Whole System Assessment of the Potential Benefits of the FlexiCell concept in the UK Low-Carbon Energy Futures

Report for the FlexiCell Project

Xi Zhang, Hossein Ameli, Danny Pudjianto, Predrag Djapic Goran Strbac

Imperial College London

1 Executive Summary

The electricity and heat sectors are major contributors to carbon emissions in the UK. While significant progress has been witnessed in the decarbonization of the electricity sector through large-scale integration of renewable energy sources (RES), there is bottleneck in decarbonizing the heat sector since space and water heating in buildings is still dominated by nature gas boilers.

Amongst the emerging low-carbon heating technologies, micro combined heat and power (micro-CHP), air source heat pumps (ASHP) and thermal energy storage (TES) are showing significant prospects and attracting increased attentions in the transition to the decarbonized energy system. Specifically: 1) Micro-CHP shows superiority due to its high overall energy efficiency (typically 90% above) and its close proximity to the end-use premises which can reduce the need for energy delivery infrastructure and losses. Micro-CHP can also provide back-up capacity to cover local peak demand, and it can serve as an alternative heating source to the conventional gas boiler in a smart home environment, improving the efficiency of the management of electricity and heat demand. Moreover, micro-CHP can provide flexibility and system services for the electricity system which is particularly valuable in the context of high penetration of renewable energy sources in the future low-carbon energy systems; 2) Heat pumps convert electric energy into thermal energy with a typical efficiency of more than 250%. It serves as a key coupling component that links the electricity system and the heat system, thus, from the whole system perspective, enabling the transfer of decarbonization pressure from the heat sector to the electricity sector; 3) TES plays an important role in supporting the economic operation of ASHP and CHPs, particularly in the context of deep electrification of the heat sector in which the flexibility of heating is critical considering the significant volatility and tremendous peak-to-valley difference of heat demand.

Therefore, the uptake of FlexiCell concept, which involves the technology combination of micro-CHP + ASHP + TES, can potentially improve the overall energy system efficiency, thereby driving significant savings in system operational costs, and also increase the heat and electricity infrastructure utilisation, which from the whole system perspective can significantly reduce the requirement for energy infrastructure expansion needed to cover the peak demand. Additionally, the FlexiCell concept can potentially provide huge amount of flexibility to the electricity system, which is particularly valuable in the context of large-scale integration of the renewable energy sources into the energy system and deep electrification of the heat sector. However, without appropriate control strategies to aggregate and coordinate these decentralised flexibilities in households, they will not be able to bring benefits from either the individual perspective or the whole system perspective, especially when a large population of consumers adopt the FlexiCell concept. Therefore, the coordinated control of operation of micro-CHP, ASHP and TES is critical for enabling the FlexiCell concept to substantively achieve economic and environmental benefits, while meeting consumer heat requirements. In this context, it is important to quantify the flexibility values of the FlexiCell concept for the whole energy system under coordinated control while not compromising on service quality delivered to consumers.

One of the objectives of the FlexiCell project is to assess the role of the FlexiCell concept in the future UK energy system, both in terms of potential for householder decarbonization and cost saving, but also as a flexible asset within the wider energy system. In the FlexiCell field trial, two types of tariff schemes, i.e., agile tariff and flat tariff, are used to determine the economically optimal heating strategy through coordinated control of micro-CHP, ASHP and TES application of individual households, that would minimise consumer bills while meeting heat requirements. This field trial is aimed to facilitate:

- Understanding the potential of a combined ASHP + micro-CHP + TES solution to meet a household requirements for heating and hot water while minimising carbon emissions and running costs, and in particular what control strategies are the most effective.
- Understanding the impact of a combined ASHP + micro-CHP + TES solutions on the householders, and the consumers attitudes towards the methods of heating and hot water provision.
- Understanding the potential benefits of an ASHP + micro-CHP + TES solution for the wider energy system, including characterisation of its electricity demand flexibility.

The focus of this report is to assess the environmental and economic values of the FlexiCell concept for energy system decarbonisation from the whole system perspective and investigate the role that coordinated control plays for large-scale adoption of the FlexiCell concept. A series of studies have been implemented to quantify the values of the FlexiCell heating technology in the future low carbon UK energy system. The benefits provided by the FlexiCell concept are derived from the economic savings obtained by adopting the technology combination of micro-CHP + ASHP + TES against the counterfactual scenario in which FlexiCell concept is not used. Sensitivity analysis is performed to find the main drivers of the value of the FlexiCell concept. Specifically, the research involves analysis on the impact of FlexiCell concept on the capacity and operation of the electricity and the heat systems and the impact on carbon emissions including gas consumption across different uptake scenarios and system backgrounds. In order to evaluate the system benefits of the FlexiCell concept, a comprehensive range of simulation studies has been carried out to examine the impact of the FlexiCell heating technology combination on different sectors of the electricity systems (low carbon and conventional generation, main transmission and distribution systems) for different future scenarios. The analysis considers present grid mix and the impact of likely changes in the future, based on national energy plans and their central projections for the change in the generation mix through time.

The benefits of the FlexiCell concept are quantified by finding the performance differences between two systems, i.e. :

(i) a system without the FlexiCell concept, called the Benchmark scenario, where the electricity is supplied by a portfolio of generation excluding fuel cell based micro-CHP, meanwhile, the heat demand is met by electric heat pump with support from TES, but without contribution from micro-CHP,

(ii) a system with the full package of the FlexiCell concept, called the FlexiCell scenario, where the electricity demand was supplied by a portfolio of generation including micro-CHP which also contributes to the heat supply.

It is important to note that the heat output of the micro-CHP only supplies part of the domestic heat demand (space heating and hot water); and therefore, in practice, other means of heating technologies, i.e., heat pumps and TES are critical in managing the balance between heat demand and supply. The economic and carbon performance of these two systems are evaluated using a set of analysis tools developed by Imperial College London, i.e., Whole Energy System Model (IWES). The key feature of the IWES is in its capability to minimise the total system operation and infrastructure investment costs while delivering the carbon target and meeting consumer requirements. The model is based on the whole system approach which is able to optimise the interactions between heat and electricity sectors. Thus, the model enables a spectrum of holistic analysis at a system level to quantify the multiple system benefits of the FlexiCell concept. The performance differences between the two investigated scenarios, i.e., with and without the FlexiCell concept determines the whole system benefits of the specified technology portfolios in the low-carbon energy system. In order to capture the range of whole system implication of integrating the FlexiCell concept in the future energy system, two uptake scenarios, i.e., low and high scenarios, are investigated in the studies. Additionally, we use the IWES model to fully optimize the penetration of FlexiCell concept as a reference scenario. The average hourly profiles of heat generated by micro-CHP in the FlexiCell project field trial are applied in the study to reflect the actual average load factor of the micro-CHP.

It should be emphasised that the involvement of micro-CHP fundamentally differentiates the FlexiCell concept from the other low-carbon heating solutions, since the benefit of micro-CHP is still open to debate while heat pumps and TES are widely regarded as effective technologies that can facilitate heat decarbonization. Therefore, the case studies highlight the important role that micro-CHP plays in the FlexiCell concept. Since micro-CHP is not expected to cover the whole heat demand, heat pump and TES can cost-effectively support the efficient operation of micro-CHP. Therefore, the FlexiCell concept requires development of advanced control strategies to facilitate the synergies between micro-CHP, ASHP and TES. In this context, the values of smart control for the FlexiCell concept are particularly investigated in this report. The uptake of the FlexiCell concept will reduce the capacity requirement in the power system and improve the overall operation efficiency of the system with lower carbon intensity. In these studies, for each case, the system capacity portfolio and the operation of both power and heat sectors is optimised using the IWES model.

The aim of the report is to provide evidence related to the overall macro-economic and macro-environmental implication of a widespread rollout of the FlexiCell concept for the future low-carbon energy systems. Based on the results of the studies and analyses, the key findings are summarized as follows:

- The FlexiCell concept can bring the following whole system benefits:
  - Displacement of capacity of conventional generation. The FlexiCell concept can provide firm capacity to the system, and also fulfil some functionalities of conventional generations, e.g., provision of balancing services, including frequency response and operating reserve. Therefore, it can provide savings in the investment in conventional generation.
  - Increase the utilization rate of heating appliances. Displace the capacity of alternative heat sources. In the short-term, micro-CHP can efficiently displace heat pumps as an alternative heat source. Additionally, large-scale deployment of micro-CHP reduces the dependence on TES for flexibility-associated motivations in the transition of large scale heat electrification.
  - Reduction is system operating costs. Net energy consumption is reduced indicating higher energy efficiency.
  - Reduction in distribution network reinforcement; Through the coordinated control of micro-CHP, ASHP and TES, the electricity peak demand van be significantly reduced without essentially undermining the environmental benefits. Moreover, by adopting the FlexiCell concept, micro-CHP generates electricity at the end-side and supplies the local electricity demand. This can significantly facilitate the alleviation/delay of distribution network reinforcement. Therefore, the deployment of the FlexiCell concept can benefit the distribution network through both the heat sector and the electricity sector.
  - Providing demand response. The heating technology combination specified by the FlexiCell concept can provide various system services to the electricity system, which can facilitate the integration of renewable energy sources and reduce the requirement of nuclear and other firm low carbon generation generation.
- The ability of biogas based micro-CHP to displace natural gas micro-CHP will depend on the cost of biogas. When biogas price is high, micro-CHP would supply peak of heat demand. In this case the load factor of micro-CHP would be particularly low, therefore undermining its operational values. When biogas price is relatively low, micro-CHP can potentially compete with ASHP to supply off-peak load, thus increasing its load factor. Additionally, since biogas micro-CHP is carbon neutral, it can also compete with RES.
- The whole system benefit of large-scale uptake of the FlexiCell concept is sensitive to the decrease of micro-CHP CAPEX, since the high capital cost of micro-CHP for end-use compared to ASHP is the key limiting factor currently.

Meanwhile, the whole system benefit of large-scale uptake of the FlexiCell concept is less sensitive to the change of the carbon target in all CAPEX scenarios.

- Large savings are driven by the provision of system services by the FlexiCell concept, from 5.94£bn/year to 9.28£bn/year in different carbon scenarios. If the FlexiCell concept provides system services, the coordinated operation of micro-CHP, ASHP and TES can reduce the system integration costs of intermittent renewables, thus increasing the penetration of RES and reducing capacity of firm low carbon technologies such as nuclear and CCS generation.
- The coordinated control of the FlexiCell concept is very important in facilitating cost-effective transition to the low-carbon energy system. The modelling demonstrated that the absence of coordinated control in the FlexiCell concept would dramatically reduce the operation efficiency of the integrated electricity and heat system, causing significant increase of OPEX. Furthermore, this would drive increase in investment in both local and national infrastructure, e.g., leading to significant distribution network reinforcement and increase in back-up generation capacity. Without smart control, micro-CHP, ASHP and TES, will not be able to provide very valuable flexibility services to energy system. As a result, the majority of system services will have to be provided by conventional generation or electric storage, which would significantly increase the system integration costs of intermittent renewables, thus increasing the costs of energy system decarbonisation. In this context, more nuclear and CCS based generation will be required.

According to the findings of the analyses carried out, it can be concluded that the FlexiCell concept can bring significant all-round benefits to the decarbonisation of the UK energy system in both short and long run. Acknowledgement of these system benefits would enable the FlexiCell concept to participate in the power and heat sectors decarbonisation and compete with other low-carbon technologies. This would require development of appropriate market framework that would enable alignment of the objectives of investors and society in the context cost effective transition to low carbon energy future.

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2 Introduction of the FlexiCell project

2.1 Aims of the FlexiCell project

The FlexiCell project aimed to investigate the potential synergies between Combined Heat and Power (CHP) units, Air Source Heat Pumps (ASHP), and phase change material (PCM) thermal energy storage (TES). This is a potentially extremely low carbon combination, as electricity is generated in the home by the CHP, which is used to power appliances in the house, as well as the heat pump, avoiding losses in electricity transmission. At the same time, "waste" heat from power generation in the CHP is used to provide domestic hot water and space heating (whereas in a power station this heat would largely be discarded). The phase change materials increase the potential to store this heat and use it later, without requiring very large physical space for a buffer tank. The downside of course is the capital cost: the combination of two expensive systems is unlikely to be commercially viable in the near future, but it is significant to explore the potential for this type of system in the longer term. The project utilised three trial homes. The FlexiCell configuration consisted of a SolidPower BlueGen fuel cell CHP, a Samsung ASHP and two SunAmp phase change material TES — one for domestic hot water provision and one to enable the CHP to contribute to space heating. Although the project was small scale in terms of number of homes, it utilised a complex arrangement of assets, and the overall approach had a research emphasis to understand how well these systems can potentially work together within the home. The interaction of these systems with the wider electricity network was also within scope, however live aggregate demand management was not explored due to the small number of homes involved.

The broad aim of the project was to gain a better understanding of the potential role for the micro-CHP + heat pump hybrid (together with thermal storage) within the future UK energy system, both in terms of potential for householder decarbonization and cost saving, but also as a flexible asset within the wider electricity grid.

In particular, the field trial is aimed to facilitate:

- Understanding the potential of a combined ASHP + micro-CHP + TES solution to meet a household's requirements for heating and hot water while minimising carbon emissions and running costs, and in particular what control strategies are the most effective.
- Understanding the impact of a combined ASHP + micro-CHP + TES solutions on the householders, and the consumer's attitudes towards the methods of heating and hot water provision.
- Understanding the potential benefits of an ASHP + micro-CHP + TES solution for the wider energy system, including characterisation of its electricity demand flexibility.

2.2 Overview of key heating components in FlexiCell concept

2.2.1 Fuel cell micro-CHP

A fuel cell micro-CHP system consists of a small fuel cell or a heat engine driving a generator which produces electric power and heat for an individual building's heating, ventilation, and air conditioning. A micro-CHP may primarily follow heat demand, delivering electricity as the by-product. Alternatively, its operation could also be driven by electrical demand especially as a mid-merit/peaking plant when a high marginal cost of generators needs to operate, or the capacity of electrical generation is scarce. The micro-CHP system may also include a thermal energy storage system enabling a smoother micro-CHP operation as the heat can be stored or released according to the temporal system requirement. The use of micro-CHP systems is appealing due to two fundamental reasons: (i) the overall efficiency of energy conversion is above 90%, much higher than the efficiency of combined-cycle gas turbine (CCGT) around 60%, (ii) the systems are installed at the end-use premises reducing the need for energy transport infrastructure and losses. The system can also provide a local backup capacity, improving the energy security at the local level. The micro-CHP system can become an alternative or supplement to the conventional gas boiler in a smart home environment where the electricity and heat demand can be managed more efficiently. However, the issue of the environmental and economic value of micro-CHP, particularly when fuelled by natural gas, is the subject of much debate. It is unclear whether the use of natural gas fuel cell micro-CHP is of limited value, as the grid is likely to decarbonize so fast that CHP-generated electricity based on natural gas will become part of a problem rather than a solution before the technology has matured. Others argue that the nature of the generation from CHP is such that it will displace high polluting central power generation plant for many decades to come and hence has huge environmental benefits in the long term. Moreover, in the long term, biogas or hydrogen at volume could provide an alternative renewable gas to natural gas, which makes a case for the fuel cell micro-CHP more appealing. In addition, it is also unclear how the roll out of fuel cell micro-CHP will benefit the power system in the future energy system. There is a view that micro-CHP may reduce the peak demand for electricity hence it reduces the system capacity (generation, transmission, and distribution) requirement while at the same time, it improves the efficiency and reduces the operating cost. On the other hand, high penetration of distributed generation may trigger voltage rises or reverse power flow problems in distribution networks, especially during off-peak demand. Therefore, it is important to understand the net benefit of the micro-CHP in this context. Another important issue that needs to be understood is the interactions between the micro-CHP and other heat decarbonization technologies such as heat pumps.

The FlexiCell field trial utilised a SolidPower BlueGen fuel cell micro-CHP.

- The electrical output can be modulated in the 500W to 1500W range
- The thermal output varies between 650W and 760W depending on the electrical power.

The hydraulic design is as follows:

- Water is drawn through the CHP heat recovery circuit unit with an external circulation pump. It is then directed to either the hot water TES or the space heating TES using a diverter valve arrangement.
- Priority is given to the hot water TES so that the space heating TES is only given heat when the hot water TES is full.
- When both TES are full the circulation pump will shut down. The micro-CHP will operate fine in this mode: excess heat simply goes out of the flue, rather than being recovered as useful heat via the heat exchanger.

2.2.2 Air source heat pump

An electric air source heat pump produces heat by consuming electricity, typically with an "efficiency" of more than 200%, and it is expected to be the technology that can most significantly decarbonize the heating sector. However, due to the considerable peak-to-valley difference of heat demand, high penetration of heat pumps will increase the electricity peak demand, driving significant reinforcement of the electricity infrastructure (distribution and transmission networks and electricity generation) while reducing the utilization of heating assets. Additionally, the efficiency of ASHP highly depends on the temperature difference between the heat source and the heat sink. Therefore, specifically for ASHP, the lower the ambient temperature (typically reflects higher heat demand), the lower the efficiency. Therefore, the system integration cost and the smart control of ASHP should be considered when optimising the design of the future energy system.

The system in the FlexiCell field trial incorporated an ASHP to provide the majority of the space heating for the houses. Samsung HPs were used for the project and were sized with the expectation that they could meet the entire space heating load of the house in the normal way, without needing to cover domestic hot water. The ASHP was connected directly to the heat delivery system (radiators etc).

The design ensured:

- The ASHP could provide heat directly and did not need to charge a TES. This would be inefficient for an ASHP as it forces a higher temperature operation than is necessarily required to heat the house. SunAmp do provide a lower temperature PCM TES, but even that requires a 45°C flow temperature to charge it (whereas we'd expect ASHPs to be operating lower than that much of the time).
- The ASHP could operate simultaneously with the micro-CHP unit, providing heat to the heating system at the same time as the micro-CHP was heating one or other of the TES. This was crucial as it enabled the ASHP to consume electricity generated by the micro-CHP. Due to the higher flow temperatures of the micro-CHP unit, it was not necessarily possible for it to put heat directly into the radiators simultaneously with the ASHP, so the TES enabled simultaneous operation.

2.2.3 Thermal energy storage

The deployment of TES, which is characterized by low capital costs relative to electric energy storage, could significantly benefit the integrated electricity and heat system by shifting a significant amount of flexibility from the heat sector to the electricity sector, thus facilitating the cost-effective transition of current fossil fuel dominated heat sector to a highly electrified heat sector and mitigating the challenges of large-scale electrification of the heat sector. TES solutions are fundamentally distinguished, based on the way heat is stored, into sensible, latent storage. Sensible solutions rely on the temperature increase/decrease of the storage medium to accumulate and retrieve heat. These are widely adopted solutions, particularly for buildings or solar power plants. The advantages are safety, abundance and low-cost of the storage material, and efficiency can be improved by ensuring optimal water stratification in the tank. However, operating temperature is limited to 100 °C and the energy density is relatively low, which may be less attractive when space is a concern. Latent heat thermal energy storage is based on the phase change of the storage medium, commonly called phase change material, and with the associated absorption/release of heat. Such TES technology allows to handle a larger amount of energy with smaller storage volume and contained temperature differences.

TES can bring significant benefits on both the consumer level and the system level. From the perspective of consumers, TES enables energy arbitrage, especially in a highly electrified heating system. Specifically, individual households increase heating power relative to the actual heat demand when the energy price is low, and charge TES with the surplus thermal energy. When the energy price is high, households can reduce the heating power and use the thermal energy in TES to compensate for the power gap, thus achieving savings in heating bills. However, with large-scale deployment of the TES and deep electrification of residential heaters, coordination of the TES operation across a large population of consumers has to be present to drive effective energy arbitrage for each individual consumer. Without whole system coordinative measures, collective unilateral charging/discharging of individual consumers would severely distort the original marginal generation costs, thereby dramatically undermining the operational value of TES. TES can also play an important role in accommodating renewable energy sources (RES) and providing various system services. In the context of mass heat electrification, TES can displace the capacity of generation as well as participating in network congestion management, thus alleviating the burden of power system expansion, e.g., generation investment and network reinforcement.

The FlexiCell field trial utilised SunAmp TES. A SunAmp TES contains a phase change material that takes a lot of energy to transition it through a phase change. This phase change happens at a particular temperature, in this case at 58°C. The SunAmp TES has four pipes connected: flow and return to charge the TES, and flow and return to discharge the TES. To charge a TES, water at a higher temperature (in this case, at least 65°C) is passed through it. To discharge a TES, a separate pair of pipe connections is used, and water passed through these will be heated by the material (and in this case will be at 50-55°C). Note that this means that the TES can only produce the same temperature that the ASHP can at the top end of its operation, so cannot provide a significant heating boost, but can enable the ASHP to be turned off for a period.

Homes utilised two SunAmp phase change TES, which were charged using heat from the micro-CHP:

- A hot water TES. This provided instantaneous domestic hot water (DHW) simply by passing cold water in, which was heated up by the TES. This TES also incorporated a 3kW immersion element which could be used to heat it up if insufficient heat was provided by the micro-CHP.
- A space heating TES. This was heated by the micro-CHP once the DHW TES was charged sufficiently or full. We had a circulation pump which could be turned on to draw heat from this TES into the radiators (or other heat delivery system) to provide space heating to the house.

2.3 Whole system analysis for the FlexiCell concept

It is important to understand whether micro-CHP competes with ASHPs and TES, or the combination of these technologies (the FlexiCell concept) can work supplementing each other on the whole system level. In this context, the work presented in this report is an attempt to gain a better understanding of the aforementioned issues. In order to do so, whole system integrated electricity and heat system models have been developed, and a range of simulation studies have been carried out to examine the impact of FlexiCell concept on the electricity system for different future scenarios. The analysis considers today’ s grid mix and the impact of likely changes in the future, based on national energy plans and their central projections for the change in the generation mix through time. The studies also explore the impact of the FlexiCell concept on future investment requirements for electricity distribution.

The aim of the analysis is to provide definitive results and a set of analyses on the overall macro-economics, in the power system context, and the macro-environmental implications of a widespread rollout of the FlexiCell concept for the future electricity systems. This involves analyses on the impact of the FlexiCell concept on the infrastructure capacity expansion (power generation, distribution, end-use heating appliances) and the operation of the electricity systems across the UK and the impact on CO2 across different uptake scenarios and system backgrounds taking into account how the generation mixes in the UK will evolve to a low-carbon and sustainable energy system. The insight obtained from these studies can facilitate informed discussions on how micro-CHP will play its roles in the future energy systems.

2.4 Research Questions

The following research questions were proposed for the FlexiCell project:

- What are the whole system benefits of a heating system which applies the FlexiCell concept that combining a micro-CHP unit with ASHP and TES?
- How are these benefits affected by the system specification?
    - Specifically, the sizing of the micro-CHP unit and the choice of fuel cell vs gas engine (balance of electricity and heat generation); and whether there could be oversupply of heat from the micro-CHP.
    - Specifically, the sizing of the ASHP and its control capabilities such as third party modulation control.
- What are the values of the flexibilities provided by the FlexiCell concept to the overall energy system?
- How can the flexibility of micro-CHP, ASHP and TES be utilised to benefit the local and national electricity grid?

3 Methodology

3.1 Overall approaches

In order to evaluate the system benefits of the FlexiCell concept, two systems were developed: (i) a system without the FlexiCell concept, called the Reference scenario, where the electricity is supplied by a portfolio of generation excluding fuel cell micro-CHP, meanwhile, the heat demand is met only using ASHP with potential support from TES, but without contribution from micro-CHP, (ii) a system with the full package of the FlexiCell concept, called the FlexiCell scenario, where the electricity demand was supplied by a portfolio of generation including micro-CHP which also contributes to the heat supply.

The economic and carbon performance of these two systems were evaluated using Imperial' s analysis tools, i.e., IWES. The performance differences between these two systems determine the costs or benefits of the FlexiCell concept on the system.

3.2 Overview of the Whole-electricity System Investment Model

The IWES model incorporates the modelling of various technologies and captures the interaction across different energy carriers (e.g., electricity, heat and gas), as illustrated in Figure 1.

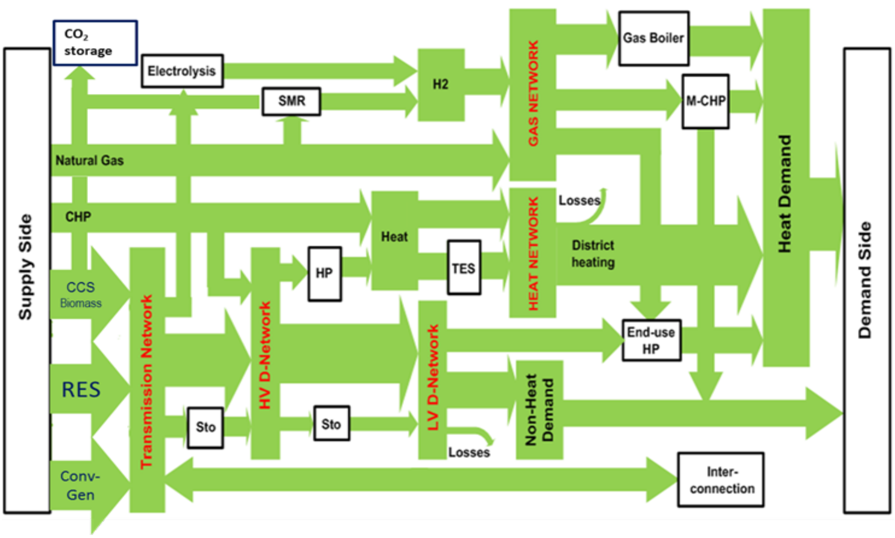
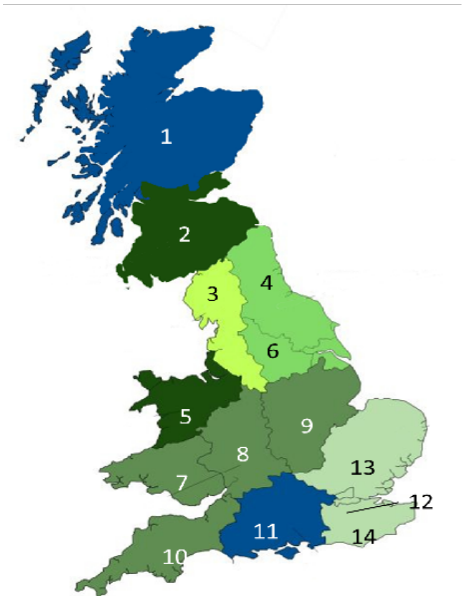


Figure 1. Modelling of technologies in IWES

For example: where actions in the heating system (such as retaining hot water stores) can complement measures in the electricity system, the model can use these as opportunities to minimise the overall energy system costs. The IWES model can optimise the energy supply, transmission and distribution infrastructure requirements and the additional system (e.g., balancing) services required in each of the above scenarios. It can also be adopted to optimise the decarbonization strategy of the combined electricity and heat system, selecting the cost-effective portfolio of heating technologies, including micro-CHP, heat pumps, gas boilers, resistive heaters, and district heating networks. In summary, the IWES model minimises the total cost of long-term infrastructure investment and short-term operating cost, while considering the flexibility provided by different technologies and advanced demand control, and meeting carbon targets. The IWES model includes electricity, gas, hydrogen, transport, and heat systems, simultaneously considering both short-term operation and long-term investment decisions, covering both local district and national/international level energy infrastructure. It also includes carbon emissions and security constraints. The spatial and temporal resolutions of IWES are illustrated in Figure 2 and Figure 3, respectively.



Region	Region name
1	North Scotland
2	South Scotland
3	North West England
4	North East England
5	North Wales, Merseyside and Cheshire
6	Yorkshire
7	South Wales
8	West Midlands
9	East Midlands
10	South West England
11	Southern England
12	London
13	East England
14	South East England

Figure 2. Spatial resolution, considering both local & national level infrastructure in IWES

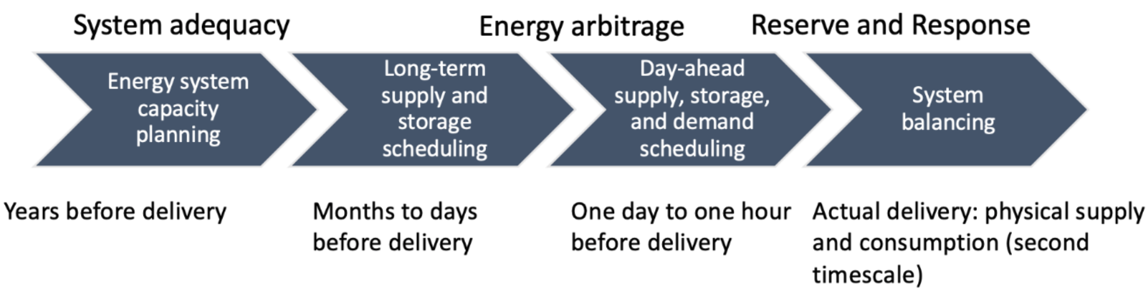


Figure 3. Temporal resolution of IWES

In this context, IWES is a holistic model that enables 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 (including the impact of inertia effects) in an economically optimal way, while at the same time ensuring efficient levels of security of supply. A key feature of IWES is in its capability to simultaneously consider system operation decisions and infrastructure additions to the system, with the ability to quantify trade-offs of using alternative technologies, for real-time balancing and transmission network and/or generation reinforcement management.

Due to various interactions between different levels of assets, the investment strategy for infrastructure at one level can influence investment at the other levels. For instance, the electrification of heat systems on the end-use side will drive:

- reinforcement of the distribution network (distribution level);
- reduced investment in the heat network (distribution level);
- consequential investment in generation (transmission level) and in the reinforcement of the transmission network (transmission level).

Therefore, it is imperative to incorporate the whole system perspective when designing micro-CHP and integrating them into energy systems. In this way, synergies between local and national system objectives can be maximised.

In a nutshell, IWES minimises the system costs by optimising the generation (both low-carbon and conventional), transmission, distribution, storage, and heating sources (heat pump, micro-CHP and TES) and their operating dispatches with hourly time resolution while maintaining the security of the system and meeting the carbon target. Through the IWES model, the whole system values of micro-CHP in supporting the cost-effective transition to a low-carbon energy system can be analysed across different vectors. This model has already been used to facilitate studies for BEIS, CCC, Ofgem and also EU addressing the questions around the integration of low-carbon technologies.

By applying a fractal-based algorithm, a series of representative local distribution networks, covering various types of areas, e.g., urban, suburban, semirural and rural, are generated. Given the length of cables, the number of consumers and substations in each generated representative network, each region in the GB area can be represented by a combination of the representative networks. The combination coefficients of different representative networks are calibrated with the realistic parameters of distribution networks on the region level, comprising the total length of cables, the total number of substations and consumers. It should be stressed that although the parameters of realistic distribution networks are typically case-specific which can be highly different from each other even of the same type, the analysis of the large regions represented by the combination of representative distribution networks provides an accurate estimation of the reinforcement cost of realistic distribution networks.

According to the distribution network reinforcement model in IWES, the reinforcing cost of distribution networks is expressed as a linearised function of the increased capacity of local network, which is determined by the increase of peak demand within the distribution network due to the electrification of the heat sector. As aforementioned, key typical representative distribution networks, covering various geographic types of areas are generated by through the fractal-based algorithm and will be incorporated into optimization problem. The design parameters of the representative networks represent those of real distribution networks of similar topologies, for instance with regards to the number and type of consumers and load density (e.g. high-load density city/town networks to low-density rural networks), associated network lengths and costs, etc. key typical representative distribution networks, covering urban, sub-urban, semi-rural, or rural areas, are created by using the fractal-based algorithm and are incorporated into this model.

The key input data for IWES are:

- Generation data which include the capacity, operational cost, production profile and technical characteristics of different generation technologies such as conventional coal and gas-fired power generation, coal/gas CCS, nuclear, wind, solar PV, Concentrated Solar Power, various hydro technologies, geothermal, biomass, micro-CHP (based on the high and low scenarios), and peaking plant such as oil or gas-fired Open Cycle Gas Turbine (OCGT). In this study, the capacity of each generation technology including micro-CHP is given except the capacity of OCGT which is optimised by the model to ensure the supply reliability.

- Electricity demand and heat demand data. The latter only comprises the heat demand which is supplied by the micro-CHP in the micro-CHP scenario. The heat demand is obtained from the derived data submitted by WP2. Demand flexibilities can also be modelled in this tool allowing flexible demand to be time-shifted for peak-load reduction or energy arbitrage and to provide balancing services such as frequency regulation and reserve services.

- Network data that include the topology and capacity of interconnectors and the cost of reinforcing the capacity. The capacity is optimised to ensure that merit generators are not constrained sub-optimally. Based on those data, IWES determines the optimal investment in generation peaking, heat pump, and network capacity and the optimal allocation of resources across the system in order to minimise the overall investment and operational costs.

Figure 4 demonstrates the framework of optimization problem in IWES.

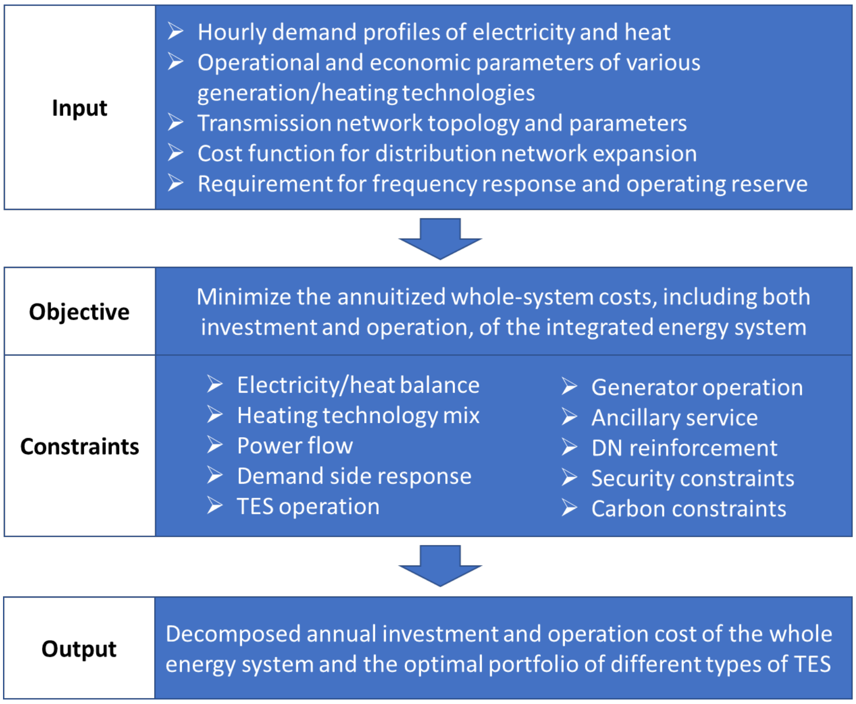


Figure 4 Optimization framework

The key output data of IWES that are used in the study are the following:

- Generation capacity and the associated capital costs;

- Capacity of heat pump and the associated capital costs;

- Network capacity and the associated capital costs;

- Electricity production from different technologies and the operation costs;

- Carbon emissions.

There are a number of assumptions used in the study as listed below.

- micro-CHP can be dispatched when its capacity is needed by the system for example as a peaking/backup capacity when there is shortage in the system capacity;

- The cost of natural gas used by micro-CHP is the same as the cost of gas used in the CCGT;

- micro-CHP is also exposed to the same carbon price (€/tonne) as applied to large-scale generators; the impact of the carbon prices is also a function of the level of emissions.

4 System benefits of the FlexiCell concept

The focus of this section is to quantify the whole system benefits of the deployment of the FlexiCell concept in different scenarios considering various impacting factors.

4.1 Value quantification of FlexiCell concept in the low-carbon energy system

4.1.1 Impacts of the FlexiCell concept on the whole system cost

The FlexiCell concept involves the technology combination of micro-CHP + ASHP + TES. The whole system assessment of the environmental and economic values of the FlexiCell concept for energy system decarbonization, particularly when competing with other heating decarbonization solutions, e.g., ASHP + TES, is the core of this subsection.

It is worth emphasizing that heat pumps and TES are widely seen as effective technologies that can facilitate heat decarbonization while the benefit of micro-CHP is still open to debate, therefore, the involvement of micro-CHP fundamentally differentiates the FlexiCell concept from the other low-carbon heating solutions. In this context, the following case studies will highlight the important role micro-CHP plays in the FlexiCell concept. Based on this note, the comparison between two heating decarbonization solutions is carried out:

(i) the FlexiCell concept in which the heating technology combination of natural gas micro-CHP + ASHP + PCM-based TES is adopted, and

(ii) the benchmark solution in which micro-CHP is excluded from the FlexiCell concept.

In both heating decarbonization solutions, TES serves as a complimentary heating device to provide flexibility for the energy system. In the FlexiCell concept, two micro-CHP uptake scenarios are considered, specifically in the low uptake scenario, 15GW (in electricity generation) of micro-CHP is considered in the overall deployment of the FlexiCell concept, while 60GW of micro-CHP is used in the high uptake scenario. Besides these two given scenarios, we demonstrate the results under the optimal penetration of micro-CHP for the FlexiCell concept based on the IWES model. Additionally, three carbon targets, i.e., 50g/kWh, 25g/kWh and 10g/kWh are considered to investigate the system benefits of the FlexiCell concept under different decarbonization requirements.

The results are presented in Figure 5, expressed in £/kW electrical capacity of micro-CHP. Explanations for different components in the figure are given in the following:

- The green block (LC-Gen CAPEX) represents the savings in CAPEX of low-carbon generation, including nuclear plants, wind and PV generation as well as CCS power plants.

- The purple block (Con-Gen CAPEX) represents the savings in CAPEX of conventional generation, particularly referring to CCGT and back-up generation, i.e., OCGT.
- The yellow block (DN CAPEX) represents the savings in CAPEX of electricity distribution network reinforcement.
- The blue block (HA CAPEX) represents the savings in CAPEX of heating appliance apart from micro-CHP, which mainly include ASHP and TES.
- The red block represents OPEX of different kinds, including conventional generation, CCS-associated operation costs and micro-CHP operation costs. Note that positive values represent savings while negative values represent additional costs.
- The black dot with numbers in the figure highlights the net system benefits of the FlexiCell concept.

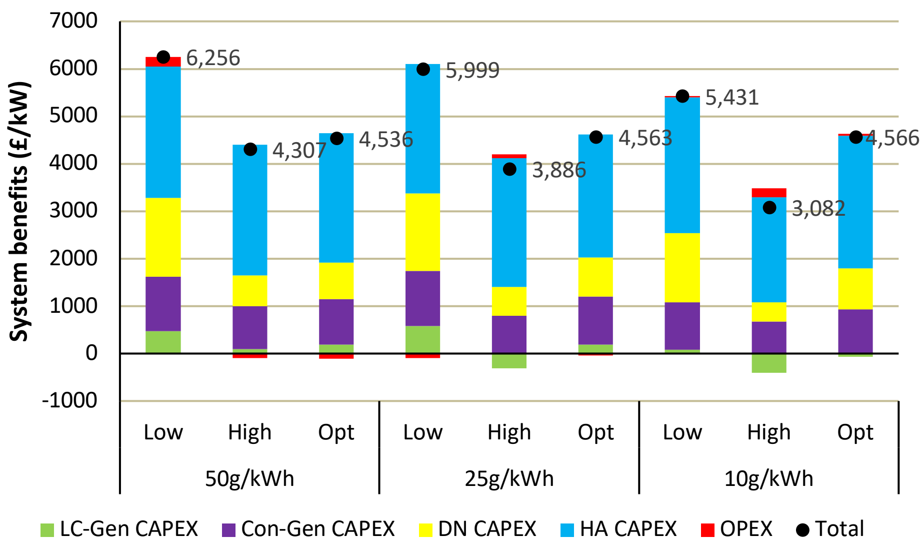


Figure 5. Unit system benefits of the FlexiCell concept

Based on the results in Figure 5, the system benefits are obtained from the following:

- The reduction in conventional generation CAPEX as the deployment of micro-CHP specified by the FlexiCell concept reduces the capacity of CCGT or OCGT or the combination of both. It is important to note that the cost of micro-CHP itself is not accounted, and therefore the figures shown in Figure 5 represent the gross value of the FlexiCell concept. Therefore, whether the FlexiCell concept can bring whole system savings highly depends on the CAPEX of micro-CHP.
- Reduction in low-carbon generation can also be observed in some scenarios, especially when the carbon target is less demanding. However, when the carbon target is tightened, additional cost associated with the expansion of low-carbon generation is likely to be incurred, particularly when the uptake of the FlexiCell concept is high.

- The savings from reduced investment in ASHP. These savings represent the avoided capital cost of ASHP as the heat demand is partly shifted to micro-CHP in the FlexiCell concept. Moreover, the results indicate that the requirement for TES is also alleviated with the deployment of the FlexiCell concept, which further increases its system values.
- The savings in distribution network reinforcement cost (DN CAPEX). The increase in distributed generation capacities due to large-scale deployment of the FlexiCell concept can reduce the distribution capacity requirements.
- Changes in the operating cost (OPEX). The overall savings in OPEX is case specific. On the one hand, the FlexiCell concept can displace a significant proportion of conventional generation due to the involvement of micro-CHP, which effectively drives reduction in OPEX. On the other hand, micro-CHP operates on natural gas, increasing OPEX. Therefore, the changes in OPEX are not consistent and depend on other factors, e.g., and the uptake of the FlexiCell concept, the carbon target, etc.

It is important to note that the CAPEX of micro-CHP is not included in the results, but the OPEX of micro-CHP has been included.

The results in Figure 5 provide the following insight:

- the savings come from three different sources:
    - Savings in HA CAPEX; as the largest saving component. This indicates that in the short-term, micro-CHP can efficiently displace ASHP as an alternative heat source in the FlexiCell concept. Additionally, large-scale deployment of the FlexiCell concept reduces the dependence on TES for flexibility-associated motivations in the transition of mass heat electrification. This is because heat demand is typically characterized by high volatility and the tremendous peak-to-valley difference. Without appropriate flexibility measures, electrification of the heat sector through ASHP, will inevitably drive significant reinforcement of the distribution network. This can pose tremendous burden to the infrastructure investment. Meanwhile, the installation of full-size ASHP for covering the peak heat demand would make the utilization of ASHP extremely low. In this context, TES, typically characterized by remarkably lower capital cost compared to electric storage, provides a promising opportunity in alleviating the challenges of mass heat electrification. Alternatively, the introduction of micro-CHP as a back-up heat source in the FlexiCell concept can reduce the capacity of ASHP, therefore, reduces the requirement of TES.
    - Savings in Con-Gen CAPEX, indicating that the FlexiCell concept can provide firm capacity to the system, and also fulfil some functionalities of conventional generations, e.g., providing frequency response and operating reserve.
    - Savings in DN CAPEX. Since micro-CHP is a type of distributed generation installed at the end-side, it supplies both electricity and heat demand locally.

Therefore, the FlexiCell concept can effectively reduce the requirement of energy distribution.

- The unit benefit (£/kW) of micro-CHP is affected by the penetration of the FlexiCell concept. As can be seen, the system benefit in the high uptake scenarios is lower than in low uptake scenarios. This indicates the marginal value of FlexiCell concept reduces with the increase in penetration. It is further observed that the benefits of both low and high uptake scenarios decrease with the tightening of the carbon target. This is because the micro-CHP operates on natural gas, therefore, its advantage decreases in tighter carbon scenarios. Regarding the optimal uptake, the system benefits do not experience significant variations in different carbon scenarios, although slight decrease is observed.
- The FlexiCell concept can provide various system services to the electricity system, which can facilitate the integration of renewables and reduce the requirements for firm low carbon generation, such as nuclear.
- Through smart control, the operation of micro-CHP, ASHP and TES in the FlexiCell concept can be coordinated in an economic manner. Since the energy efficiency of ASHP can be affected by the outer environment, e.g., ambient temperature, when the heat conversion efficiency of ASHP is high, the ASHP supplies heat load while micro-CHP stands by. When the weather is cold which significantly reduces the efficiency of ASHP, micro-CHP can be switched on to support the heat supply, meanwhile, TES can discharge to complement heat provision. Since this period is typically characterized by demand peaks, micro-CHP serves as a complimentary heating measure, which is responsible for the peak demand so that heating power of ASHP can be considerably reduced during these low-efficiency periods. Additionally, the coordination of the ASHP and micro-CHP can also be motivated by decarbonization. For instance, when the system carbon intensity is low, i.e., the output of RES is high, the utilization of ASHP is prioritised; when the system carbon intensity is high, micro-CHP can serve as the main heating source.

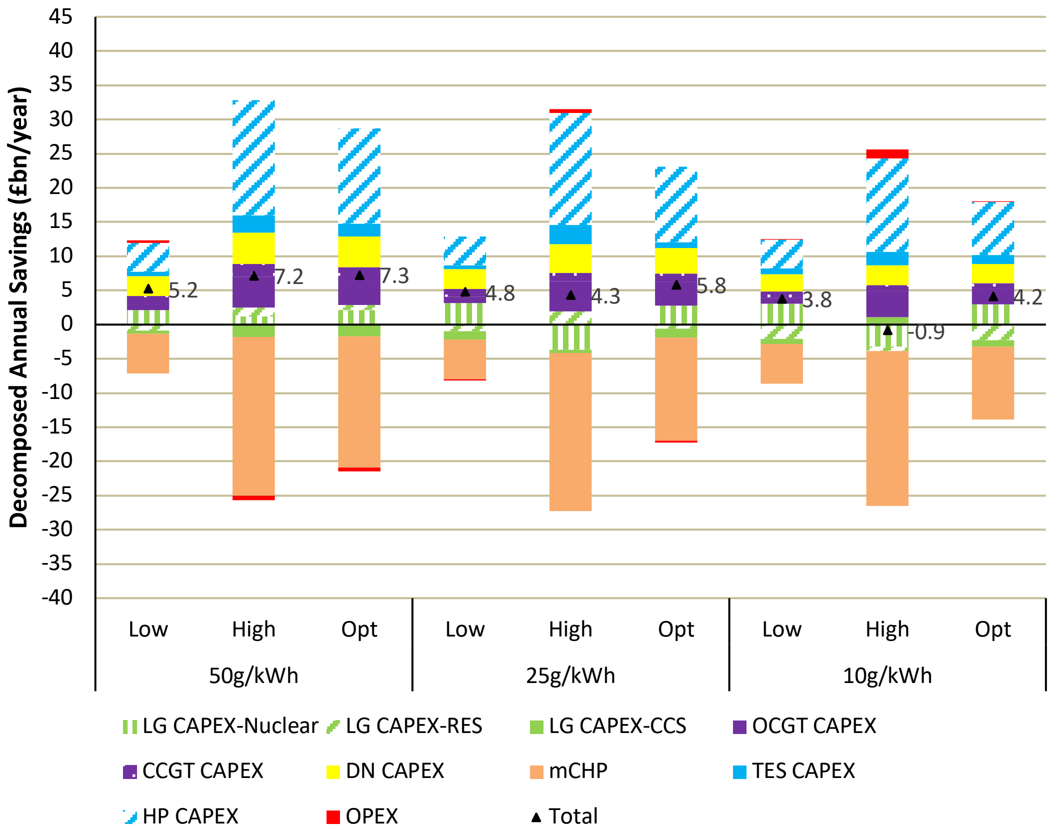


Figure 6. Decomposed whole system annual savings through the adoption of the FlexiCell concept

Figure 6 demonstrates the decomposed whole system annual savings through the adoption of the FlexiCell concept with micro-CHP in different uptake and carbon scenarios. Note that different from Figure 5, the CAPEX of micro-CHP is considered in this result. More details about the CAPEX of various generation and heating technologies are given in Figure 6. Specifically,

- Green blocks of different patterns represent the savings in CAPEX of different types of low-carbon generation, including nuclear plants (LG CAPEX-Nuclear), wind and PV generation (LG CAPEX-RES) as well as CCS power plants (LG CAPEX-CCS).
- Purple blocks of different patterns represent the savings in CAPEX of conventional generation, including CCGT (CCGT CAPEX) and OCGT (OCGT CAPEX).
- Blue blocks of different patterns represent the savings in CAPEX of heating appliance apart from micro-CHP, including ASHP (HP CAPEX) and TES (TES CAPEX).
- The orange block represents the additional investment costs driven by the deployment of the FlexiCell concept.
- The yellow block (DN CAPEX) represents the savings in CAPEX of electricity distribution network reinforcement.
- The red block (OPEX) represents combined OPEX of different kinds.

- The black dot with numbers in the figure highlights the net whole system savings due to the deployment of the FlexiCell concept.

Note that each bar in Figure 6 demonstrates the difference between two cases:

1) The benchmark case (counterfactual): micro-CHP is not used, only ASHP is involved in the optimization. micro-CHP is involved in the optimization
2) The investigated FlexiCell concept: both micro-CHP and ASHP are involved in the optimization.

Figure 6 is drawn by stacking the cost difference of all considered sectors (blocks) in these two cases.

The analysis of these results is given as follows:

- Significant savings can be achieved through large-scale deployment of the FlexiCell concept. The total savings decrease with the tightening of carbon targets from 4.5£bn/year to 2.5£bn/year, mainly because the investigated micro-CHP in this case study is based on natural gas, which loses advantages in tight carbon scenarios. In low uptake scenarios, although the unit system benefit of the FlexiCell concept is the highest in Figure 5, there is huge space for further cost reductions through increasing the uptake of micro-CHP. However, if micro-CHP is over-deployed for the FlexiCell concept, as in the high uptake scenario under 10g/kWh carbon target, the whole system cost will be increased, e.g., by 2.6£bn/year in this case.
- The capacities of micro-CHP in the low and high uptake scenarios under different carbon scenarios are the same, while the optimal uptake is affected by the carbon target. Since micro-CHP operates on nature gas in this case study, less micro-CHP is installed with the tightening of the carbon target.
- Consistent with the previous analysis, micro-CHP displaces a remarkable amount of ASHP at the end-side heating system, which makes the largest contribution to the total cost reduction. Meanwhile, significant savings in TES is also seen, particularly with high micro-CHP uptakes.
- Regarding the electricity generation, considerable savings are achieved in both CCGT (as firm generation), OCGT （as back-up capacities） and nuclear generation (as firm low-carbon generation). The change of RES accommodation, including wind and solar, is affected by both the uptake and carbon scenarios. The reason includes:
    - On the one hand, large-scale deployment of the FlexiCell concept can displace a significant amount of generation capacities, not only including firm capacities, like CCGT and nuclear, but also intermittent renewables, therefore, when the uptake of micro-CHP is high, the requirement of RES can be reduced.
    - On the other hand, micro-CHP in the FlexiCell concept can provide various system services to the electricity system, and it is more flexible

compared to ASHP as it consumes gas. Both characteristics are beneficial to the integration of RES, especially under tight carbon scenarios, in which both system services and flexibilities are scarce. Combining the two reasons, the impacts on RES integration due to large-scale deployment of the FlexiCell concept is case-specific, but the general conclusion is higher micro-CHP uptakes tend to reduce RES integration while tighter carbon targets tend to improve the capability of micro-CHP in facilitating RES integration.

- Additionally, the reduction in DN CAPEX also increases the values of the FlexiCell concept.

4.1.2 Impacts of the FlexiCell concept on the capacity of energy sources

The micro-CHP specified by the FlexiCell concept can provide firm capacity as long as they can be dispatched when it is needed by the TSO to improve the capacity margin, especially during peak demand periods. However, this requires new control infrastructure which, to date, is not present; in the absence of this control capability, the capacity value of micro-CHP is less, and its related benefit cannot be included in the value of the FlexiCell concept to the grid. In this study, it is assumed that the micro-CHP in the FlexiCell concept can be dispatched when the system needs it, and therefore it can provide firm capacity to the system.

Figure 7 shows the impact of the FlexiCell concept on the generation system. In each bar, two cases, comprising the FlexiCell concept case (combined ASHP, micro-CHP and TES) and the benchmark case without micro-CHP, are compared with the difference in each generation technology illustrated.

Regarding the FlexiCell concept, it can be observed that the micro-CHP displaces by higher than one-to-one ratio the capacity of other gas-fired technologies such as CCGT and OCGT. This indicates micro-CHP can reduce the electricity peak demand, therefore, less firm generation capacity is required. This is because the presence of micro-CHP can support the operation of ASHP. During cold periods with high heat demand, micro-CHP can serve as supplementary heaters by consuming nature gas, which significantly reduces burden of ASHP, and therefore reduce the electricity demand. Without micro-CHP in the benchmark, all heat demand has to be met by ASHP, which poses huge burden to the electricity system. In this case, large amount of peaking capacities, such as OCGT, have to be available. From this perspective, micro-CHP can double-displace generation capacities considering its contribution to both the electricity systems and the electrified heat systems.

Micro-CHP can displace the capacity of CCGT in the FlexiCell concept, due to its higher overall energy efficiency and capability of providing various system services. Figure 7 indicates the amount of CCGT displacement decreases when the carbon target is tightened. This is because the amount of CCGT decreases in tighter carbon scenarios.

Figure 8 compares the optimal generation capacity mix between the FlexiCell concept with micro-CHP and the benchmark case without micro-CHP. It can be found that micro-CHP completely displaces CCGT since it can fulfil all the functionality of CCGT with higher energy efficiency. Note that this is based on the assumption that a fully effective smart control system is available so that micro-CHP can be dispatched when the system needs it. However, OCGT cannot be fully replaced because it is cheaper as back-up capacity.

Regarding low carbon generation, appropriate deployment of the FlexiCell concept can reduce the investment in nuclear plants as in Figure 8, but over deployment of the FlexiCell concept in tight carbon scenarios can cause increased requirement for nuclear plants. It is also observed that more CCS plants are deployed when micro-CHP is present. This is mainly due to the restrictions of decarbonization. Since micro-CHP is powered by natural gas, CCS is required to limit the level of carbon emission. Additionally, the introduction of micro-CHP in the FlexiCell concept also impacts the capacity of RES. On the one hand, micro-CHP, as a type of generation source, can displace RES capacities. On the other hand, micro-CHP can facilitate the integration of RES by providing flexibility and various system services to the electricity system. Therefore, the impact of the FlexiCell concept on RES capacities can vary in different scenarios. But in tight carbon scenarios, appropriate deployment of the FlexiCell concept tends to support the accommodation of RES, which will be analysed in the next section.

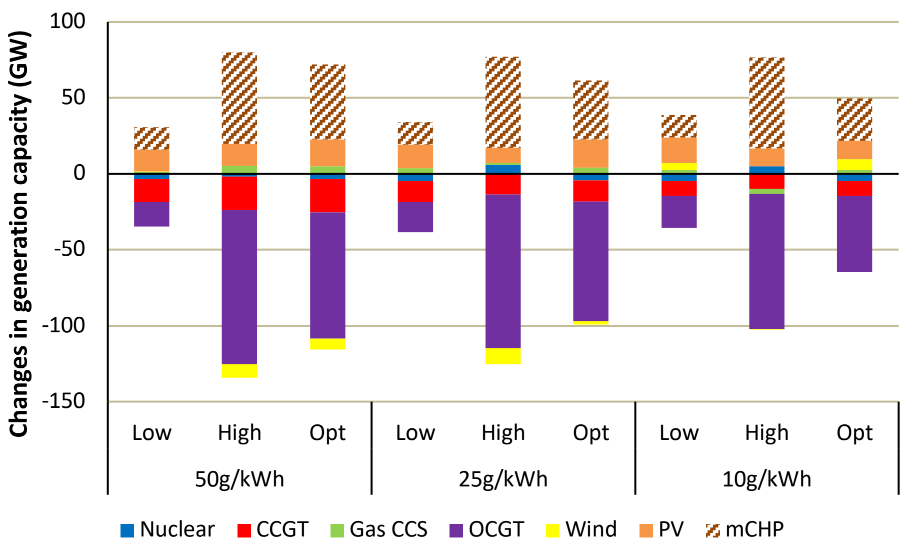


Figure 7. Impact of FlexiCell concept on the generation capacity

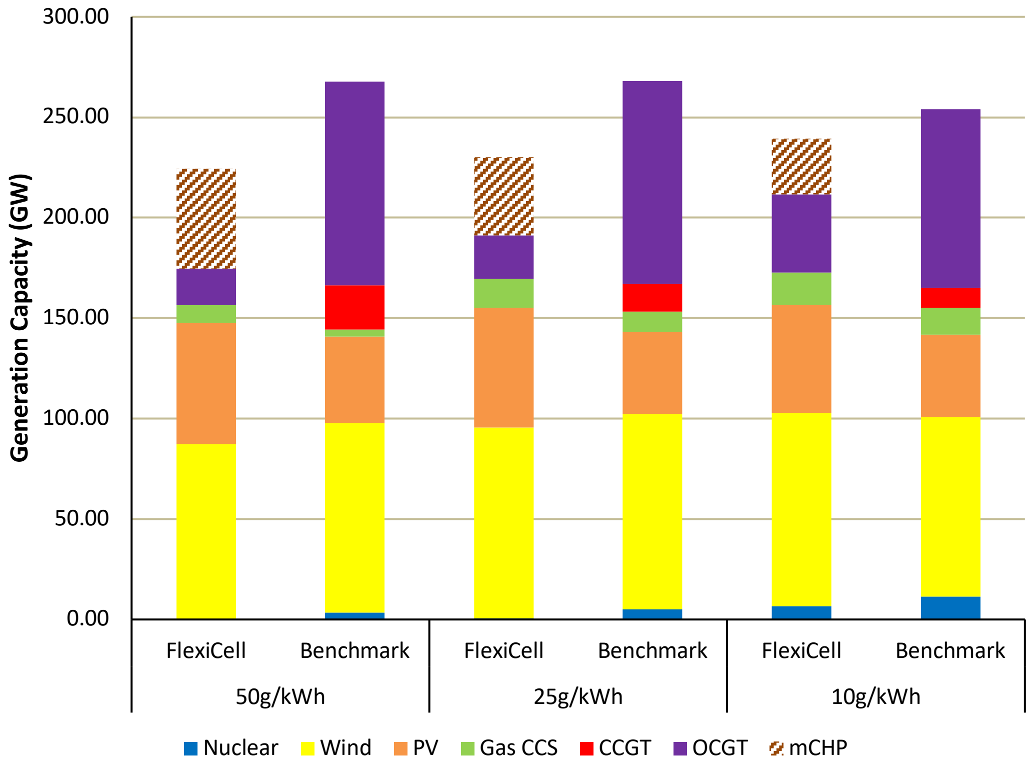


Figure 8. Generation capacity mix in different cases

Figure 9 shows the impact of the FlexiCell concept on the heating appliance capacity. Note that the capacity of micro-CHP is given in its thermal capacity.

Based on the results, key findings are summarised as follow:

- It can be observed that the micro-CHP displaces by one-to-one ratio the capacity of ASHP. Recall the results in Figure 7, the micro-CHP displaces by higher than one-to-one ratio the capacity of the other generation capacities since it reduces the electrified heat demand thus reducing the overall generation capacity. In contrast, the heat demand cannot be reduced through the deployment of the FlexiCell concept, therefore, the overall heating capacity is not changed.
- The optimal capacity of micro-CHP reduces with the tightening of the carbon targets. This indicates that the advantage of natural gas micro-CHP diminishes when more ambitious carbon targets are imposed, although the various benefits it can provide, e.g., increasing the overall energy efficiency, linking electricity and heat systems and shifting flexibilities within the two systems.
- In the FlexiCell concept, micro-CHP significantly reduces the amount of TES. On the on hand, heat load has significant volatility and huge peak-to-valley difference, the absence of flexibility in the energy system will make the mass deployment of electric ASHP prohibitive. Therefore, TES plays an important role in the electrification of the heat systems through shifting huge amount of flexibility from the heat sector to the electricity sector. On the other hand, micro-CHP provides an alternative solution to the decarbonization of the heat sector

other than electrification. Serving as a back-up heat source, micro-CHP can displace TES to reduce electricity peak demand, thus alleviating the challenges in large-scale electrification of heating appliance and distribution network expansion.

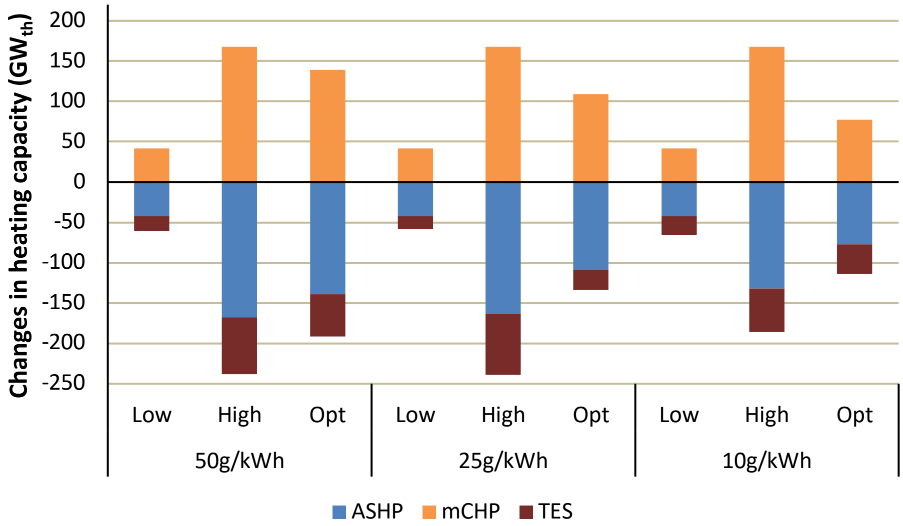


Figure 9. Impact of micro-CHP on the heating appliance capacity

4.1.3 Impacts of the FlexiCell concept on energy production

It is expected that the FlexiCell concept will reduce the operating cost of electricity production as the overall energy efficiency of micro-CHP, operated in a combined heat and power mode, is higher compared to the efficiency of conventional coal/gas/oil-fired thermal generators. In the FlexiCell concept where both micro-CHP and ASHP are available, the total electricity production is lower as the heat produced by micro-CHP is used to supply the heat demand directly. In the benchmark scenario, the heat is supplied by ASHP which requires electricity that needs to be produced by power generation. The changes in the electricity production of the two scenarios ("FlexiCell" and "Benchmark" scenarios) are shown in Figure 10.

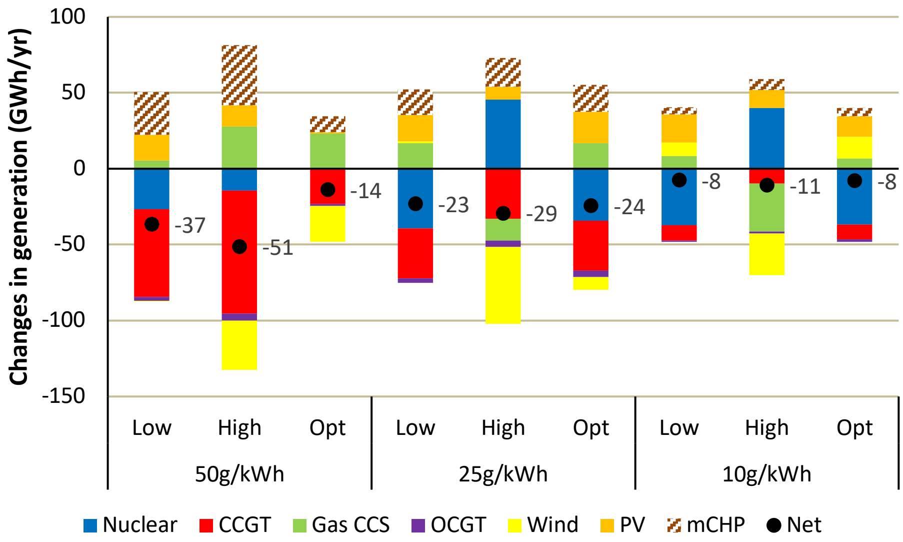


Figure 10. Impact of the FlexiCell concept on the electricity production of different generating technologies

The results provide the following insight:

- The net changes in electricity production are negative, which means that there is reduction of electricity needed to supply the energy demand in the FlexiCell concept compared to the electricity production in the benchmark case without micro-CHP. This also indicates that the efficiency of the system, in terms of meeting the electricity and heat demand, is higher with micro-CHP compared with the efficiency of the system with ASHP.
- The electricity production gap between the FlexiCell concept and benchmark scenario diminishes with the tightening of the carbon target. This can be more clearly observed in Figure 11, which demonstrates the optimized annual electricity production of different generation technologies. This is because less micro-CHP in the FlexiCell concept is deployed under tighter carbon targets.
- Since micro-CHP displaces considerable capacities of nuclear and CCGT, their corresponding electricity production is consequentially reduced, which forms the largest part of the generation decrease for most scenarios.
- Although significant amount of OCGT is displaced by micro-CHP, its electricity production does not decrease much. This is because OCGT serves as back-up capacity, the utilization of which is low.
- More electricity is produced by CCS plants in the FlexiCell concept. This is because the operation of natural gas micro-CHP adds to the carbon emission, as a result, more CCS is needed to decarbonize the electricity. If micro-CHP is powered by low-carbon fuels, such as biogas, CCS plants will not be required to offset the increase carbon emission. This will be analysed in later sections.
- PV generation is boosted in the FlexiCell concept. Wind generation is increased in 10g/kWh carbon scenarios when micro-CHP is not over-deployed. This indicates appropriate deployment of the FlexiCell concept, particularly micro-CHP

can facilitate the accommodation of intermittent renewables in ambitious carbon scenarios.

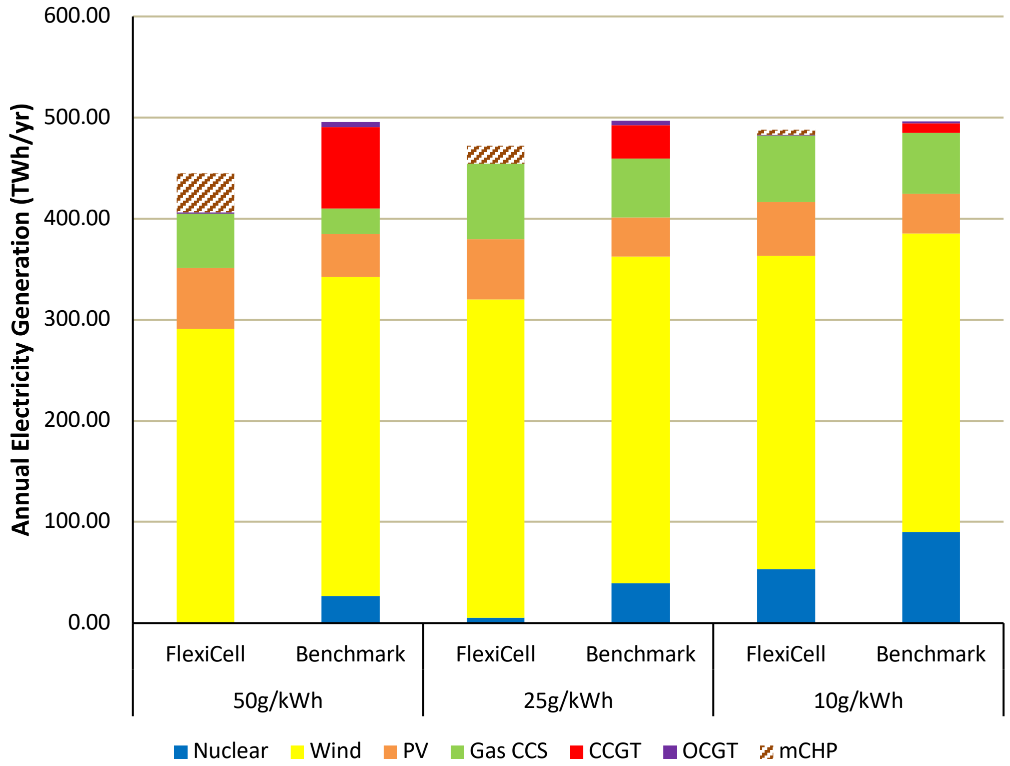


Figure 11. Annual electricity production of different generation technologies

Figure 12 shows the impact of the FlexiCell concept on the heat production of different heating technologies, particularly including micro-CHP and ASHP.

Based on the results, key findings are summarised as follow:

- Similar to the results for the electricity production, the net changes in heat production are also negative across different scenarios. on the electricity side, demand is reduced because less heat is electrified with the presence of micro-CHP in the FlexiCell concept, which requires less electricity production. However, the reason in heat production reduction is not due to the decrease in heat demand but is associated with the displacement of TES. Since TES is characterized by constant heat loss, the more TES is deployed, the more heat loss is incurred. Since the FlexiCell concept can reduce the requirement of TES, less heat will be lost, thus further improving the energy efficiency.
- Under the same carbon target, the more FlexiCell concept is deployed, the more energy loss can be avoided. When the carbon target changes, the energy loss avoided through the same amount of FlexiCell concept varies. Specifically comparing the results in the 25g/kWh high scenario and 10g/kWh high scenario, the reduced energy loss changes from 15.1 TWh_{th}/year to 5.3 TWh_{th}/year.

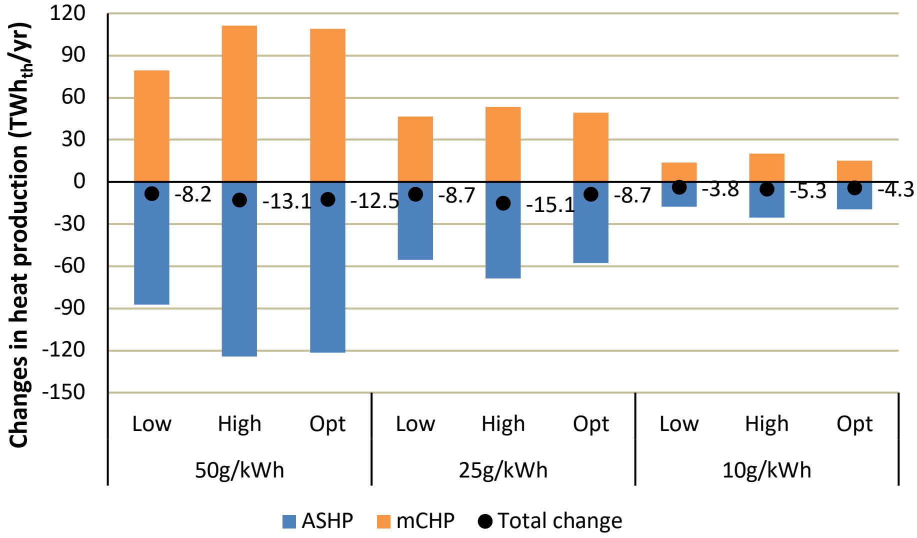


Figure 12. Impact of the FlexiCell concept on the heat production of different heating technologies

4.2 Values of the alternative FlexiCell concept with biogas micro-CHP

The above analysis has quantified the values of the FlexiCell concept with natural gas mCHP in the low-carbon energy system. However, its value is limited with the tightening of the carbon target due to the involvement of natural gas consumption. This subsection aims to investigate the values of an alternative FlexiCell concept in which natural gas micro-CHP is replaced by biogas micro-CHP.

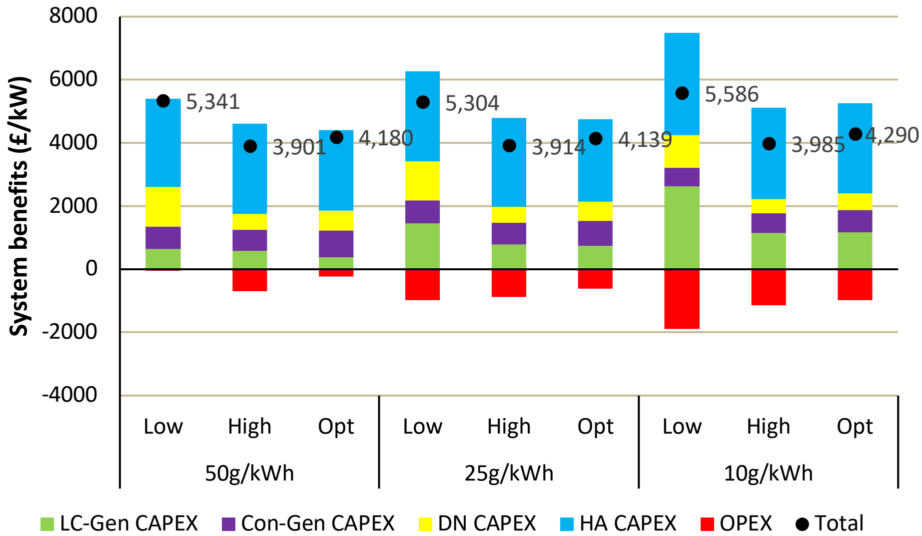


Figure 13. Unit system benefits of the FlexiCell concept with biogas micro-CHP

Figure 13 shows an increasing total cost saving with the tightening of carbon targets. Among all the saving components, HA CAPEX is the largest which is the same as in the original FlexiCell concept (with natural gas micro-CHP). However, the second largest saving is LC-Gen CAPEX in the alternative FlexiCell concept where the micro-CHP operates on biogas. Con-Gen CAPEX, which is the second largest saving component for the original FlexiCell concept, is still significant, but its contribution is smaller. Moreover, unlike the impact of the original FlexiCell concept on OPEX, the deployment of the alternative FlexiCell concept increases the OPEX because the biogas is much more expensive.

The analysis of these results is drawn as follows:

- Since the biogas micro-CHP has no carbon emission, it can effectively displace low carbon generation. The capacities of low carbon generations including nuclear, wind, PV and CCS power plants are lower in Figure 14 than the corresponding values in Figure 8.
- The large-scale deployment of the alternative FlexiCell concept reduces benefits due to Con-Gen CAPEX compared to the result of the original FlexiCell concept. This is because the biogas micro-CHP cannot massively displace CCGT in the conventional generation due to its high OPEX, whereas the natural gas micro-CHP can displace CCGT on a large scale with its higher energy efficiency.
- Compared to the results in Figure 8, the required capacity of OCGT is significantly alleviated by using the alternative FlexiCell concept as shown in Figure 14.

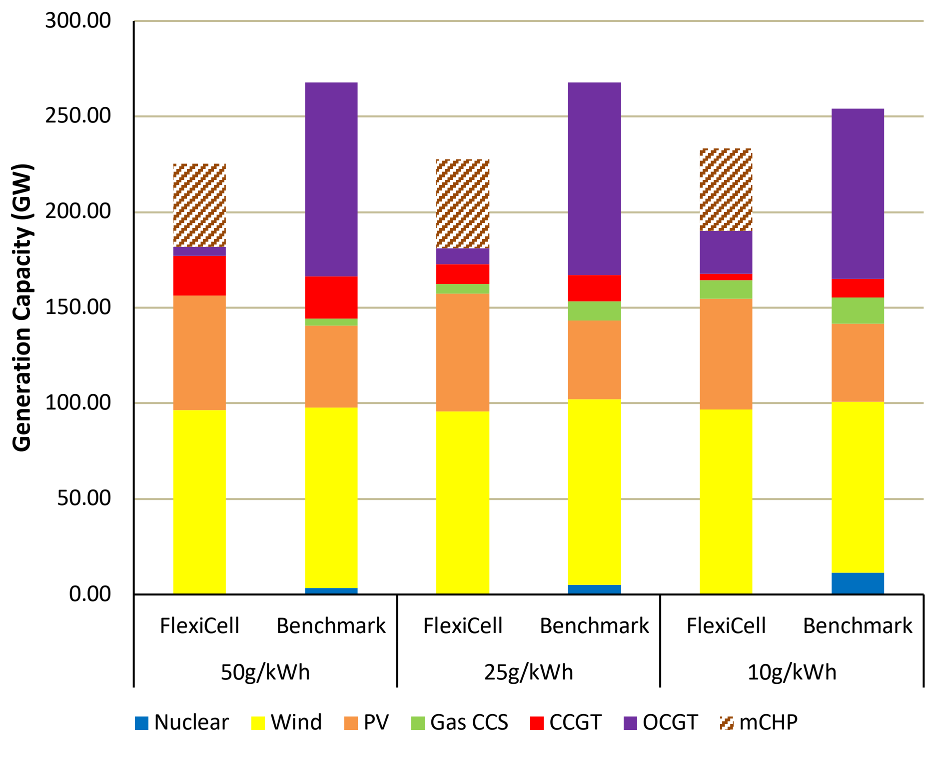


Figure 14. Generation capacity mix in different cases

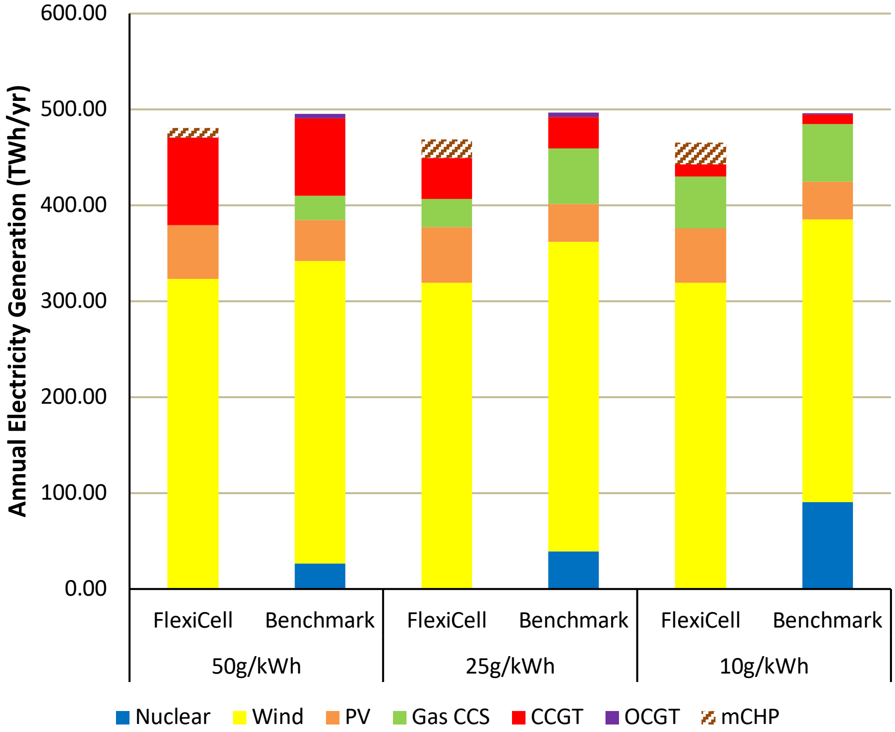


Figure 15. Annual electricity production of different generation technologies

The impact of the alternative FlexiCell concept on annual electricity generation is shown in Figure 15. In contrast to the original FlexiCell concept in Figure 11, reduction of nuclear generation is more significant, especially in the scenario of low carbon targets. The CCGT generation in the alternative FlexiCell concept is similar to the benchmark result, whereas the original FlexiCell concept completely displaces the CCGT generation. Regarding CCS, more generation is displaced by micro-CHP when the carbon target is less demanding.

These results provide the following insight:

- Since micro-CHP in the alternative FlexiCell concept can provide low-carbon firm generation while providing system services, it is a good alternative of nuclear capacities.
- The electricity generation, as well as the load factor, is increasing with the tightening of carbon targets. This further verifies the significant value of biogas micro-CHP in tight carbon targets. Although the operational cost of the alternative FlexiCell concept is high, it can provide low carbon associated value which would offset the high OPEX.
- The original FlexiCell concept can displace CCGT due to the lower operational cost of natural gas micro-CHP. The alternative FlexiCell concept cannot significantly reduce the annual generation from CCGT because of the high OPEX.

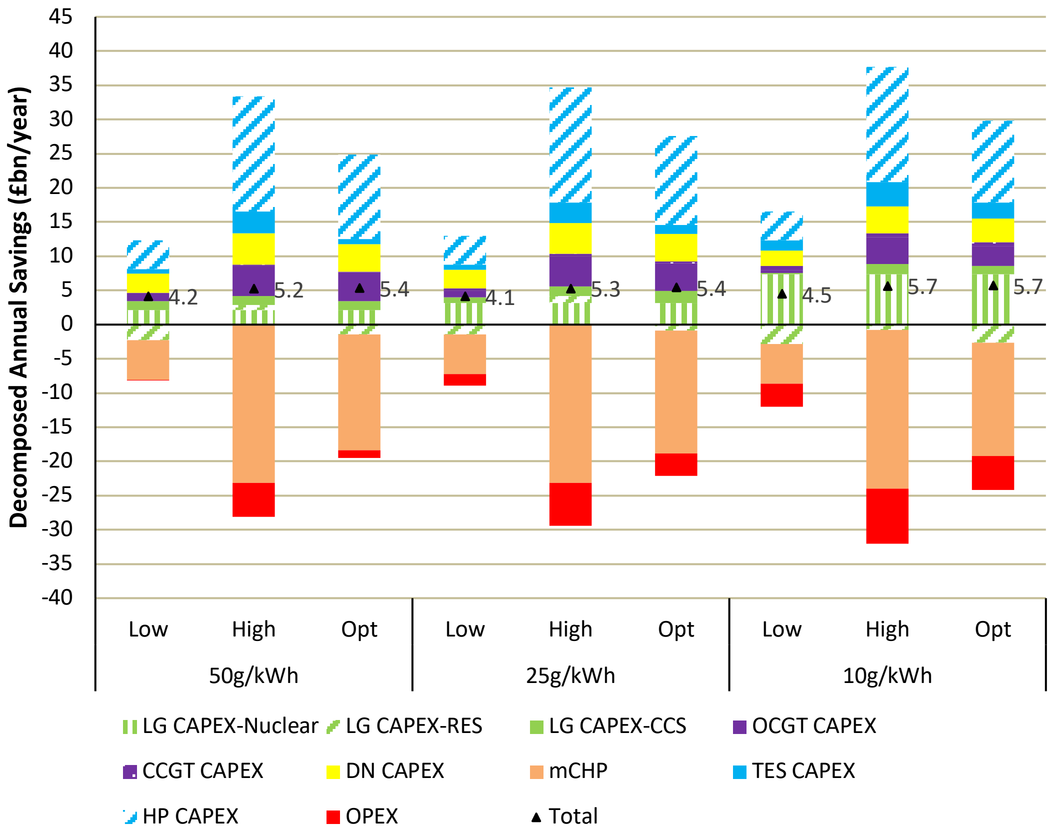


Figure 16. Decomposed whole system annual savings through the deployment of the alternative FlexiCell concept

The whole system annual savings under different uptake and carbon scenarios by deploying the alternative FlexiCell concept are depicted in Figure 16. It can be seen that the overall annual savings tend to increase with the tightening of carbon target, but the change is not significant. Note that CAPEX-CCS is reduced due to the deployment of biogas micro-CHP while the annual cost of CCS is increased with the original FlexiCell concept. Moreover, higher OPEX is also observed while deploying the alternative FlexiCell concept, especially at low carbon scenarios. The alternative FlexiCell concept manages to reduce the CAPEX of low-carbon energy infrastructure at the expense of higher OPEX.

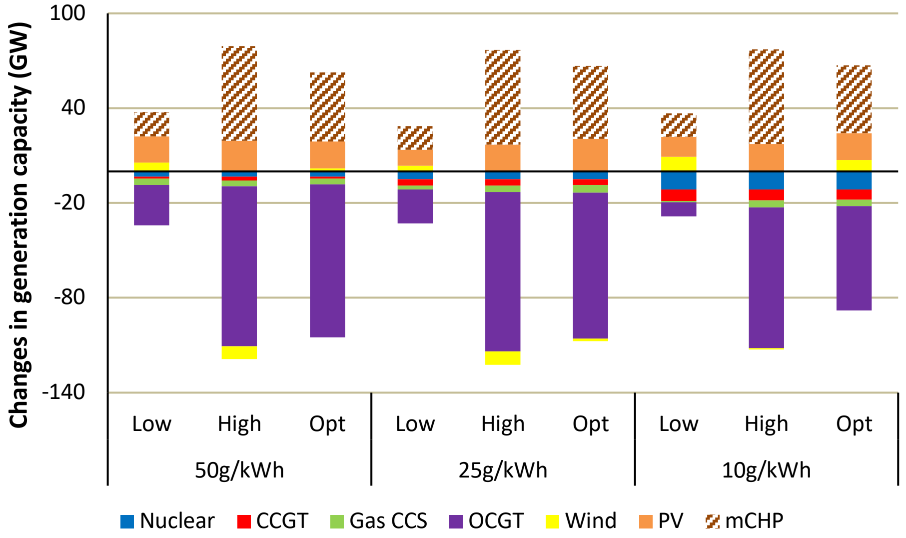


Figure 17. Impact of the alternative FlexiCell concept on the generation capacity

In Figure 17, the amount of CCGT displacement by biogas micro-CHP increases with the tightening of the carbon target, which shows an opposite trend compared to the original FlexiCell concept. The reduction of CCGT is less significant compared with the original FlexiCell concept because the operation cost of biogas micro-CHP in the alternative FlexiCell concept is relatively high. Meanwhile, the alternative FlexiCell concept also reduces the capacity of CCS which is consistent with previous analysis. Furthermore, it is important to note that the deployment of the alternative FlexiCell concept also displaces a lot of OCGT. This is because the micro-CHP can dramatically reduce the peak demand of electrified heat, and therefore less back-up generation is needed.

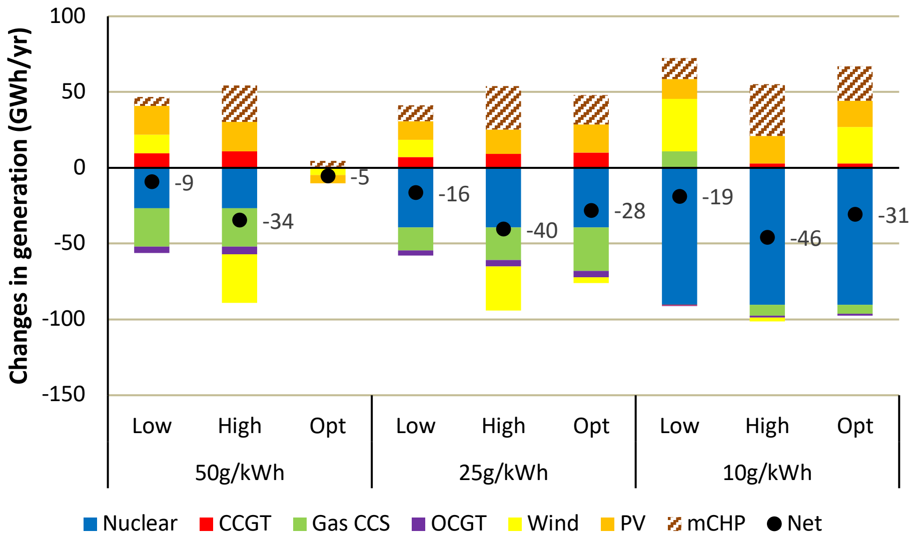


Figure 18. Changes in generation

Based on Figure 18, the following key findings are remarked:

- In contrast to the original FlexiCell concept in Figure 10 where the electricity production gap between the "FlexiCell" scenario and the "Benchmark" scenario diminishes with the tightening of the carbon target, the alternative FlexiCell concept increases the gap because it is more valuable to be deployed under tighter carbon target.
- Since biogas is carbon neutral, less amount of nuclear and CCS generation is needed. However, due to its high OPEX, more CCGT is required as complementary supply.

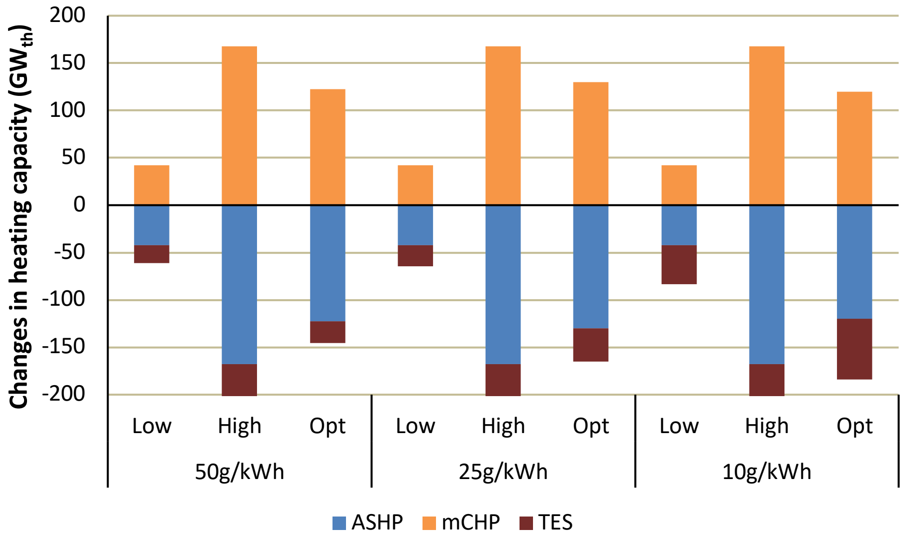


Figure 19. Impact of the alternative FlexiCell concept on the heating appliance capacity

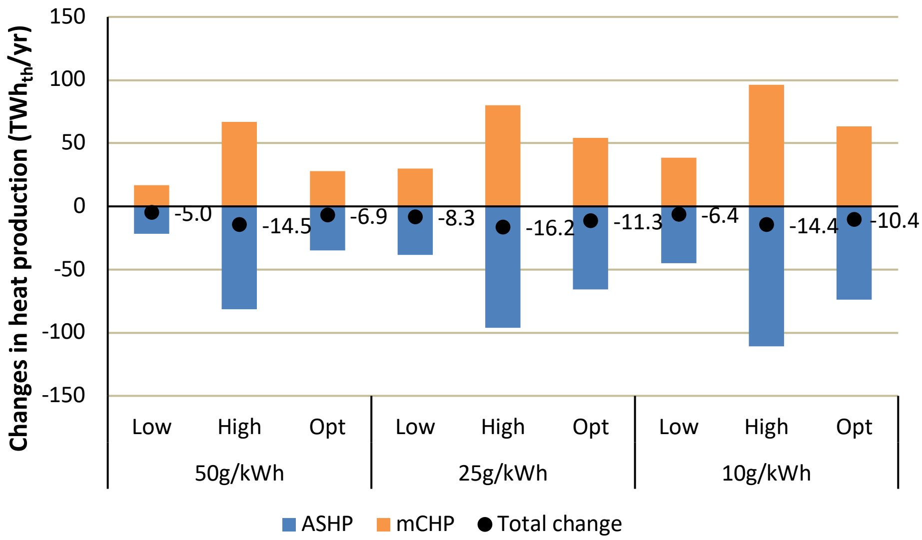


Figure 20. Impact of the alternative FlexiCell concept on the heat production of different heating technologies

The changes in the heating sector considering the impact of the alternative FlexiCell concept are shown in Figure 19 and Figure 20, which provide the following insights:

- In Figure 19, it is indicated that the changes of optimal micro-CHP capacities under different carbon scenarios are similar. Since the optimal micro-CHP generation is increasing with the tightening of carbon target as demonstrated in Figure 18, the load factor of biogas micro-CHP is higher in lower carbon scenarios.
- The deployment of TES is remarkably reduced when the alternative FlexiCell concept is deployed. As a result, less amount of heat energy loss in TES is incurred which corresponds to the changes of the total energy production in Figure 20. Note that positive values represent additional energy.

4.3 Impacts of micro-CHP cost on the whole system benefits of FlexiCell concept

Biogas-based micro-CHP in the alternative FlexiCell concept is characterized by zero-carbon operation and high overall energy efficiency, which provides a promising opportunity for the decarbonization of the future energy systems. Based on the previous studies, the alternative FlexiCell concept shows good potential in lower carbon scenarios. However, its low-carbon advantages can be undermined by its high OPEX, i.e., the cost of biogas. At present, the cost of biogas is much higher than natural gas. However, the development of various decarbonization technologies and the rollout of associated infrastructure can potentially facilitate the reduction of biogas cost. Since the OPEX of the alternative FlexiCell concept is a key limiting factor for its large-scale deployment while significant uncertainties exist in the cost of biogas, this subsection performs sensitivity studies to investigate the whole system benefits of the alternative FlexiCell concept under different biogas costs.

Three scenarios are studied: 1) low biogas cost, 2) medium biogas cost and 3) high biogas cost. Note that the previous studies are performed based on the medium biogas cost. It is assumed that the low scenario cost is determined by reducing the medium scenario cost by 1/3 while the high scenario cost is determined by increasing the medium scenario cost by 1/3.

Figure 21 demonstrates the whole system benefits of the alternative FlexiCell concept under different scenarios.

Key results can be summarized as follows:

- The whole system benefit of the alternative FlexiCell concept dramatically increases with the decrease of biogas cost.
- More micro-CHP capacities are deployed, displacing a considerable amount of ASHP and reducing the requirement of TES.
- The CAPEX of RES is reduced with the decrease of biogas cost. The change of back-up capacities, i.e., OCGT is minor.

➢ Increased OPEX is incurred due to the increased micro-CHP capacities. The load factor of micro-CHP rapidly increases with the decrease of biogas cost. The load factor of micro-CHP also increases with the tightening of the carbon target.

The analysis of these results is given as follows:

➢ When biogas cost is high, micro-CHP plays as a complimentary heating measure, prioritizing the supply of peak heat demand. Since heat demand is volatile, the load factor of micro-CHP is low, therefore undermining its operational values.
➢ When biogas cost is reduced, e.g., in the low scenario, micro-CHP can compete with ASHP to supply off-peak load, thus increasing its load factor. As a type of low-carbon generation, biogas micro-CHP can also compete with RES.
The decrease of biogas cost boosts the deployment of the alternative FlexiCell concept and its utilization. Although the fuel cost is reduced, the total OPEX is significantly increased.

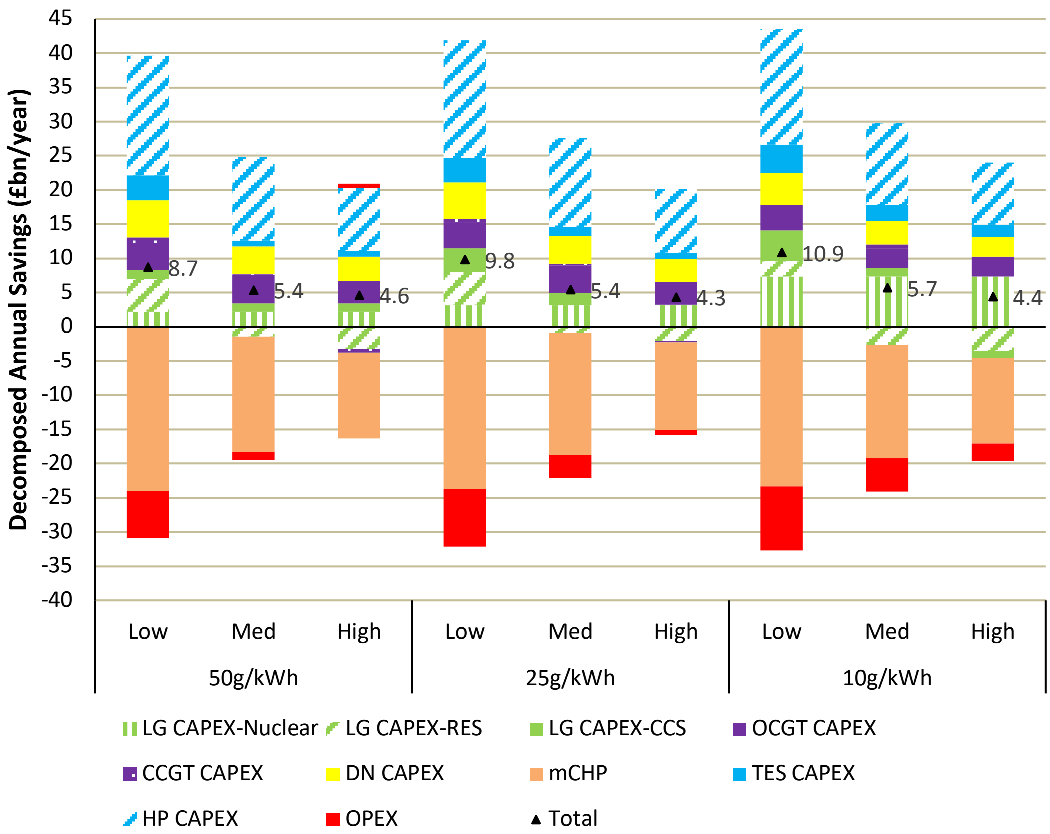


Figure 21. Whole system benefits of the alternative FlexiCell concept in different scenarios

The CAPEX of the alternative FlexiCell concept is another key limiting factor for the large-scale deployment of micro-CHP. Therefore, it would be useful to demonstrate how the CAPEX impacts the whole system value of the alternative FlexiCell concept. In this section, the biogas micro-CHP of the alternative FlexiCell concept is used to perform sensitivity studies on the CAPEX of micro-CHP.

For achieving so, three scenarios are studied: 1) low CAPEX, 2) medium CAPEX and 3) high CAPEX. The previous studies are based on the high CAPEX scenario. In this study, we assume that the medium CAPEX is 75% of the high CAPEX while the low CAPEX is 50% of the high CAPEX.

Figure 22 demonstrates the whole system benefits of the alternative FlexiCell concept under different CAPEX scenarios, which provides the following results and insights:

- The whole system benefits are sensitive to the decrease of micro-CHP CAPEX, mainly due to the displacement of ASHP and TES by micro-CHP. More OPEX is incurred due to the increased deployment of the alternative FlexiCell concept. Additionally, less RES is used with the increased competitiveness of low-carbon micro-CHP due to CAPEX decrease. The changes in the other components are minor.
- The whole system benefits through the alternative FlexiCell concept are less sensitive to the change of carbon target in all CAPEX scenarios. But noticeable increase can be observed when the carbon target is tightened from 25g/kWh to 10g/kWh.

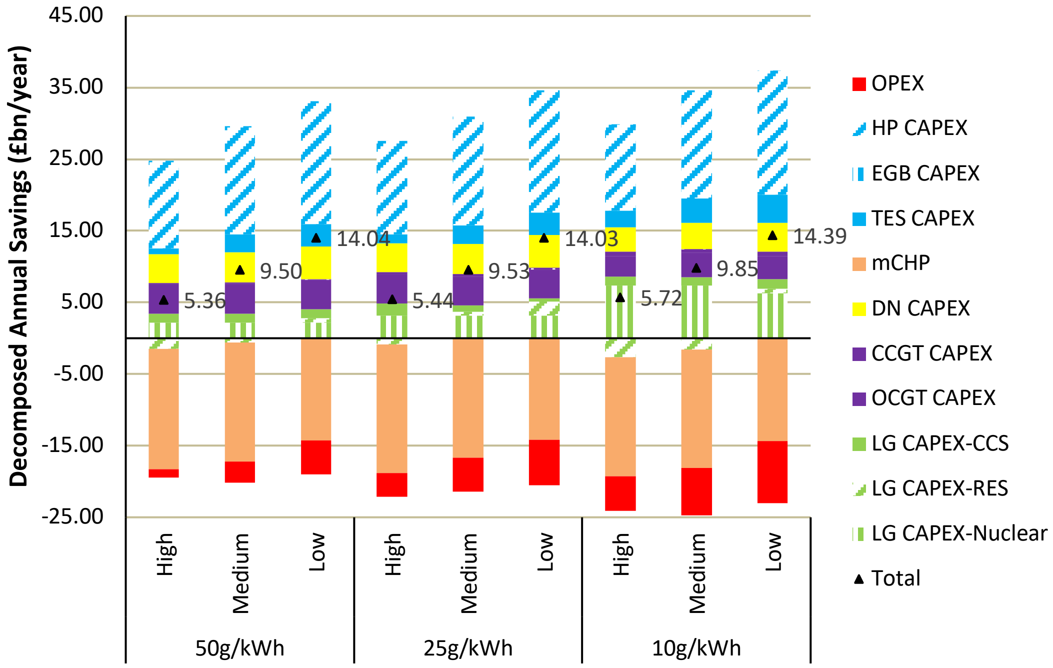


Figure 22. whole system values of the alternative FlexiCell concept under different CAPEX scenarios

5 Assessment of the value of smart control of FlexiCells

Since the FlexiCell concept involves the heating technology combination of micro-CHP + ASHP + TES, it can potentially provide huge amount of flexibility to the electricity system, which is particularly valuable in the context of large-scale integration of renewable energy sources into the energy system and deep electrification of the heat sector. However, the coordinated control of operation of micro-CHP, ASHP and TES is critical for enabling the FlexiCell concept to deliver the corresponding economic and environmental benefits. In this context, this section is dedicated to quantification of benefits of the FlexiCell concept for the whole energy system, highlighting the importance of the coordinated control approach.

5.1 The value of FlexiCell concept in providing system services

In order to assess the flexibility values of the FlexiCell concept from the whole system perspective, it is necessary to consider the potential system services it can provide at various timescales. All the heating technologies involved in the FlexiCell concept can provide system balancing services, including frequency response (from seconds timescale) and operating reserve (minutes to hour timescale). Furthermore, the FlexiCell concept, due to the involvement of micro-CHP, can enhance system adequacy that would reduce investments in conventional generation capacity and network reinforcements. Regarding system balancing, the frequency regulation is fundamentally determined by the amount of inertia in the power system, which is driven by online capacity of synchronous generatios. As a result, the relationship between the post-fault dynamic frequency requirement and the online synchronous capacity can be obtained by analysing the transient process of ROCOF in the power system with the loss of the largest generator. To this end, the function of the response requirement against the online synchromous capacity is integrated into the IWES model. Additionally, the requirement of operating reserve, which is associated with forecasting errors of RES output and demand, and potential outage is also included in the model.

It is expected that the value of the FlexiCell concept can pentially be improved by providing various system services, e.g., frequency response and operationg reserve, especially in the future low inertia system driven by high penetration of RES, network congestion management, security of supply etc, which is the focus of this section.

Two cases are investigated:

1) Benchmark (counterfactual): the FlexiCell concept does not provide system services. System services are provided by conventional generation and energy storage. The uptake of natural gas micro-CHP, ASHP and PCM-based TES is fully optimized in different carbon scenarios.
2) Investigated case: apart from the conventional firm generation and storage, all the heating technologies in the FlexiCell concept contribute to system service

provision in a coordinated manner. The uptake of natural gas micro-CHP, ASHP and PCM-based TES is fully optimised in different carbon scenarios.

Figure 23 demonstrates the cost savings across different sectors driven by provision of system service by the FlexiCell concept. Each bar is shown by stacking the cost difference in all considered sectors (blocks) in these two cases.

Based on the results, key findings are drawn as below:

- Large savings are driven by the provision of system services through the FlexiCell concept, from 3.94£bn/year to 9.28£bn/year in different carbon scenarios, particularly due to cost reductions in OPEX, micro-CHP CAPEX, nuclear CAPEX and CCS CAPEX. Additionally, CCGT CAPEX is also reduced in all scenarios.
- More RES, OCGT, ASHP and TES are deployed. It is also observed that more distribution network reinforcement cost is incurred.
- The whole system benefit of the FlexiCell concept providing system services slightly increases with the tightening of the carbon target.

The findings in Figure 23 provide the following insights:

- If the FlexiCell concept cannot provide system services, these would be provided by conventional firm generation and energy storage, which are either less efficient or more costly. This would pose significant challenges to the accommodation of intermittent renewables, thus reducing the investment of RES. In order to fulfil the carbon target, more nuclear and CCS would be required to displace RES. Since nuclear and CCS can provide firm low-carbon generation, the corresponding load factor is much higher than RES, therefore, more gas can be used in the heat systems without violating the carbon constraints. As a result, more micro-CHP is used in this case.
- If the FlexiCell concept can provide system services, the deployment of micro-CHP, ASHP and TES can reduce the system integration costs of intermittent renewables, thus increasing the investment of RES and reducing nuclear and CCS. Moreover, it facilitates the electrification of the heat systems so that the flexibility of the heat systems can be shifted to the electricity side to further support the accommodation of RES. As a result, the investment of both ASHP and TES is increased while the deployment of micro-CHP is reduced. Additionally, further distribution network reinforcement is required due to deeper electrification of the heat systems and more back-up OCGT is needed to displace part of micro-CHP.

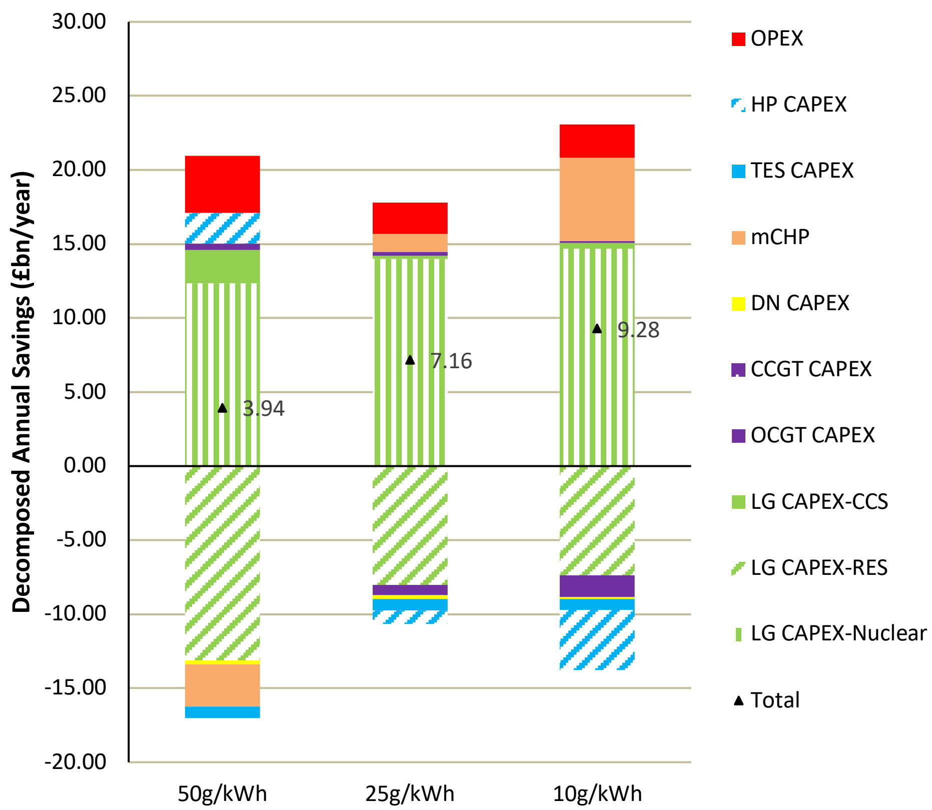


Figure 23. Impact of the FlexiCell concept providing system services on the system costs

It is worth noticing that the significant benefit from the FlexiCell concept providing system services highly depends on the coordination between all the involved heating technologies, i.e., micro-CHP, ASHP and TES. To further clarify this insight, additional modelling was carried out to quantify the whole system benefits of natural gas micro-CHP alone in the FlexiCell concept, providing system services, as demonstrated in Figure 24. Compared to the case where control of micro-CHP, ASHP and TES is fully coordinated, as shown in Figure 23, the total benefits in Figure 24 in all carbon scenarios are significantly reduced.

It is further observed in Figure 24 that the whole system benefit of natural gas micro-CHP alone providing system services does not experience significant change with the tightening of the carbon target. This is because the advantage of natural gas micro-CHP reduces when more ambitious carbon targets are imposed, even though the importance of system service is higher due to its scarcity in lower-carbon systems. This phenomenon highlights the limitation of whole system value of natural gas micro-CHP in the energy system decarbonisation.

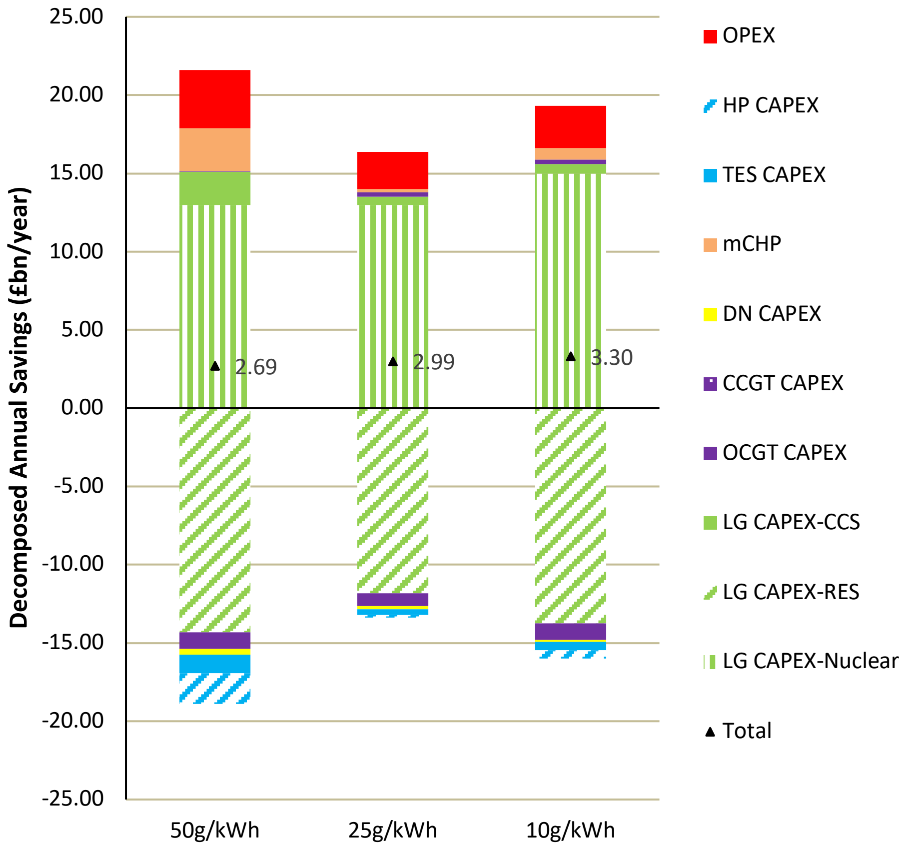


Figure 24 Impact of only natural gas micro-CHP providing system services on the system costs

Since micro-CHP plays a particularly significant role in the FlexiCell concept, as analysed before, we also demonstrate the impact of system service provision on unit value of natural gas micro-CHP, as shown in *Figure 25*. The results are expressed in £/kW electrical capacity of micro-CHP, the CAPEX of micro-CHP is not included in the optimization.

Key findings are given as follows:

- The unit value of micro-CHP providing system services remarkably increases with the tightening of carbon targets, i.e., from 404£/kW to 841£/kW when the carbon target is tightened from 50g/kWh to 10g/kWh.
- The benefit of micro-CHP providing system services is mainly due to OPEX reduction and low carbon generation CAPEX reduction. Meanwhile, negative values in conventional generation CAPEX, distribution network CAPEX and heating appliance CAPEX are observed.

The analysis and insights for these findings are given as below:

- Under ambitious carbon targets, the source of system service is particularly limited. Although conventional generation plants can provide system services, their load factors would be extremely low due to the high carbon intensity. In this case, the FlexiCell concept providing system services would be significantly valuable.

- The FlexiCell concept providing system services can significantly increase the accommodation of RES, thereby reducing the OPEX from conventional generation and CCS plants. Additionally, the system integration cost of RES is effectively reduced through the FlexiCell concept providing system services, therefore, the overall low-carbon generation CAPEX is reduced.

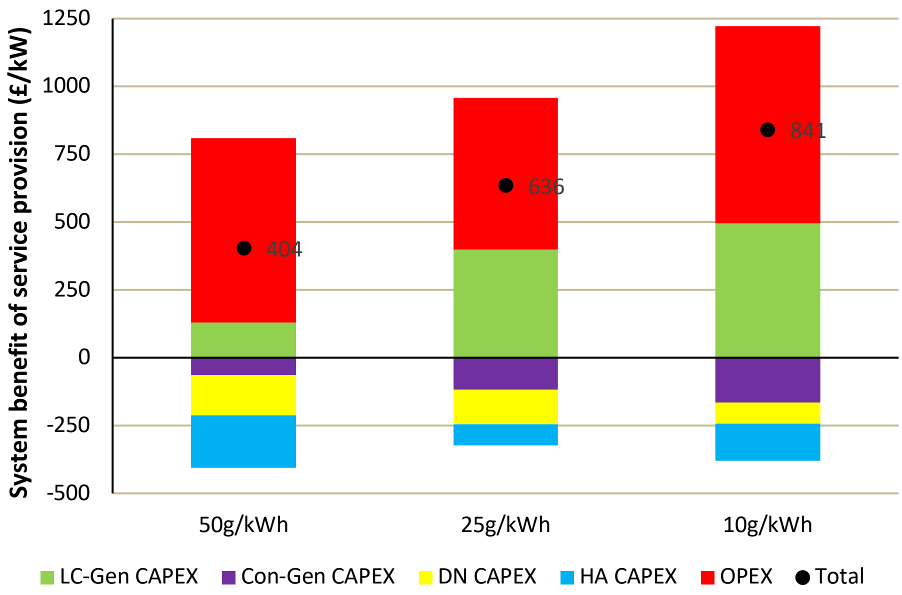


Figure 25. Impact of system service provision on unit value of natural gas micro-CHP

Apart from the studies for the FlexiCell concept with natural gas micro-CHP, we also investigate the alternative FlexiCell concept with biogas micro-CHP displacing nature gas micro-CHP. Comparisons are also made between two cases including 1) the alternative FlexiCell concept provides system services and 2) the alternative FlexiCell concept does not provide system services. To further demonstrate the impact of biogas OPEX on the value of system service provision, three OPEX scenarios defined in Section 4.3, i.e., 1) low biogas cost, 2) medium biogas cost and 3) high biogas cost, are included.

Figure 26 demonstrates the impact of system service provision on unit value of biogas micro-CHP.

Key findings are given as follows:

- The unit value of biogas micro-CHP providing system services is simultaneously dependent on the carbon target and OPEX. Specifically, the value for high OPEX scenarios is consistently higher than the low and medium OPEX scenarios, indicating the ability of system service provision is more valuable when the OPEX of micro-CHP is higher.
- The benefit of biogas micro-CHP providing system services is mainly driven by OPEX reduction, indicating the availability of system service provision can improve the system operation efficiency.

➢ In the 50g/kWh carbon scenario, increased LC-GEN CAPEX is driven by micro-CHP providing system services, while in the 10g/kWh carbon scenario, decreased LC-GEN CAPEX is observed. This is mainly because more nuclear is replaced by RES due to the availability of system service through micro-CHP in tight carbon scenarios.

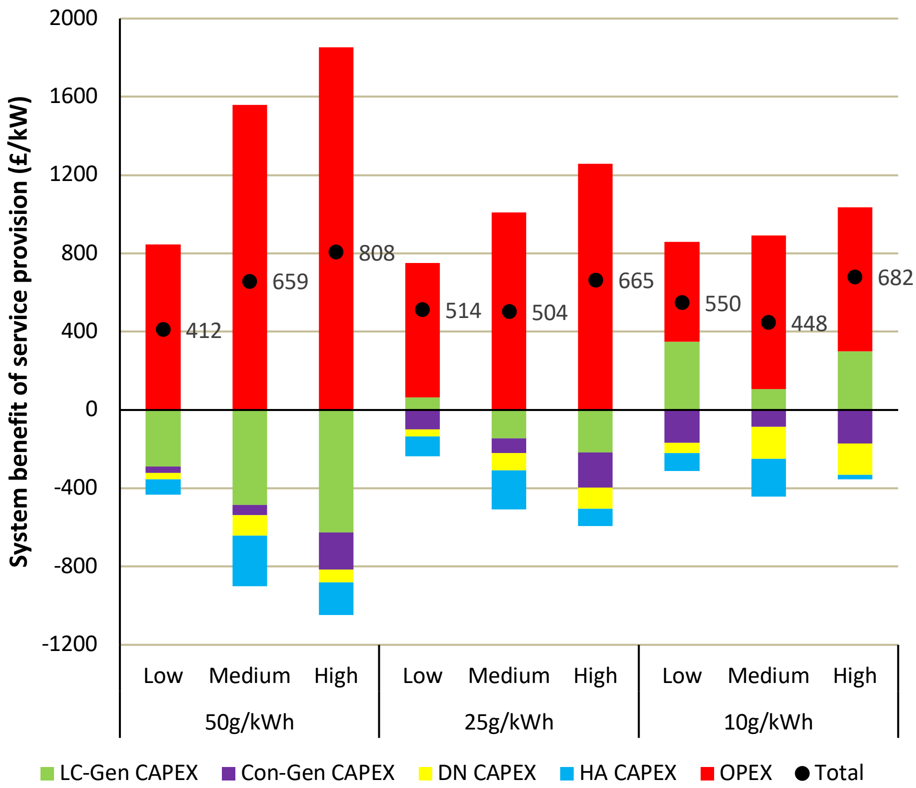


Figure 26. Impact of system service provision on unit value of biogas micro-CHP

Considerable potential savings can be achieved through the FlexiCell concept in the combined electricity and heat system according to the previous analysis. However, the value of the FlexiCell concept may be significantly influenced by the availability of flexibility options in the electricity system. Therefore, we also investigate the values of the FlexiCell concept providing system services in the context of low and high level of flexibility in the electricity system and reveals the impact of the electricity-based flexibility measures on the values of the FlexiCell concept. For illustrative purposes, this case study is carried out by enhancing the flexibility of the electricity system through:

1) Utilizing more efficient and more flexible thermal generators. The comparison of the operating parameters between generators with low and high flexibility and efficiency are presented in

Table 1.

2) Assuming that 15GW of electrical energy storage have already been deployed in the electricity system and can provide system services.

3) Assuming that 20% of the non-heat driven electricity load is flexible to provide demand side response.

The OPEX savings and CAPEX savings in both electricity and heat sectors through the FlexiCell concept providing system services when different flexibility measures are available in the electricity system are demonstrated in Figure 27.

Table 1. Operating parameters of generators in different scenarios

Flexibility & efficiency	Generation	MSG	Maximum response (% rating)	Efficiency (%) MSG	Efficiency (%) FULL
Low	CCGT	50%	12%	51.5%	58.8%
	Gas CCS	50%	7%	45.2%	51.3%
	Nuclear	60%	0	-	-
	OCGT	40%	30%	31.2%	35.0%
	Coal CCS	40%	5%	25.4%	35.0%
High	CCGT	40%	17%	55.1%	58.8%
	Gas CCS	40%	10%	48.1%	51.3%
	Nuclear	80%	0	-	-
	OCGT	40%	40%	33.0%	35.0%
	Coal CCS	40%	5%	29.7%	35.0%

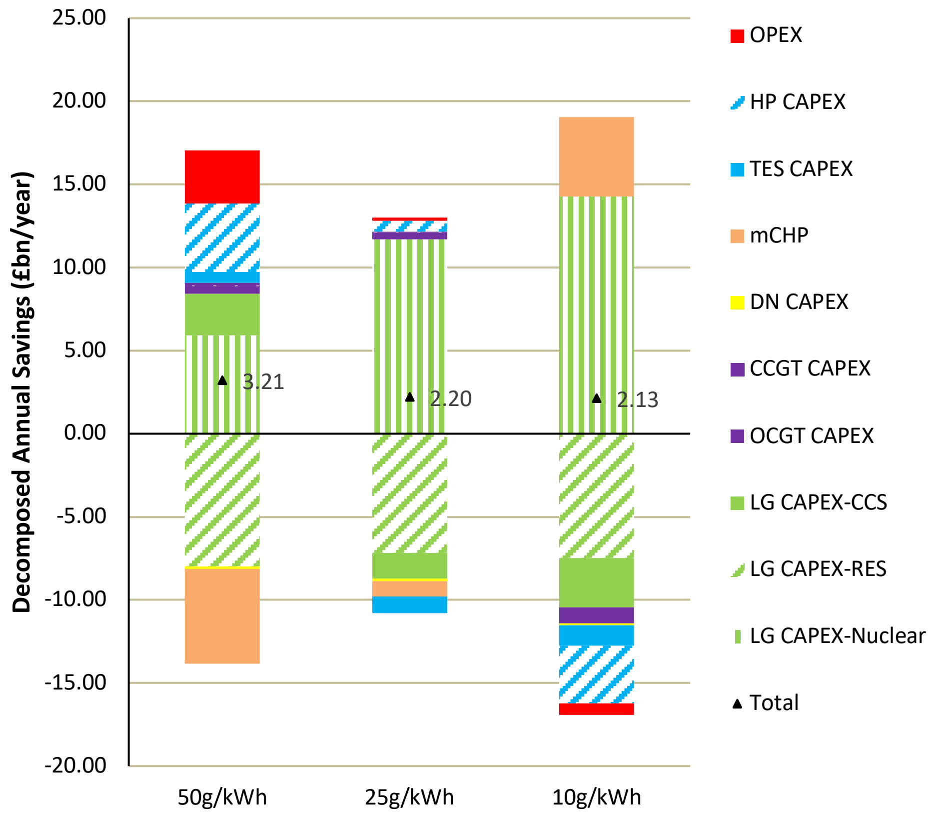


Figure 27. Savings from the FlexiCell concept providing system services when different flexibility measures are available in the electricity system

Compared with Figure 23, the total saving of the FlexiCell concept providing system services in this case reduces significantly. This demonstrates that the values of the flexibility from the FlexiCell concept may reduce accordingly if the flexibility within the electricity system increases. It is however important to note that the additional cost associated with enhancing the flexibility of the electricity system is not taken into account. To be specific, it is assumed that flexible thermal generators, electrical storage are already deployed in the electricity system while DSR can be dispatched without incurring miscellaneous costs. In fact, it can be very capital-intensive to improve the flexibility of thermal generation and deploy electrical energy storage on a large scale. The potential cost that DSR can incur depends on consumers' willingness and behaviour, which have significant uncertainty. Meanwhile, the FlexiCell concept can provide substantial flexibility for the electricity system through energy system integration which otherwise will not be put into any use. If we consider the additional cost associated with flexible generators, electrical storage and DSR, the model will choose the FlexiCell concept as the prioritised flexibility source.

To summarise, the flexibility level in the electricity system, particularly determined by the flexible resources enabling energy arbitrage, frequency response, operating reserve provision, etc., is crucial for the added values of the FlexiCell concept in facilitating the transition to a low-carbon energy system. Although there are many ways, most of which are costly, to improve the flexibility of the electricity system, the FlexiCell concept is a highly cost-effective alternative.

5.2 Value of coordinated control in the FlexiCell concept

The previous studies are based on the assumption that the FlexiCell concept is carried out with perfect coordinative control across numerous households. Specifically, the operation of micro-CHP, ASHP and TES within a single household is fully coordinated so that they can work in the most cost-efficient manner. Moreover, the whole system optimization of energy system investment and operation is based on the assumption that all components, including micro-CHP, ASHP, TES, etc. in different households can be aggregated without loss of efficiency such that they can provide system services as long as they can be dispatched when it is needed by the system to improve the capacity margin, especially during peak demand periods, facilitate the accommodation of RES etc., while not compromising the delivery of heat to households. The absence of the coordination between different heating appliances in the FlexiCell concept would lead to inefficient operation in both electricity and heat systems and drive additional infrastructure investments at both the local and national level.

In this context, two cases in the following are compared to quantify the whole system value of the coordinative control in the FlexiCell concept:

1) The benchmark case (counterfactual) – Coordinated control is not integrated to the FlexiCell concept: the operation of micro-CHP, heat pumps and TES are uncoordinated.

2) The investigated case – The FlexiCell concept is implemented with coordinative control: the operation of micro-CHP, ASHP and TES is fully coordinated in an economic manner. Specifically:
    - Heat supply of the FlexiCell concept can be switched between micro-CHP, ASHP and TES based on the real-time energy efficiency of individual technologies. For example, when the operation efficiency of ASHP is high, based on the weather condition, the use of ASHP is prioritised to supply heat load while micro-CHP operates when heat pumps cannot meet the full demand. When the efficiency of heat pumps is low, e.g., in extremely cold weather, micro-CHP is switched on to support the heat supply, the heat supply from both appliances is optimized considering the real-time operational conditions.
    - TES can perform energy arbitrage. Due to the presence of coordinative control, the real-time electricity price (determined by the marginal operational cost of the whole system) is known to the local controller. Therefore, individual consumers can increase the heating power of ASHP during low-price periods and store the surplus heat in TES. When the electricity price is high, heat demand can be partially supplied through TES discharging, thus achieving cost savings.
    - The FlexiCell concept can provide system services as long as they have the capacity margin to be dispatched when it is needed by the system. Decentralized micro-CHP, ASHP and TES across numerous households can be effectively aggregated and respond to the system requirements.

Figure 28 demonstrates the cost savings across different sectors due to presence of smart control which coordinates the FlexiCell concept across numerous households. Each bar is formed by stacking the cost difference of all considered sectors (blocks) in the benchmark case and the investigated case.

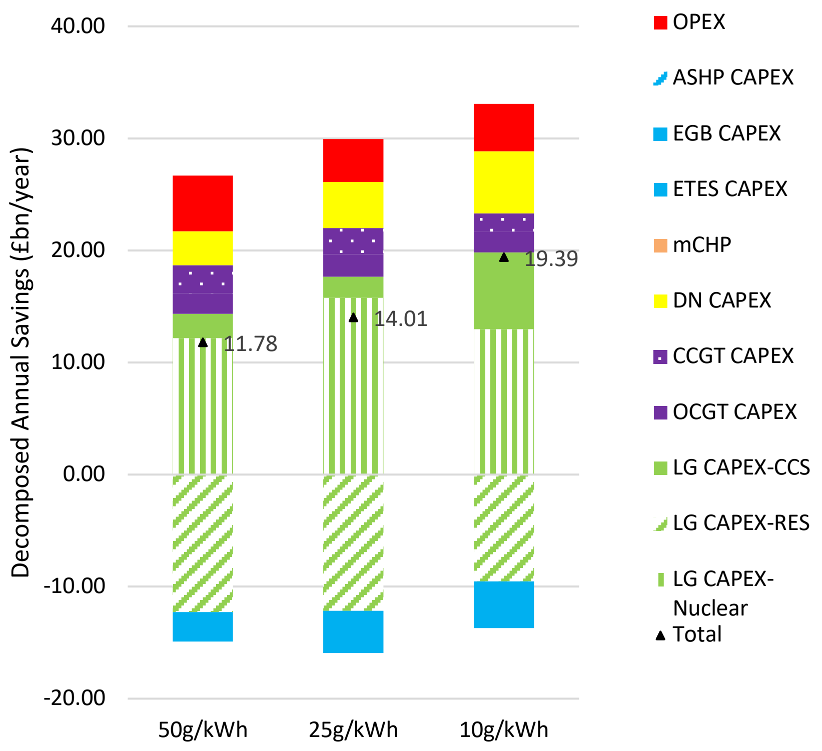


Figure 28. Impact of coordinative control for the FlexiCell concept on the whole system costs

The following key findings can be drawn from Figure 28:

- Significant savings are achieved through the coordinative control. Specifically, 11.78£bn/year, 14.01£bn/year and 19.39£bn/year of savings are delivered under the carbon target of 50g/kWh, 25g/kWh and 10g/kWh, respectively. Key contributions of cost reduction are from savings in nuclear CAPEX, CCS CAPEX, OCGT CAPEX, CCGT CAPEX, distribution network CAPEX and OPEX.
- Significantly more RES is integrated into the system. Meanwhile, more TES is required.
- The whole system benefits of coordinative control increase with the tightening of the carbon target.

These findings provide the following insights:

- The integration of effective coordinative control approaches into the FlexiCell concept and the large-scale deployment of the associated infrastructure is particularly important in facilitating cost-effective transition to the low-carbon energy system. Huge savings can be achieved by introducing smart control to coordinate the operation of decentralized heating technologies covered in the FlexiCell concept.
- The absence of coordinative control in the FlexiCell concept would dramatically reduce the operation efficiency of the integrated electricity and heat system, causing significant increase of OPEX.
- The FlexiCell concept with coordinative control can drive more efficient investment decisions for both the local and national level infrastructure, e.g.,

optimizing the distribution network reinforcement and the sizing of back-up capacities.

- Without smart control, decentralised resources, e.g., micro-CHP, ASHP and TES, will not be able to interact with the electricity system. As a result, all system services will have to be provided by conventional generation or electric storage, which significantly increase the system integration costs of intermittent renewables, thus increasing the economic burden for decarbonizing the energy system. In this context, more nuclear and CCS will be involved, posing environmental issues.
- Moreover, end-use TES, which can potentially provide a promising opportunity in alleviating the challenges of mass heat electrification, highly relies on coordinative control approaches to unify the benefits of both individual consumers and system operators.

Figure 29 further demonstrates the impact of smart control on the system costs with the alternative FlexiCell concept characterized by biogas micro-CHP.

The overall savings and variation trend across different carbon scenarios are similar to the original FlexiCell concept (with natural gas micro-CHP). This is because the studies in this section are focused on the values of coordinative control, which is irrelevant to micro-CHP types. But there are still some differences between Figure 28 and Figure 29:

- More CCS capacity is saved. In the 10g/kWh scenario, more nuclear capacities are saved while more RES is integrated. This indicates that the presence of coordinative control plays a more important role in supporting the alternative FlexiCell concept to integrate RES in low-carbon scenarios.
- Less OPEX is saved. Particularly in the 10g/kWh scenario, OPEX is not reduced with the presence of coordinative control. This is because the operation cost of biogas micro-CHP is much higher. When coordinative control is absent from the FlexiCell concept, biogas micro-CHP only serves as back-up capacity, therefore, its utilisation is particularly low. However, when coordinative control is present, the utilization of biogas micro-CHP can be significantly improved, which increases the operation cost.

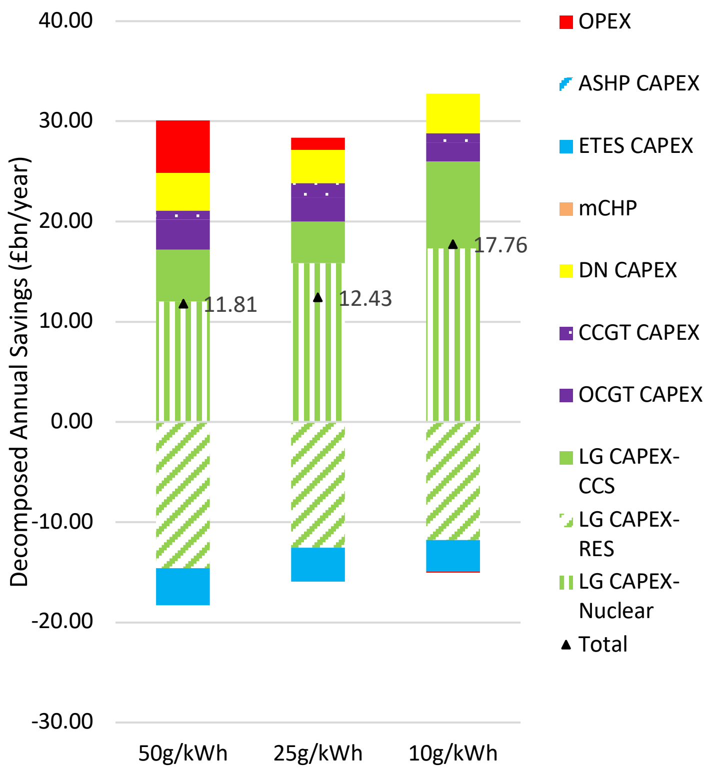


Figure 29. Impact of coordinative control for the alternative FlexiCell concept, biogas based micro-CHP, on the whole system costs

6 Impacts of FlexiCell concept for local distribution networks

6.1 Incorporation of both national and local networks

There are interactions between different levels of assets, e.g., generation, transmission infrastructure at the national level and distribution and demand side at the local level. Therefore, the operation and investment of the infrastructure at one level can potentially influence the operation and investment of the other levels. For instance, on the one hand, the electrification of heating at the end-use side, e.g., by utilizing ASHPs, can potentially result in reinforcement of distribution network and reduced investment in heat network; on the other hand, the deployment of micro-CHP will partially displace the capacity of end-use electrified heating devices, thus alleviating the burden of network reinforcement at the distribution level, and it can also reduce the requirement of new generation capacities at the national level. Without considering the impacts on the other levels of assets, the potential values of the FlexiCell concept cannot be comprehensively assessed. Therefore, it will be important to incorporate both the national and local level infrastructure in the whole system modelling of the integrated energy system.

For the national level infrastructure, different regions of the UK and the topology of the transmission network are considered. Each region covers numerous local distribution networks of different geographic types.

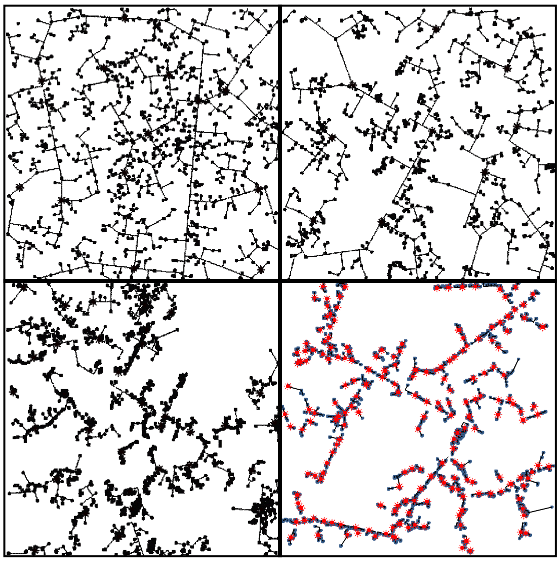


Figure 30 Generated representative distribution networks

For the local level infrastructure, Figure 30 illustrates four representative types of distribution networks. Specifically, the upper left network represents an urban prototype in which consumers are evenly distributed while the lower right network represents a rural one where the layout of consumers tends to be clustered. The other two with mixed characteristics of the urban and rural networks are suburban and semirural prototypes. Note that the red dots highlight the substations. A detailed description of the integration of the representative networks into the whole system modelling will be given in Appendix A.3.

In the context of deep decarbonization, large-scale electrification of the heat system will remarkably boost the requirement for local distribution network reinforcement. Due to the involvement of micro-CHP, the FlexiCell concept can supply the peak heat demand by consuming gas thus reducing the electrified heat demand and consequently alleviating the burden of distribution network reinforcement. In this section, we discuss the approach and the results of the studies analysing the impact and the benefits of the FlexiCell concept on the electrical distribution systems in the UK. The studies complement the previous analyses and enable the impact of the FlexiCell concept on the electrical system to be analysed in a holistic manner.

In order to enable the studies, a set of representative network models has been developed by Imperial College. The models resemble the characteristics of distribution systems across Europe in terms of the load density, network length, number of substations, number and type of transformers, etc. Details of the models can be found in Appendix A.3.

Studies were carried out to determine the required reinforcement measures and estimate the reinforcement cost for different network classes (rural, urban, semi-rural/urban) for a given FlexiCell concept uptake level. The integration of the FlexiCell concept may trigger thermal and/or voltage-driven problems in the network; in order to solve the problems, the network will need to be reinforced. If the problems are voltages, there may be possibilities to solve by optimising the position of tap-changing transformers. The studies consider some discrete reinforcement options, which may create some headroom in the network. By aggregating the reinforcement costs across all network classes, it is possible to determine accurately the impact of the FlexiCell concept on different network classes and estimate the total distribution reinforcement costs at the national level. Figure 31 depicts the approach to estimating distribution reinforcement cost for a given scenario.

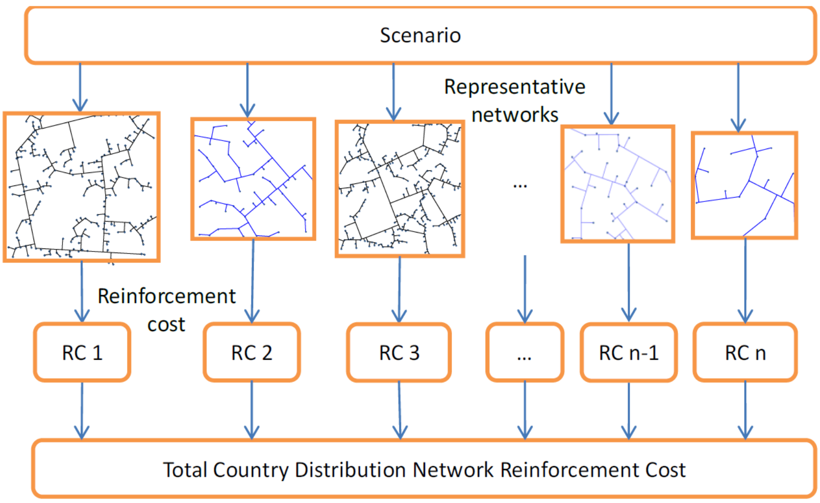


Figure 31 Estimating distribution reinforcement cost for a given scenario

In order to quantify the impact of the FlexiCell concept, three market uptake projection scenarios of the FlexiCell concept (Low, High and Optimal) as employed in Section 4 are used in the studies. For each scenario, the benefit of the FlexiCell concept under a specific uptake scenario is derived by calculating the cost with respect to the reference case where the FlexiCell concept is not chosen. It should be emphasized that the involvement of micro-CHP fundamentally differentiates the FlexiCell concept from the other low-carbon heating solutions, since the benefit of micro-CHP is still open to debate while heat pumps and TES are widely regarded as effective technologies that can facilitate heat decarbonization. Therefore, the case studies will highlight the important role micro-CHP plays in the FlexiCell concept.

6.2 Benefits of the FlexiCell concept for distribution network

Based on the approach described in Section 3, the differences between two heating strategies (i) the FlexiCell concept with the combination of natural gas micro-CHP + ASHP + PCM-based TES, and heating strategy (ii) ASHP + PCM-based TES are analysed to investigate the benefit of using the FlexiCell concept for local distribution networks.

Figure 32 demonstrates the system benefits of per unit capacity of micro-CHP under different carbon targets, i.e., 50g/kWh, 25g/kWh and 10g/kWh. Note that the area enclosed by green curves represents CAPEX savings of all categories of generation. The area enclosed by blue curves represents CAPEX savings of all types of heating appliances while the area enclosed by red curves represent OPEX savings. Cost savings for distribution network reinforcement is particularly highlighted by the yellow blocks at the top of each bar. The results are expressed in £/kW electrical capacity of micro-CHP. Since the CAPEX of micro-CHP is not included in the optimization, therefore, the results represent the gross benefits.

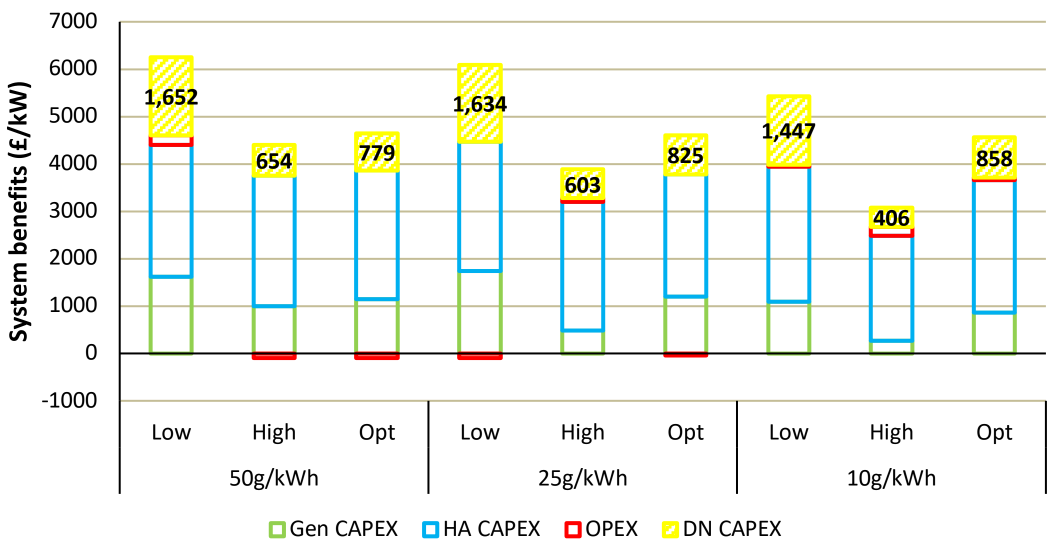


Figure 32: Unit system benefits of the FlexiCell concept for distribution network

According to the results in Figure 32, the following observations and analysis are addressed:

- The penetration of the FlexiCell concept, particularly micro-CHP, significantly affects its unit benefits (£/kW) for distribution networks. It is observed that the values of DN CAPEX in the high uptake scenarios are significantly lower than those in low uptake scenarios. This indicates the marginal value of the FlexiCell concept for distribution network reduces with the increase in the penetration of micro-CHP. It is further observed that the benefits of both low and high uptake scenarios decrease with the tightening of the carbon target. This is because the FlexiCell concept involves the consumption of natural gas, therefore, its advantage decreases in tighter carbon scenarios.
- By optimizing the uptake of the FlexiCell concept, the unit benefit of micro-CHP for distribution networks can increase with the tightening of carbon target, as shown in the optimal uptake scenario.
- Due to the large-scale deployment of the FlexiCell concept, natural gas serves as a supplementary energy source to meet the heat demand, which reduces the peak of electrified heat demand and therefore alleviates costs in distribution network reinforcement (DN CAPEX).
- Since the considerable peak-to-valley difference of heat demand, the installation of full-size ASHP for covering the peak heat demand would make the utilization of ASHP extremely low. Meanwhile, distribution networks must be accordingly expanded to accommodate the installation of ASHP, which would also be characterized by low utilization. In this context, the displacement of ASHP by micro-CHP, as in the FlexiCell concept, not only alleviates the electricity requirement for heating, thus achieving cost savings for distribution networks, but also improves the utilisation efficiency of distribution networks.

Figure 33 demonstrates the annual savings for the distribution network through the deployment of the FlexiCell concept in different uptake and carbon scenarios. Different from Figure 32, the results in Figure 33 represent the decomposed annual whole system savings driven by the deployment of the FlexiCell concept under different scenarios. Specifically, as can be seen, the FlexiCell concept can facilitate increased reductions in DN CAPEX in the high uptake scenarios, while this saving decreases with the tightening of the carbon target.

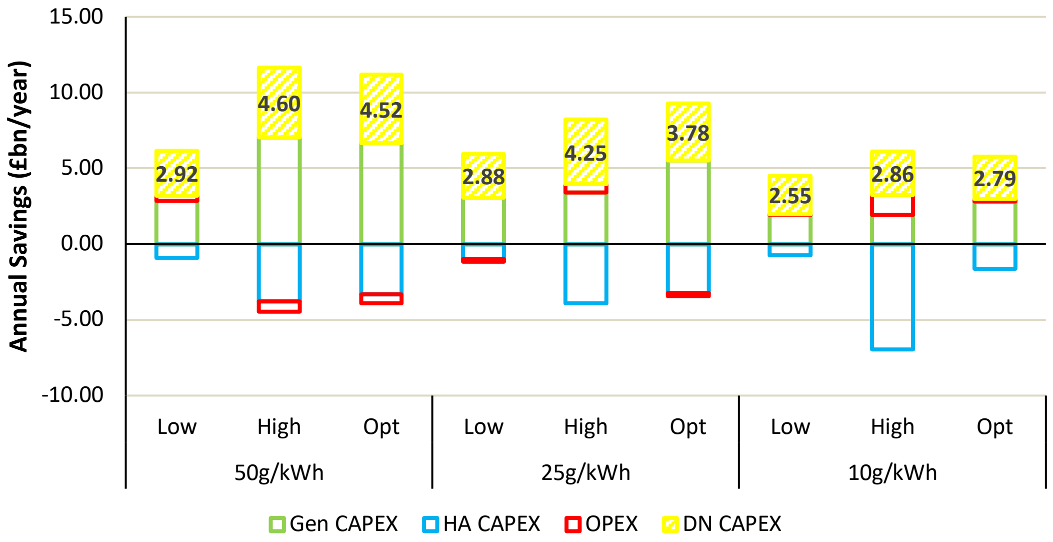


Figure 33: Annual savings for distribution network through the deployment of the FlexiCell concept

The savings in distribution networks is mainly driven by the reduction in electricity peak demand due to the displacement of electric heat pumps by micro-CHP based on the FlexiCell design. Through the coordination between micro-CHP, ASHP and TES, heat demand is supplied by gas during peak time which only lasts for very limited hours and is supplied by electricity during off-peak periods which account for most of the time. Therefore, the electricity peak demand is significantly reduced without essentially undermining the environmental benefits.

Moreover, in the FlexiCell technology combination, the micro-CHP generates electricity at the end-side and locally supplies the electricity demand. This can significantly facilitate the alleviation/delay of distribution network reinforcement. Therefore, the deployment of the FlexiCell concept can benefit the distribution network through both the heat sector and the electricity sector.

Based on the analysis above, the benefits of FlexiCell concept will be limited in extremely low carbon scenarios, due to its involvement of natural gas consumption. Compared to the natural gas micro-CHP, biogas micro-CHP is carbon neutral, which indicates its potential values in low carbon scenarios. Therefore, we also investigated the performance of the alternative FlexiCell concept in which natural gas micro-CHP is replaced by biogas micro-CHP.

The unit benefits and whole system benefits of employing the alternative FlexiCell concept (with biogas micro-CHP) are presented in Figure 34 and Figure 35, respectively.

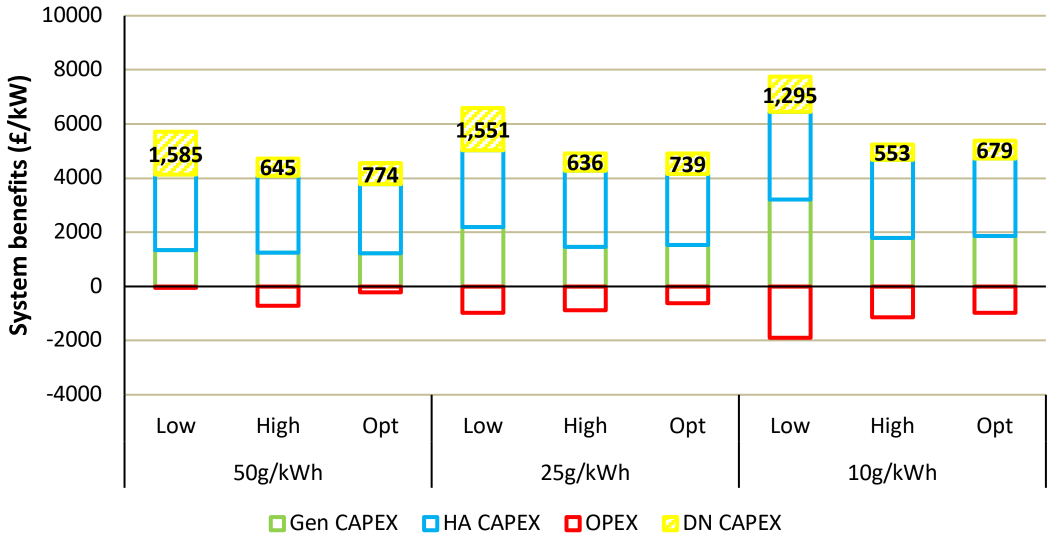


Figure 34: Unit system benefits of the alternative FlexiCell concept for distribution network

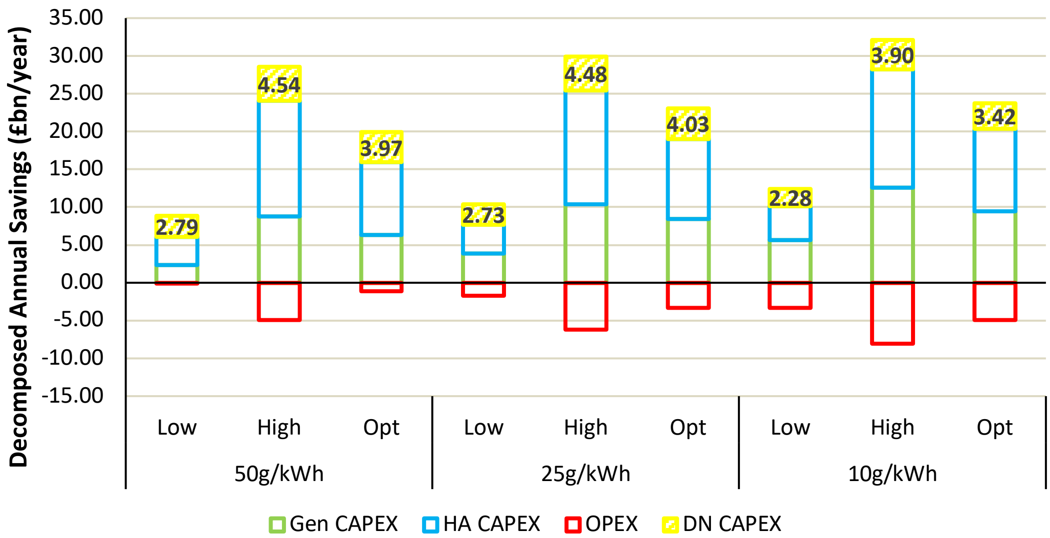


Figure 35: Annual savings for distribution network through the deployment of the alternative FlexiCell concept

Compared with the results for the original FlexiCell concept (with natural gas micro-CHP), the following key findings are summarized:

- The unit benefits of micro-CHP in the alternative FlexiCell concept for distribution network is relatively low compared to the original FlexiCell concept. This is mainly because biogas micro-CHP displaces fewer heat pumps, as can be observed in HA CAPEX savings in Figure 32 and Figure 34, due to its high OPEX. As a result, less electricity peak demand is reduced.

- Comparing the whole system savings of DN CAPEX in Figure 33 and Figure 35, it can be seen that more benefits are achieved in distribution networks with the deployment of the optimal uptake alternative FlexiCell concept in tight carbon scenarios (10g/kWh and 25g/kWh), while in the 50g/kWh scenario the original FlexiCell concept delivers more benefits in DN CAPEX. This indicates biogas micro-CHP is advantageous in benefiting distribution networks in low carbon scenarios.

7 Conclusions

In this section, the whole system benefits of the FlexiCell concept are comprehensively overviewed. Based on the results of the studies and the analysis that have been carried out, a set of conclusions can be derived as follows:

- The FlexiCell concept can bring the following whole system benefits:
  - Displace capacity of central generators. The capacity value of micro-CHP in the FlexiCell concept is comparable to traditional gas-fired plant providing it can be dispatched as back-up; The FlexiCell concept can provide firm capacity to the system, and also fulfil some functionalities of conventional generations, e.g., providing frequency response and operating reserve. Therefore, it can drive savings in the CAPEX of conventional generation.
  - Increase the utilization rate of heating appliances. Displace the capacity of alternative heat sources. In the short-term, micro-CHP can efficiently displace heat pumps as an alternative heat source. Additionally, large-scale deployment of micro-CHP reduces the dependence on TES for flexibility-associated motivations in the transition of mass heat electrification.
  - Reduce operating costs. Net energy consumption is reduced indicating higher energy efficiency.
  - Release network capacity/postpone reinforcement at distribution networks; Through the coordination between micro-CHP, ASHP and TES, the electricity peak demand is significantly reduced without essentially undermining the environmental benefits. Moreover, by adopting the FlexiCell concept, micro-CHP generates electricity at the end-side and locally supplies the electricity demand. This can significantly facilitate the alleviation/delay of distribution network reinforcement. Therefore, the deployment of the FlexiCell concept can benefit the distribution network through both the heat sector and the electricity sector.
  - Providing demand response. The heating technology combination specified by the FlexiCell concept can provide various system services to the electricity system, which can facilitate the integration of renewable energy sources and reduce the requirement of nuclear and other firm generation.
- The benefits of alternative FlexiCell concept with biogas micro-CHP displacing natural gas micro-CHP highly depends on the price of biogas. When biogas price is high, micro-CHP tend to play as a complementary heating measure in the alternative FlexiCell concept, prioritising the supply of peak heat demand. Since heat demand is volatile, the load factor of micro-CHP in the alternative FlexiCell concept is particularly low, therefore undermining its operational values. When biogas price is relatively low, micro-CHP can potentially compete with ASHP to supply off-peak load, thus increasing its load factor. Additionally, since biogas micro-CHP is carbon neutral, it can also compete with RES.

- The whole system benefit of large-scale uptake of the FlexiCell concept is sensitive to the decrease of micro-CHP CAPEX, since the high capital cost of micro-CHP for end-use compared to ASHP is the key limiting factor currently. Meanwhile, the whole system benefit of large-scale uptake of the FlexiCell concept is less sensitive to the change of carbon target in all CAPEX scenarios.
- Large savings are driven by the provision of system services through the FlexiCell concept, from 5.94£bn/year to 9.28£bn/year in different carbon scenarios. If the FlexiCell concept provides system services, the coordinated operation of micro-CHP, ASHP and TES can reduce the system integration costs of intermittent renewables, thus increasing the investment of RES and reducing nuclear and CCS. Moreover, it facilitates the electrification of the heat systems so that the flexibility of the heat systems can be shifted to the electricity side to further support the accommodation of RES. As a result, the investment of both ASHP and TES is increased while the deployment of micro-CHP is reduced. Additionally, further distribution network reinforcement is required due to deeper electrification of the heat systems and more back-up OCGT is needed to displace part of micro-CHP.
- The integration of effective coordinative control approaches into the FlexiCell concept and the large-scale deployment of the associated infrastructure is particularly important in facilitating the cost-effective transition to the low-carbon energy system. Huge savings can be achieved by introducing smart control to coordinate the operation of decentralized heating technologies covered in the FlexiCell concept. The absence of coordinative control in the FlexiCell concept would dramatically reduce the operation efficiency of the integrated electricity and heat system, causing significant increase of OPEX. Meanwhile, the FlexiCell concept with coordinative control can drive more efficient investment decisions for both the local and national levels of infrastructure, e.g., optimizing the distribution network reinforcement and the sizing of back-up capacities.
- Without smart control, decentralized resources, e.g., micro-CHP, ASHP and TES, will not be able to interact with the electricity system. As a result, all system services will have to be provided by conventional generation or electric storage, which significantly increase the system integration costs of intermittent renewables, thus increasing the economic burden for decarbonizing the energy system. In this context, more nuclear and CCS will be involved, posing environmental issues. Moreover, end-use TES in the FlexiCell concept, which can potentially provide a promising opportunity in alleviating the challenges of mass heat electrification, highly relies on coordinative control approaches to unify the benefits of both individual consumers and system operators.

Based on these results and the analysis, it can be concluded that the FlexiCell concept, which involves the heating technology combination of micro-CHP, ASHP and TES can bring all-round benefits to the decarbonization of the UK energy system in both short and long run. The whole system benefits of the FlexiCell concept arising from these analyses suggest that appropriate mechanisms should be put in place including removal of barriers and establish a framework in system services markets and coordinative control to enable wide deployment of the FlexiCell concept across the UK energy system. Acknowledgement of its system benefits and a full framework for participation in the system services market, will allow the FlexiCell concept to fully participate in the power and heat sectors and to compete with other low-carbon technologies.

Appendix

A.1. Description of IWES

When considering system benefits of enabling technologies such as storage, Demand-Side Response (DSR), interconnection and flexible generation, it is important to consider two key aspects:

- Different time horizons: from long-term investment-related time horizon to real-time balancing on a second-by-second scale (Figure 36); this is important as the alternative balancing technologies can both contribute to savings in generation and network investment as well as increase the efficiency of system operation.

- Different assets in the electricity system: generation assets (from large-scale to distributed small-scale), transmission network (national and interconnections), and local distribution network operating at various voltage levels. This is important as alternative balancing technologies may be placed at different locations in the system and at different scales. For example, bulk storage is normally connected to the national transmission network, while highly distributed technologies may be connected to local low-voltage distribution networks.

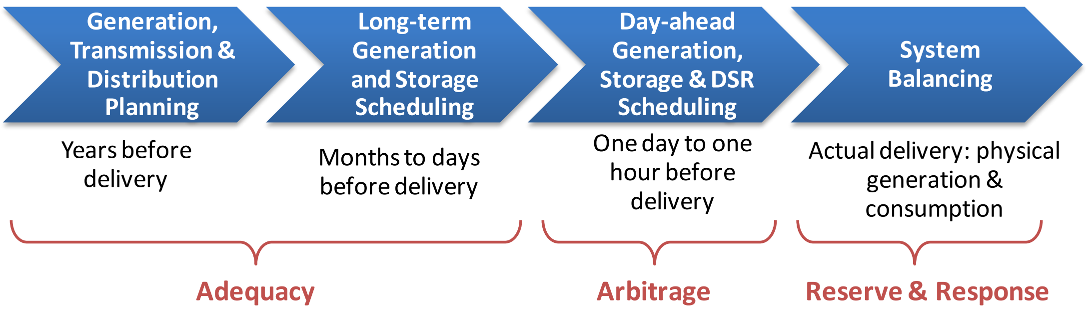


Figure 36. Balancing electricity supply and demand across different time horizons

Capturing the interactions across different time scales and different asset types is essential for the analysis of future low-carbon electricity systems that includes alternative balancing technologies such as storage and demand side response. Clearly, applications of those enabling technologies in the system can improve not only the economics of short-run system operation, but they can also reduce the necessary investment into generation and network capacity in the long-run.

In order to capture these effects and in particular 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, we have developed IWES, 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.

This holistic model provides 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. The IWES has been extensively tested in previous projects studying the interconnected electricity systems of the UK and the rest of Europe. An advantage of IWES 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. For example, the model captures potential conflicts and synergies between different applications of distributed storage in supporting intermittency management at the national level and reducing necessary reinforcements in the local distribution network.

A.2. IWES problem formulation

IWES 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 requirements), which is coupled with (ii) long-term investment i.e. planning decisions with the time horizon of multiple years (e.g. 2015-2050). All investment decisions and operation decisions are determined simultaneously in order to achieve the overall optimality of the solution. An overview of the IWES model structure is given in Figure 37.

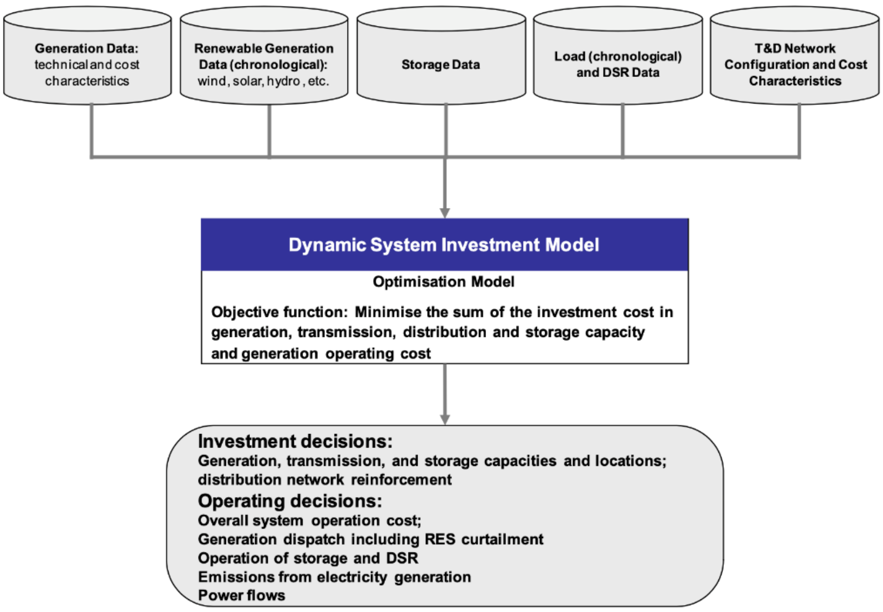


Figure 37. Structure of the Whole-electricity System Investment Model (IWES)

The objective function of IWES is to minimise the overall system cost, which consists of investment and operating cost:

- The investment cost includes (annualised) capital cost of new generating and storage units, the capital cost of new interconnection capacity, and the reinforcement cost of transmission and distribution networks. In the case of storage, the capital cost can also include the capital cost of storage energy capacity, which determines the amount of energy that can be stored in the storage. Various types of investment costs are annualised by using the appropriate Weighted-Average Cost of Capital (WACC) and the estimated economic life of the asset. Both of these parameters are provided as inputs to the model, and their values can vary significantly between different technologies.

- System operating cost consists of the annual generation operating cost and the cost of energy not served (load-shedding). Generation operating cost consists of: (i) variable cost which is a function of electricity output, (ii) no-load cost (driven by efficiency), and (iii) start-up cost. Generation operating cost is determined by two input parameters: fuel prices and carbon prices (for technologies which are carbon emitters).

There are a number of equality and inequality constraints that are considered in the model while minimising the overall cost. These include:

- Power balance constraints: ensure that supply and demand are balanced at any time.
- Operating reserve constraints include various forms of fast and slow reserve constraints. The amount of operating reserve requirement is calculated as a function of uncertainty in generation and demand across various time horizons. The model distinguishes between two key types of balancing services: (i) frequency regulation (response), which is delivered in the timeframe of a few seconds to 30 minutes; and (ii) reserves, typically split between spinning and standing reserve, with delivery occurring within the timeframe of tens of minutes to several hours after the request (this is also linked with the need to re-establish frequency regulation services following an outage of a generating plant). The need for these services is also driven by wind output forecasting errors and this will significantly affect the ability of the system to absorb wind energy. It is expected that the 4 hours ahead forecasting error of wind, being at present at about 15% of installed wind capacity, may reduce to 10% post-2020 and then further to less than 6%, may have a material impact of the value of flexibility options. Calculation of reserve and response requirements for a given level of intermittent renewable generation is carried out exogenously and provided as an input into the model. IWES then schedules the optimal provision of reserve and

response services, taking into account the capabilities and costs of potential providers of these services (response slopes, efficiency losses of part loaded plant etc.) and finding the optimal trade-off between the cost of generating electricity to supply a given demand profile, and the cost of procuring sufficient levels of reserve and response (this also includes alternative balancing technologies such as storage and DSR as appropriate).

In order to take into account the impact of having less inertia during low demand and high renewable output conditions, the IWES' s formulation has been enhanced by including additional constraints that dictate the minimum response requirements to meet the RoCOF specification, the minimum frequency at the nadir point, and the steady state frequency deviation from the nominal frequency as illustrated in Figure 38.

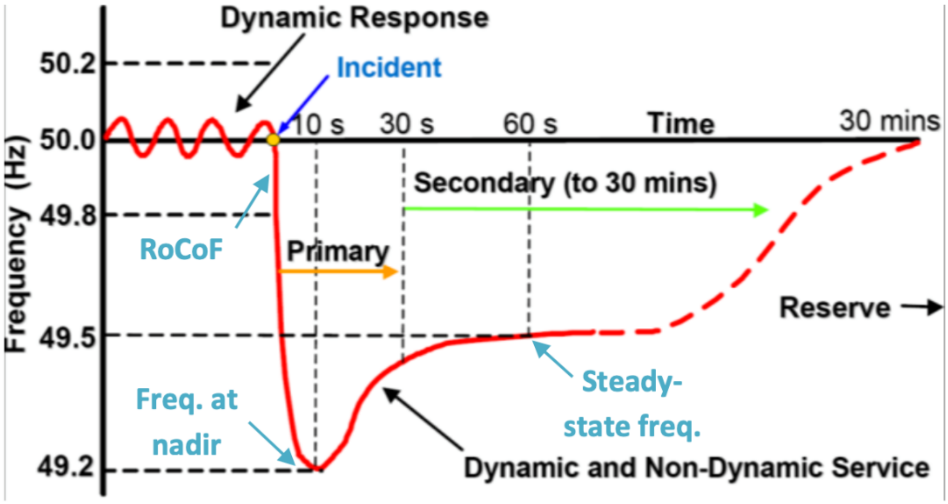


Figure 38. System frequency evolution after a contingency (source: National Grid)

-
- In IWES, the frequency response can be provided by:
- Synchronised part-loaded generating units
- I&C flexible demand
- Interruptible charging of electric vehicles
- Smart domestic appliances
- Interruptible heat storage when charging
- A proportion of wind power being curtailed
- A proportion of electricity storage when charging
- Interconnections
- While reserve services can be provided by:
- Synchronised generators

- Wind power or solar power being curtailed
- Stand-by fast generating units (OCGT)
- Electricity storage
- The amount of spinning and standing reserve and response is optimized ex-ante to minimise the expected cost of providing these services, and we use our advanced stochastic generation scheduling models to calibrate the amount of reserve and response scheduled in IWES. These models find the cost-optimal levels of reserve and response by performing a probabilistic simulation of the actual utilisation of these services. Stochastic scheduling is particularly important when allocating storage resources between energy arbitrage and reserve as this may vary dynamically depending on the system conditions.
- Generator operating constraints include: (i) Minimum Stable Generation (MSG) and maximum output constraints; (ii) ramp-up and ramp-down constraints; (ii) minimum up and down time constraints; and (iv) available frequency response and reserve constraints. In order to keep the size of the problem manageable, we group generators according to technologies, and assume a generic size of a thermal unit of 500 MW (the model can however commit response services to deal with larger losses, e.g. 1,800 MW as used in the model). The model captures the fact that the provision of frequency response is more demanding than providing operating reserve. Only a proportion of the headroom created by part-loaded operation, as indicated in Figure 39.
- Given that the functional relationship between the available response and the reduced generation output has a slope with an absolute value considerably lower than 1, the maximum amount of frequency regulation that a generator can provide (Rmax) is generally lower than the headroom created from part-loaded operation (Pmax – MSG).

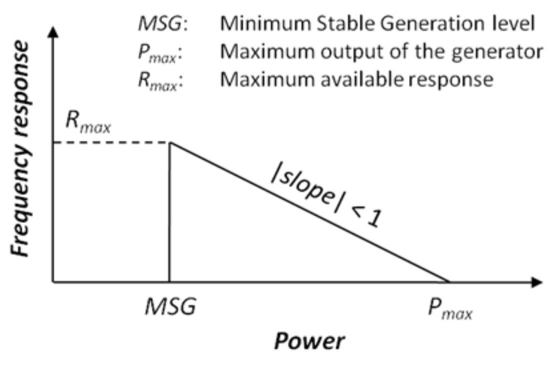


Figure 39. Provision of frequency regulation from conventional generation

- Generation: IWES optimises the investment in new generation capacity while considering the generators' operation costs and CO2 emission constraints, and maintaining the required levels of security of supply. IWES optimises both the quantity and the location of new generation capacity as a part of the overall cost minimisation. If required, the model can limit the investment in particular generation technologies at given locations.

- Annual load factor constraints can be used to limit the utilisation level of thermal generating units, e.g. to account for the effect of planned annual maintenance on plant utilisation.
- For wind, solar, marine, and hydro run-of-river generators, the maximum electricity production is limited by the available energy profile, which is specified as part of the input data. The model will maximise the utilisation of these units (given zero or low marginal cost). In certain conditions when there is an oversupply of electricity in the system or reserve/response requirements limit the amount of renewable generation that can be accommodated, it might become necessary to curtail their electricity output in order to balance the system, and the model accounts for this.
- For hydro generators with reservoirs and pumped-storage units, the electricity production is limited not only by their maximum power output, but also by the energy available in the reservoir at a particular time (while optimising the operation of storage). The amount of energy in the reservoir at any given time is limited by the size of the reservoir. It is also possible to apply minimum energy constraints in IWES to ensure that a minimum amount of energy is maintained in the reservoir, for example, to ensure the stability of the plant. For storage technologies, IWES takes into account efficiency losses.
- Demand-side response constraints include constraints for various specific types of loads. IWES broadly distinguishes between the following electricity demand categories: (i) weather-independent demand, such as lighting and industrial demand, (ii) heat-driven electricity demand (space heating/cooling and hot water), (iii) demand for charging electric vehicles, and (iv) smart appliances' demand. Different demand categories are associated with different levels of flexibility. Losses due to temporal shifting of demand are modelled as appropriate. Flexibility parameters associated with various forms of DSR are obtained using detailed bottom-up modelling of different types of flexible demand.
- Power flow constraints limit the energy flowing through the lines between the areas in the system, respecting the installed capacity of the network as the upper bound (IWES can handle different flow constraints in each flow direction). The model can also invest in enhancing network capacity if this is cost-efficient. Expanding transmission and interconnection capacity is generally found to be vital for facilitating the efficient integration of large intermittent renewable resources, given their location. Interconnectors provide access to renewable energy and improve the diversity of demand and renewable output on both sides of the interconnector, thus reducing the short-term reserve requirement. Interconnection also allows for sharing of reserves, which reduces the long-term capacity requirements.
- Distribution network constraints are devised to determine the level of distribution network reinforcement cost, as informed by detailed modelling of representative UK networks. IWES can model different types of distribution networks, e.g. urban, rural, etc. with their respective reinforcement cost.

- Emission constraints limit the amount of carbon emissions within one year. Depending on the severity of these constraints, they will have an effect of reducing the electricity production of plants with high emission factors such as oil or coal-fired power plants. Emission constraints may also result in additional investment in low-carbon technologies such as renewables (wind and PV), nuclear or CCS in order to meet the constraints.
- Security constraints ensure that there is sufficient generating capacity in the system to supply the demand with a given level of security. If there is storage in the system, IWES may make use of its capacity for security purposes if it can contribute to reducing peak demand, given the energy constraints.
- IWES allows for the security-related benefits of interconnection to be adequately quantified. Conversely, it is possible to specify in IWES that no contribution to security is allowed from other regions, which will clearly increase the system cost, but will also provide an estimate of the value of allowing the interconnection to be used for sharing security between regions.

A.3. Description of distribution network analysis methodology

The purpose of the distribution network modelling approach is to understand and quantify the impact of future load growth, including the impact of electrification of heat and transport sectors, on necessary distribution network reinforcements and to assess the benefits of smart control of network and load in avoiding or postponing network investments. The approach to distribution network modelling is based on analysing statistically representative networks rather than actual networks. This method allows the formulation of computationally feasible analytical models with only a minor sacrifice in terms of the accuracy of estimating reinforcement cost.

The use of statistically representative networks is motivated by the fact that the reinforcement cost in distribution networks tends to be driven by the network length, which can be expressed as a function of customer density. Using a limited number of these statistically representative network types, although not representing any particular physical networks, results in very accurate estimates of reinforcement costs in larger areas such as countries and regions.

Figure 40 shows the block diagram of the proposed methodology. The impact assessment of alternative network control strategies (“Business as Usual” and “Smart”) involving heat pumps, electric vehicles, and smart appliances on heat investment in network reinforcement and emissions will be assessed. The investment needed to reinforce the network will be determined considering a range of reinforcement strategies under different penetration levels of responsive demand technologies. The difference between the control strategies will give benefits of Smart Grid based solutions in terms of investment cost and emissions savings.

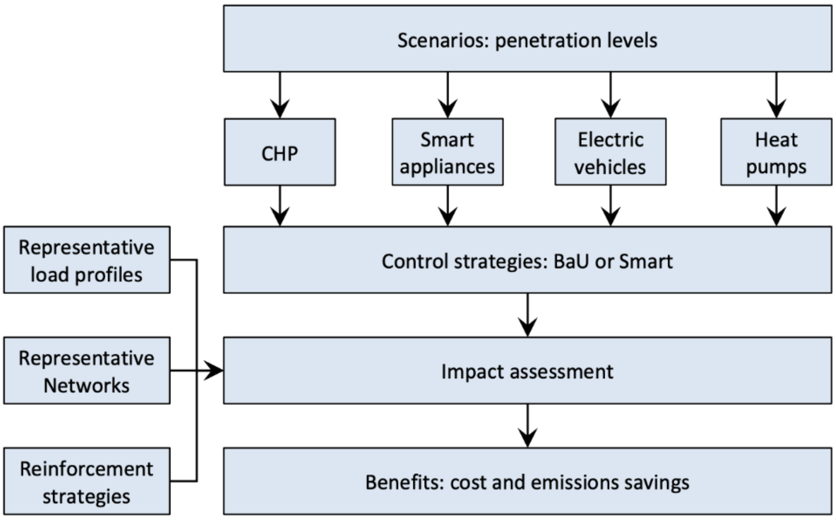


Figure 40. Methodology block diagram

In order to deal with overloads of feeders and transformers and inadequate network voltages network caused by the uptake of transport and heat demand, two network reinforcement strategies are investigated. One is based on reinforcing feeders with inadequate voltage profiles or feeder sections with thermal overloads, while maintaining the original structure of the network. This like-with-like reinforcement strategy would correspond to an upper bound on network reinforcement cost. The other network reinforcement strategy involves injecting additional distribution transformers that split the existing LV network hence reducing the length and loading of the feeders. Given that the total distribution network reinforcement cost is dominated by LV network reinforcement, this would correspond to a lower bound on network reinforcement costs.

A.3.1. Statistically representative networks

The applied distribution investment model tests whether thermal or voltage constraints are violated and proposes appropriate upgrades of assets based on a defined reinforcement strategy. The associated upgrade cost for a given scenario and control strategy (resulting in a given level of peak demand) is used to build reinforcement cost characteristics. The model can also include alternative network reinforcement and design strategies, quantifying the potential benefits of alternative mitigation measures such as demand response and other active network management techniques.

The developed modelling approach includes three distribution network models:

- Low Voltage (LV) network model;
- Medium Voltage (MV); and
- High Voltage (HV).

The LV network model is based on representative fractal networks with the parameters that represent the key characteristics of typical LV networks supplied from individual distribution transformers. The MV network model contains feeders with a voltage of approximately 6-20 kV starting from secondary busbars in the HV/MV substations and finishing with distribution substations. The HV network finally contains assets from the Grid Supply Point, i.e. the connection to transmission (220-400 kV) or sub-transmission grids (72-132 kV) down to HV/MV transformers in primary substations.

A.3.2. Fractal network models

The consumer distribution pattern varies greatly from one area to another. The Inner city area would have a very different consumer distribution pattern than the rural area. Furthermore, the consumers are not normally distributed uniformly along the feeder. The conventional geometric model, which assumes equal spacing between the consumers, is not adequate to represent the consumer distribution realistically. In order to capture the consumer position and hence the network length more realistically, the statistically similar network models based on fractal science are used.

The key element of the distribution network analysis is the Fractal Distribution Networks Model (Fractal Model). The Fractal Model can create representative LV, HV and EHV distribution networks that capture statistical properties of typical network topologies that range from high-load density city/town networks to low-density rural networks. The design parameters of the representative networks represent those of real distribution networks of similar topologies, e.g. the number and type of consumers and load density, ratings of feeders and transformers used, associated network lengths and costs, etc.

Due to the lack of detailed information and the large degree of diversity in distribution network planning and design, it is not feasible to perform a detailed assessment of the existing distribution networks in different countries or regions within a relatively short timeframe. Nevertheless, experience has shown that it is possible to represent real networks through a limited number of typical networks with statistically similar network configurations. This approach allows for a number of design policies to be tested on a network with the same statistical properties as the network of interest, with only a minor sacrifice in terms of the accuracy of reinforcement cost estimates. Moreover, any conclusions reached are applicable to other areas with similar characteristics.

For this purpose, we rely on a limited number of typical representative LV networks, such as those typical for urban, semi-urban, semi-rural, or rural areas. Our fractal LV network models have the capability to generate many statistically similar networks (in terms of key network parameters) that resemble different area types, thus allowing statistically significant conclusions to be drawn. These models can reproduce realistic network topologies and particularly network lengths, which represent one of the main drivers for the cost of network reinforcement.

The procedure of generating representative networks consists of the following steps: (i) creation of consumer layouts, (ii) generation of supply networks, and (iii) supply network design.

A.3.2.1. Consumer point generation

Consumers' position plays the most critical role in terms of network design, as together with the specific demand load patterns it affects the design and the length of the network. In this respect, previous research has shown that typical consumer positions characteristic for different areas, such as urban or rural, can be modelled through spatial distributions of fractional dimension. The number of consumer points in a given squared area and the area itself are inputs to the developed tool. Examples of the different consumer patterns/layouts that can be created by specifying the desired capacity dimension of a fractal (i.e. Fractal Dimension or FD) are shown in Figure 41 for different (typical) urban, rural and intermediate layouts. These consumer patterns are characterised by different FDs, ranging from 1.9 for urban areas to 1.4 for rural ones. If all consumers were located along a single line, the FD of this layout would be equal to one (minimum value), while if the consumers fill the space uniformly, the FD would be two (maximum value). Clearly, in an urban situation (a), the consumers are distributed almost evenly across the area, while in a rural situation (d), consumers are grouped into distinct clusters, with significant parts of the area that are empty.

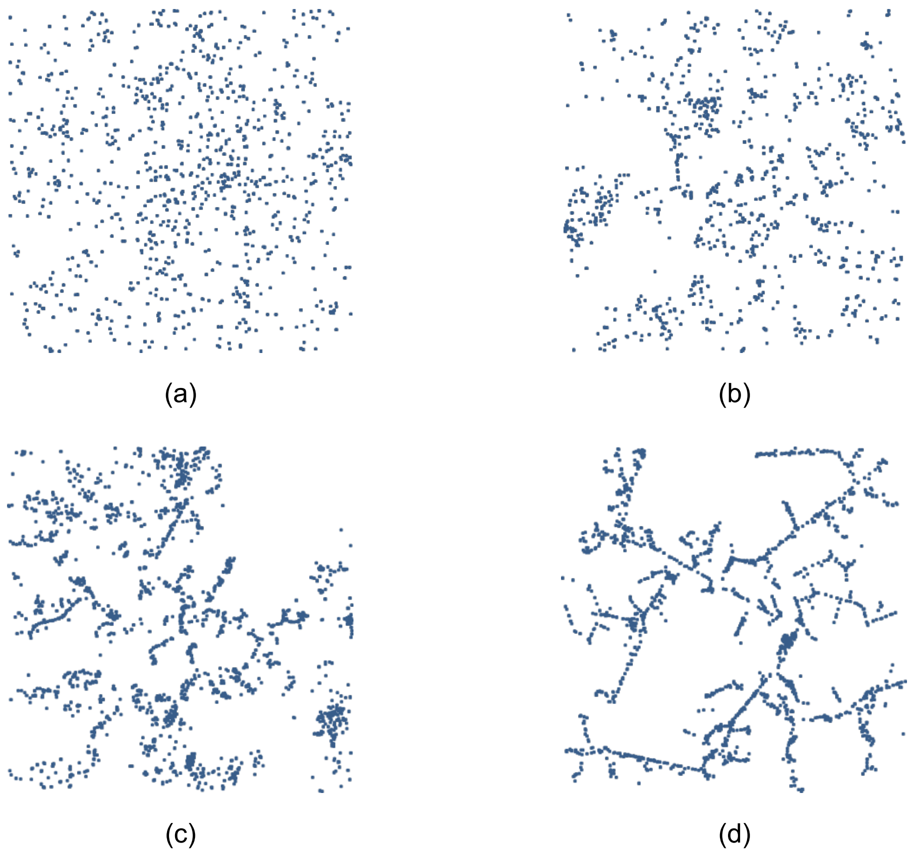


Figure 41: Examples of generated consumer layouts: (a) urban area (FD = 1.9); b) semi-urban area (FD = 1.75); c) semi-rural area (FD = 1.55); and d) rural area (FD = 1.4)

A.3.2.2. Network branch connections

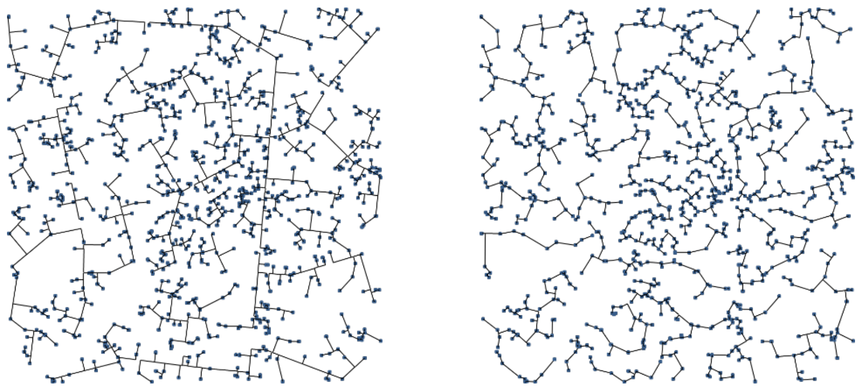
Once the consumer points are generated, they are connected with a number of connections that can be identified by using the concept of branching rate (BR), that is, the ratio of the number of (T-points) to the total number of consumers' nodes of the generated network. In practice, a lower BR means that the network tends to follow the consumer base as normally encountered in the LV network. On the other hand, a MV network path is influenced more by other factors such as the avoiding of lakes and parks, which in turn leads to a higher network BR. The developed tool combines two algorithms for connecting consumers to the network:

In the first algorithm, the next consumer to be dynamically connected to the network is chosen randomly. This algorithm leads to networks with higher BR.

In the second algorithm, the next consumer to be connected is always the nearest one to the previous one connected to the existing network. This approach produces a much lower BR than the previous algorithm.

Combining these two approaches, it is possible to control the branching rate (that is an input to the model) and to generate networks with BR in the range 0.2÷0.6. Typical branching rates for different areas have been estimated through empirical calculations as shown in Green et al. (1999). Examples of two networks with different BR for the same consumer set are shown in Figure 42 for BR = 0.6 (a) and BR = 0.2 (b), indicative of high and low branching rates, respectively. Despite the same consumer layout, the resulting network topologies are visibly different – the network layout on the left has frequent branch splitting, whereas the one on the right contains far fewer branching points.

The network generated is weakly meshed. However, further adjustments are carried out (see below) to transform the network into a number of radial ones.



(a)High branching rate (b) Low branching rate

Figure 42: Impact of branching rate in LV networks with 1500 consumers for an urban area with a) high branching rate (BR = 0.6) and b) low branching rate (BR = 0.2)

A.3.2.3. Statistical network creation algorithm

The final network topology information is the input data to the LV network design module. The complete network creation algorithm is shown in Figure 43.

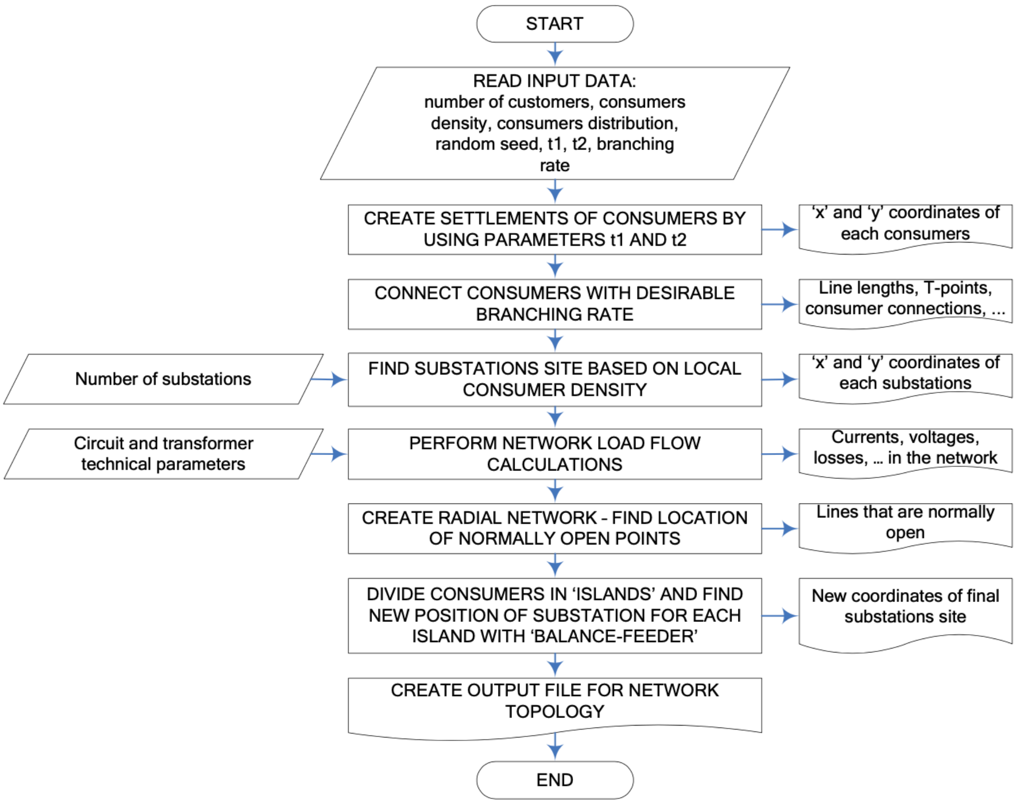


Figure 43: Representative network creation flow chart

The statistically similar networks can be generated by manipulating the input parameter seed. With different seed numbers, a completely new set of random numbers (representing consumer load points) can be generated. These random numbers, under the continued influence of fractal and economic interaction with other points, generate a new set of realistic consumer positions, which have similar network characteristics (consumer distribution, load density, substation density, etc.), as shown in Figure 44. The capability to generate many statistical similar network sets would allow a number of design policies to be tested on a network with the same specific characteristics. Nevertheless, these networks are statistically similar as they are characterised by the same FD, same number of customers and similar network length. Thus, the conclusion reached is applicable to all areas with similar characteristics and not only to a specific or particular area.

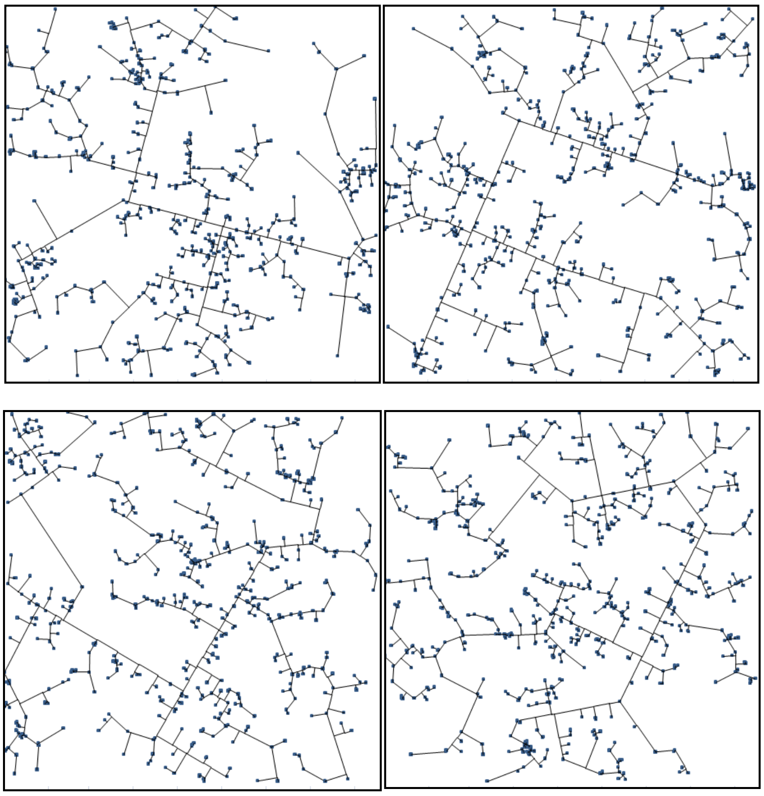


Figure 44: Example of four statistically similar LV networks

The obtained network lengths for statistically similar networks are shown in Figure 45, which suggests a very strong correlation between different consumer patterns (characterised by the appropriate FD) and the network length density. The error bars in the figure indicate the minimum and maximum network density values obtained in a large number of model runs.

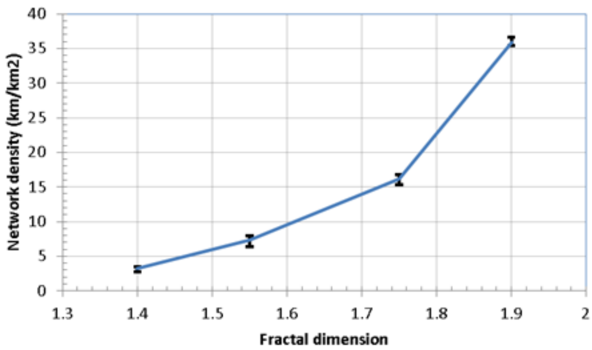


Figure 45: Relationship between length density of LV network and FD

The functional relationship between the network length density (total length of LV cables and lines per square kilometre) and the total LV network cost is illustrated in Figure 46, suggesting an almost linear relationship. In other words, network length density represents a key driver for the LV network cost, which also applies to the cost of reinforcing existing LV networks.

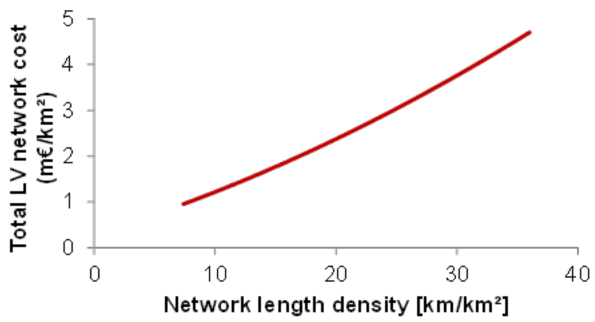
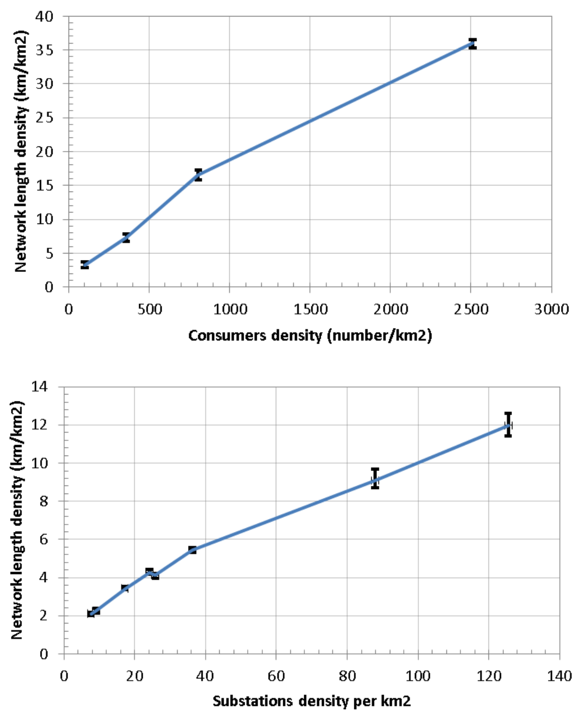


Figure 46: Total LV network cost as a function of length density

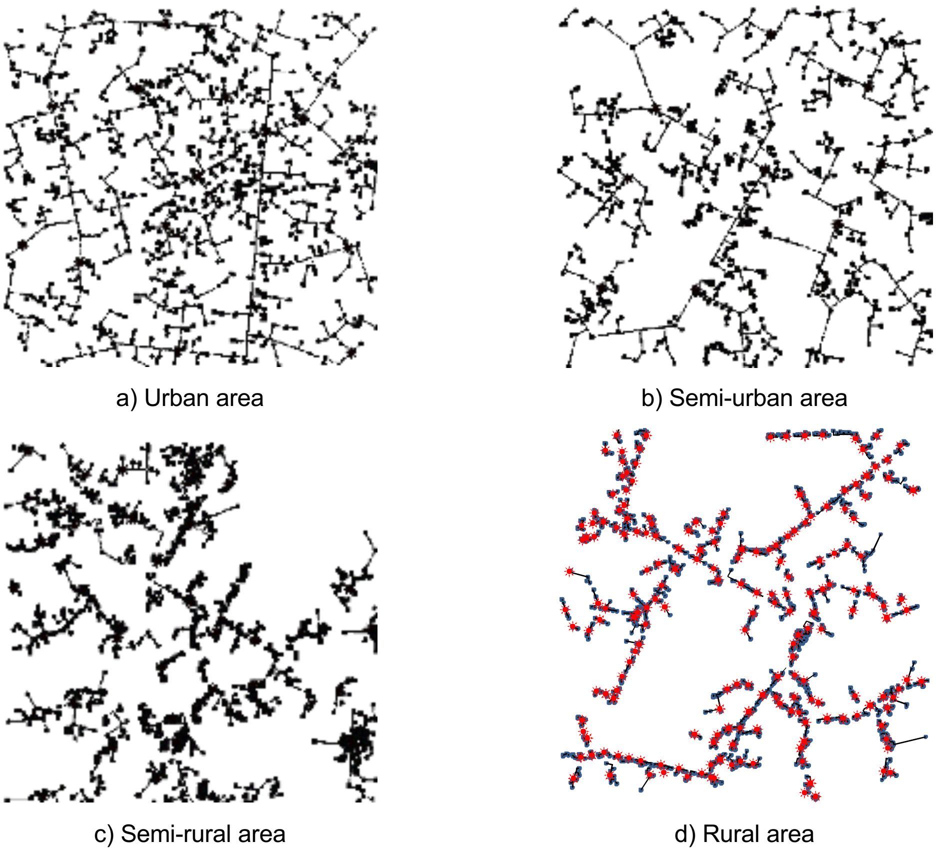
Given the observed correlation between the FD and consumer density (Figure 45), it is possible to establish the correlation between consumer density and network length density illustrated in Figure 47a (the error bars show the minimum and maximum values observed). Our analysis has further revealed that similar to the close correlation between the LV network length density and consumer density, there is also a strong link between the HV network length density and the distribution substation density, as illustrated in Figure 47b. This demonstrates that HV distribution network lengths can be reasonably well estimated from the number of distribution substations (the estimation is more accurate for rural areas where the number of substations is higher). These correlations suggest that if realistic networks with actual consumers i.e. substation density could be generated, they would be representative of actual networks in terms of network length density, and consequently in terms of total network cost.



(a) LV network *(b) HV network*

Figure 47: Correlation between network length density and: (a) consumer density in LV networks; (b) substation density in HV networks

Examples of different network topologies that can be created by specifying the desired layout parameters are shown in Figure 48 for urban, rural and mixed areas, characterised by different consumer densities, areas and branching rates. In this procedure, the parameters of representative networks are chosen to calibrate them against the actual distribution networks of the analysed system.



Note: Blue dots represent consumers, red stars represent distribution substations.

Figure 48. Different examples of consumer layouts generated using the fractal model

A.3.3 Representative HV Distribution Network Creation Methodology

The key network characteristics of HV networks are driven by LV networks. The HV network will supply the HV/LV transformers as well as some industrial customers. It is also important to note that the load density of LV networks within the HV network varies from region to region. Thus, to address this situation, the HV network was modelled by inputting different sets of LV networks, which can have different load and substation densities, into a grid-matrix. The location of HV/LV transformers and their annual loading profiles for each of the HV/LV transformers are recorded in the LV networks and become the input parameter of the HV distribution network. By doing so, the loading characteristics and the distances between the HV/LV transformers were kept on the HV distribution network. Figure 49 shows how different LV networks can be ‘entered’ into a HV distribution network.

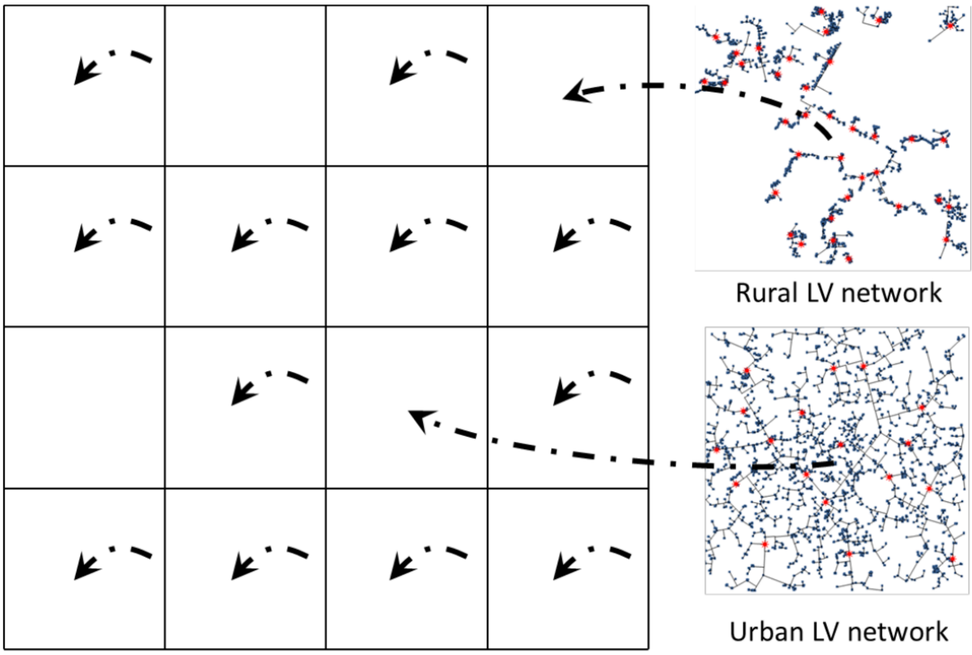


Figure 49: HV network grid-matrix

The HV customers are then connected with a controllable branching rate. Figure 50 shows a representative HV distribution network which supplies 65 representative LV networks. It is then connected with a 69% branching rate. The input LV networks have load density ranging from 5MVA/km2 to 25MVA/km2. The small 'dots' are HV/LV transformers and the 'red stars' being HV network substations.

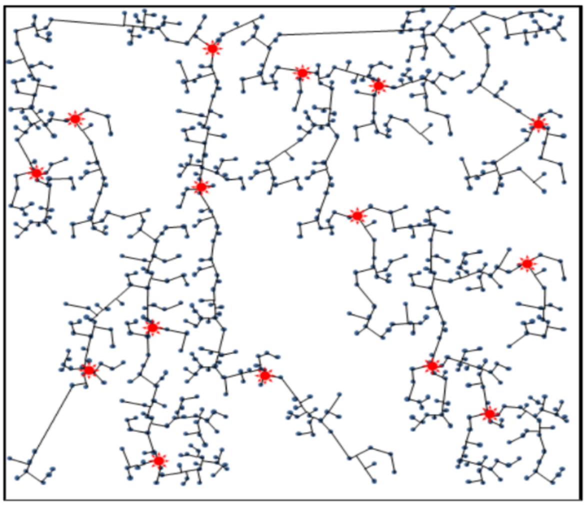


Figure 50: Representative HV distribution network (200,000 LV consumers, 300MVA-peak, 6MVA/km2, 0.3 sub/km2) supplying 65 representative LV networks

An important feature of this model is the capability to mix both LV rural networks and LV urban networks and supply them with OHL/Cable or Indoor/Outdoor substations according to LV network type.