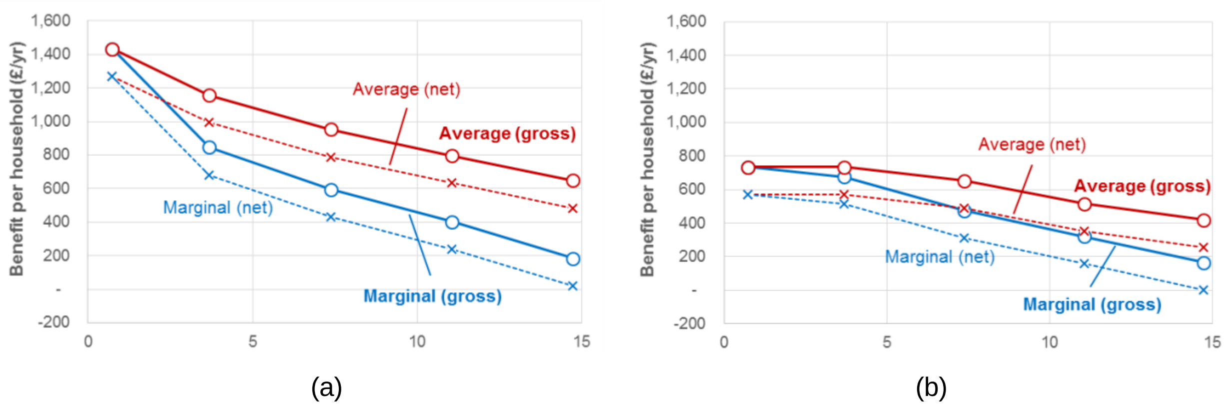


Figure 9. Comparison between average and marginal value of MADE concept (a) and silo asset operation (b) estimates

Both average and marginal value characteristics start from the same value at silo asset operation levels, but soon diverge. For the coordinated MADE concept estimate the value drops rather steeply from a rather high value at 5% penetration: at 25% penetration (around 4 million households) the net marginal benefit is 46% lower than at 5%, while at 50% (around 7.5 million households) it is 66% lower. In the silo asset operation estimate the net marginal benefit starts from a lower value (£570), but its decline is slower (10% less for 25% uptake, and 45% less at 50% uptake). Nevertheless, in both estimates we observe that the net marginal benefit curve approaches zero at full penetration, as the incremental cost of MADE reach the level of the available incremental system benefits.

4.3. Key observations

Commercial benefits of flexible services potentially offered by MADE households have been quantified based on marginal system benefits. The results show a relatively high level of net benefit available to early adopters of the MADE concept, with around £1,270 per year. At 50% MADE penetration this reduces to between £310 and £430 per year, while at 100% penetration net benefits drop to close to zero in both coordinated MADE concept and silo asset operation estimates, suggesting that the opportunities to add value to the system are offset by the cost of implementing MADE functionality at very high uptake levels.

In order for the system value to be extracted by the participating households, the prices paid by the customers will need to more accurately reflect the cost of providing energy and network infrastructure and operating the system than today's pricing structures. This will also require removing a number of barriers that hinder the participation of highly distributed flexibility providers in markets for electricity and grid services. Adequate remuneration mechanisms will be necessary to ensure that the system benefits, quantified as avoided cost in this analysis, actually flow to flexible consumers in the form of revenues; nevertheless, developing such mechanisms is beyond the scope of this report.

5. Conclusions

The analysis by Imperial College has shown that there is significant potential for distributed flexibility to deliver whole-system cost savings with over £8.3bn/yr. net value provided in 2035. Unsurprisingly a large portion of this is attributed the deployment of Smart LCTs (£6.2bn/yr.), however the benefits associated to coordinated control, the MADE concept, remain substantial at £2.1bn/year. Even at lower penetration of the MADE concept, the value that can be unlocked is significant. Imperial College has shown that there is significant potential for distributed flexibility to deliver distribution network cost savings across different voltage levels and asset types, which can reach £200m to £500m of avoided annualised reinforcement cost in the longer term.

References

1. Imperial College London, "High-level assessment of the benefits of large-scale deployment of the MADE concept", report for MADE project, June 2019.

2. Committee on Climate Change, "Net Zero – The UK's contribution to stopping global warming", May 2019. https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

3. Vivid Economics and Imperial College London, "Accelerated electrification and the GB electricity system", report for the CCC, May 2019. https://www.theccc.org.uk/publication/accelerated-electrification-and-the-gb-electricity-system/

4. Imperial College London, "Analysis of alternative UK heat decarbonisation pathways", report for the CCC, 2018. https://www.theccc.org.uk/publication/analysis-of-alternative-uk-heat-decarbonisation-pathways/

5. OVO Energy & Imperial College: "Blueprint for a post-carbon society: How residential flexibility is key to decarbonising power, heat and transport", 2018. https://www.ovoenergy.com/binaries/content/assets/documents/pdfs/newsroom/blueprint-for-a-post-carbon-society-how-residential-flexibility-is-key-to-decarbonising-power-heat-and-transport/blueprintforapostcarbonsocietypdf-compressed.pdf

6. Pöyry Management Consulting and Imperial College London, "Roadmap for flexibility services to 2030", report for the Committee on Climate Change, 2017. https://www.theccc.org.uk/publication/roadmap-for-flexibility-services-to-2030-poyry-and-imperial-college-london/

7. Imperial College London, "Value of flexibility in a decarbonised grid and system externalities of low-carbon generation technologies", report for the Committee on Climate Change, 2015. https://www.theccc.org.uk/publication/value-of-flexibility-in-a-decarbonised-grid-and-system-externalities-of-low-carbon-generation-technologies/

8. Imperial College London, "Value of baseload capacity in low-carbon GB electricity system", report for Ofgem, 2018. https://www.ofgem.gov.uk/publications-and-updates/value-baseload-capacity-low-carbon-gb-electricity-system-2018

9. "Freedom Project: Final Report", October 2018. https://www.westernpower.co.uk/projects/freedom

10. G. Strbac, D. Pudjianto, M. Aunedi, D. Papadaskalopoulos, P. Djapic, Yujian Ye, R. Moreira, H. Karimi, Ying Fan, "Cost-Effective Decarbonization in a Decentralized Market: The Benefits of Using Flexible Technologies and Resources", IEEE Power & Energy Magazine, pp. 25-36, March/April 2019. DOI: 10.1109/MPE.2018.2885390

11. M. Sun, P. Djapic, M. Aunedi, D. Pudjianto, G. Strbac, "Benefits of smart control of hybrid heat pumps: An analysis of field trial data", Applied Energy, August 2019, vol. 247, pp. 525-536, DOI: 10.1016/j.apenergy.2019.04.068