PACE

Pathway to a Competitive European Fuel Cell micro-CHP Market

REPORT

D4.1: Literature review of projects exploring the potential for fuel cell micro CHP to act within a virtual power plant for the provision of flexibility services

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Contents

1   Introduction

As electricity generation transitions from large thermal power stations towards smaller and more distributed renewable generation, fundamental changes to the electricity system are required. Balancing supply and demand becomes a challenge as the contribution from intermittent energy sources (such as wind and solar) increases, since their generation cannot be modulated to match demand. [1]. Other solutions for grid balancing must therefore be found if renewables are to reach their full potential. Distribution network operators are also facing new challenges from the increase of distributed generation, and the electrification of heat and transport, which require greater network capacity and congestion management [2]. These challenges present new opportunities for grid balancing and distribution network management on the demand side, and the possibility of earning revenue through modulation of demand or microgeneration [3]. The ability to modulate demand or generation is referred to as "flexibility", which is defined by the Universal Smart Energy Framework (USEF) as "The ability to purposely deviate from a planned / normal generation or consumption pattern" [4].

Fuel cell micro Combined Heat and Power (mCHP) generates heat and electricity for the home from a fuel source, usually natural gas. Since the electricity generation is controllable, fuel cells have the potential to exploit opportunities for grid balancing [5]. The electricity generating capacity of mCHP units is typically 1 kW$_e$, meaning they must be aggregated in a virtual power plant (VPP) in order to unlock their value [5].

This literature review will investigate the use of mCHP in a virtual power plant by reviewing projects where this has been demonstrated, along with wider literature on VPPs and mCHP individually. The concept of a VPP, its functions and potential revenue streams will be introduced, along with the technologies that enable VPPs to operate and a brief overview of the types of distributed energy resource that have been aggregated in a VPP to date. Chapter 2 will outline projects implementing VPPs which include mCHPs and list some examples of companies operating VPPs in the domestic sector. Chapter 3 will go on to review some of these projects in more detail, outlining the roles of market parties and the commercial partnerships involved. The suitability of using mCHP for providing various services will be assessed in Chapter 4. Chapter 5 will draw together some of the recommendations from demonstration projects and how these address any barriers to market. Conclusions are drawn in Chapter 6.

1.1   What is a Virtual Power Plant (VPP)?

A Virtual Power Plant is generally defined as a portfolio of Distributed Energy Resources (DERs) (generation, storage or controllable demand) collectively monitored and controlled by a central entity (an aggregator) for some objective [6] [7] [4]. Some possible objectives of a VPP are described in Section 1.2, and relate to the use of flexibility by various parties. Some of the key components of a VPP are outlined in the text and shown in Figure 1.

1.1.1 Aggregated Portfolio of Distributed Energy Resources (DERs)

Since the individual output of a DER is typically small, grouping of these resources into larger clusters is required to provide useful services and participate in markets [5]. An aggregated size of at least 1 MW is required to provide most balancing services in Europe, with some services requiring larger sizes (e.g. Germany requires 5 MW minimum size for Frequency Restoration Reserve (FRR)) [8]. A second advantage of the aggregated portfolio is that the available flexibility is more predictable and more constant than that of an individual DER. [6] Historically, the high value grid services such as Frequency Response reward provision based on the minimum guaranteed capacity that can be provided over a unit of time. Individual assets, whether mCHP units or electric car chargers, cannot be relied upon and so their reliable capacity goes to zero. However, across large enough a portfolio of assets, statistics can be used to provide a guaranteed minimum capacity, albeit that declared capacity will need to be discounted ("derated") from the theoretical capacity of all units added together. Modelling has shown that the ratio of appliances switched on to the total number is constant when 5000 or more households are aggregated [9]. This means that availability and profile predictability increase as households are added, but beyond 5000 households there are almost no additional benefits of increasing the aggregated size other than increasing the total flexible capacity. Aggregated DERs can also provide finer control of power output than individual units – for example, a gradual decrease of power can be achieved with hundreds of DERs by consecutively turning off each DER unit, even if the power consumption of an individual unit cannot be modulated [9]. The ability to control the DER may be built in by the manufacturer or installed separately by the aggregator.

1.1.2 Communication and Control

Aggregating many DERs requires the ability to reliably communicate with resources of various types in distributed locations. The communication method must be scalable and take account of data security requirements [1]. One-way communication is easily implemented e.g. by using a radio teleswitch (ripple control), and is a very well established technology often used to activate night-time meters for storage heating and simple time-of-use tariffs [10]. While radio control of fuel cells has been demonstrated [10], implementation of a VPP requires two-way communication, since it is necessary to know the state of the DERs to predict the available flexibility [6]. Two-way communication is usually achieved via the internet [10].

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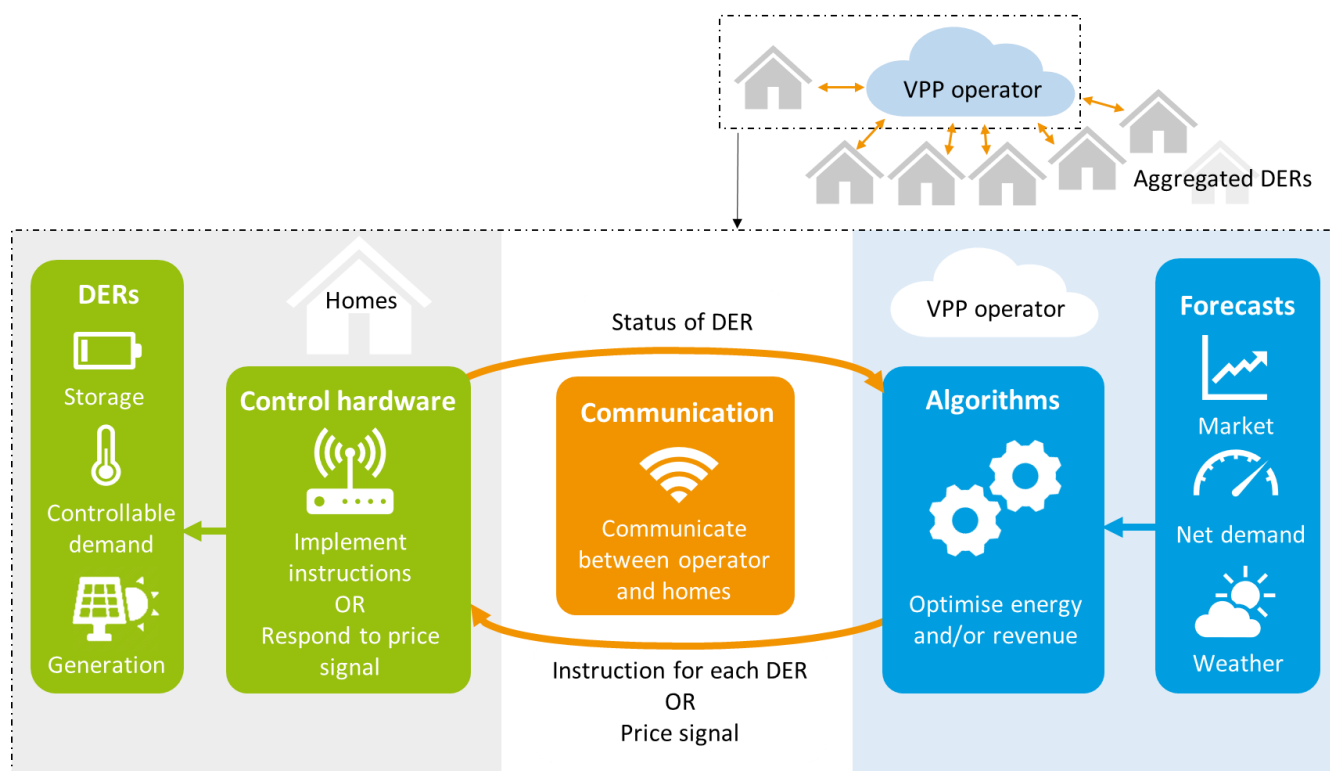
Figure 1 Components of a VPP © Element Energy

Control of the DERs can be direct or indirect [4] [6]. For direct control, the VPP operator sends control signals to each household. Decisions on when to deploy flexibility are made centrally, and a set of instructions are dispatched to household devices. For indirect control, households respond automatically to price signals e.g. via a dynamic tariff [6]. This tariff is calculated with knowledge of the flexible DERs and the required response, and can therefore be considered as a VPP (see PowerMatcher for an example of this type of control [11]). This is different to a simpler Home Energy Management System (HEMS), which may control appliances in response to an energy supplier time-of-use-tariff in order to save money for the consumer but does not need to aggregate multiple homes (referred to as implicit flexibility [3]). Decisions on how to respond to the price signal must be made locally, which requires more complex (and therefore more expensive) hardware to be deployed in each household than if direct instructions are sent [6].

Another situation in which local decision making is required is when the power output is controlled in response to the grid frequency to provide grid balancing services. To provide a fast enough response, the grid frequency must be measured and responded to locally. Hybrid approaches may also be deployed. For example, Glen Dimplex has worked with VPP company Vcharge (now part of Kaluza) to develop grid responsive electric resistance heaters [12]. A cloud-based platform calculates optimal positioning of each asset under control (e.g. depending on predictions of temperature or energy prices, when to begin consuming electricity). In addition,

there is a low power "edge" computing device, either embedded in the heater or adjacent to it, which has automated response algorithms specifically for rapid-response such as grid frequency response [12].

1.1.3 Algorithms and forecasts

The generation/demand profile of DERs must be scheduled in a way that meets the objective of the VPP. PowerMatcher is an open source algorithm commonly used in VPP demonstration projects which controls aggregated DERs such that the net demand is as close as possible to a set level [11]. If the objective is to trade flexibility, forecasting the available flexibility of the DERs is a key function which prevents non-delivery of sold flexibility [13]. Algorithms must take into account the status of the DER, any owner-specified limitations (e.g. acceptable temperature range of the house), and predictions for the state of the DERs in the future which may include weather forecasts and learnings from historic data [6]. This is often achieved using machine learning, which enables predictions and control strategies to improve as more data is gathered [14].

1.2 Functions of a VPP

The aggregated flexibility of a VPP can be utilised for a range of objectives, some of which will be outlined in this section and are summarised in Figure 2. Multiple objectives can be achieved with the same VPP by trading flexibility with parties who require it through bilateral agreements or flexibility markets [13] [15].

Energy services
- Optimise day ahead and intraday trading
- Optimise position in imbalance market
- Maximise auto-consumption

Capacity services
- Provide adequate capacity to ensure security of supply
  ▸ Capacity market
  ▸ Strategic reserve

Flexible Resources

Balancing services
- Provide reserves to balance the system
  ▸ Frequency Control Reserve
  ▸ Frequency Restoration Reserve
  ▸ Replacement Reserve

Network services
- Balance local supply and demand to avoid network congestion
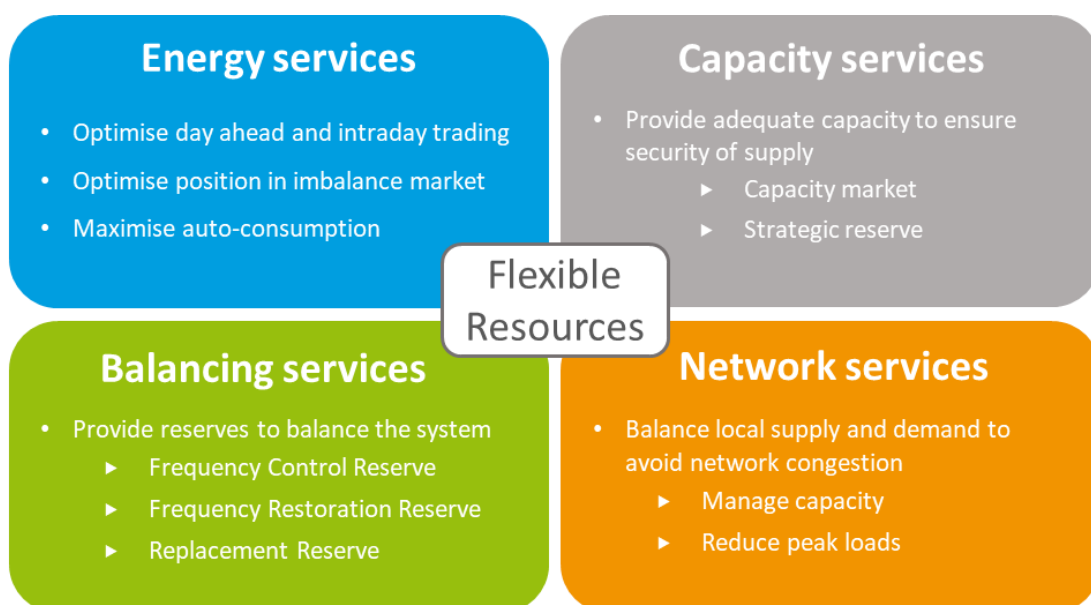 ▸ Manage capacity
  ▸ Reduce peak loads

Figure 2 Summary of uses for flexibility © Element Energy

Within the categories of services identified in Figure 2 are many more individual services that may be used, either for routine system operation, or to improve system resilience and restore services after an outage. A full description of all services procured by all TSOs across Europe is outside the scope of this project. We note that some TSOs are exploring innovative ways to procure services; for example through its Distributed ReStart project [16], NG-ESO in the UK is exploring how DERs (as opposed to very large, transmission connected assets) could provide "black start" services to help re-energise a grid after an outage. While inverter-controlled loads could provide Reactive Power, and could be supplied with grid forming inverters, the procurement of such services from the lowest voltage levels on the network is not a priority at the current time.

1.2.1 Energy services

Optimise day ahead and intraday energy market trading

Wholesale energy trading in Europe is well established with various markets for sale of energy on timescales from years ahead up to the day of use. The day ahead and intraday markets are most relevant to the use of flexibility, and prices reflect the abundance of available generators relative to the demand. [3] Extreme prices in these markets are becoming more common as shown in Figure 3. For example, in Germany where there are many wind turbines, strong winds cause surplus generation which can result in negative prices, whereas when there is no generation from wind and demand is high, prices can be over 100 EUR/MWh. [13] The ability to reduce demand at times when wholesale market prices are high and increase it at times when prices are low is therefore a valuable service. Hedging can also be used to mitigate price risks associated with volatile supply and demand, and flexibility can be used as an instrument to provide this. [3]
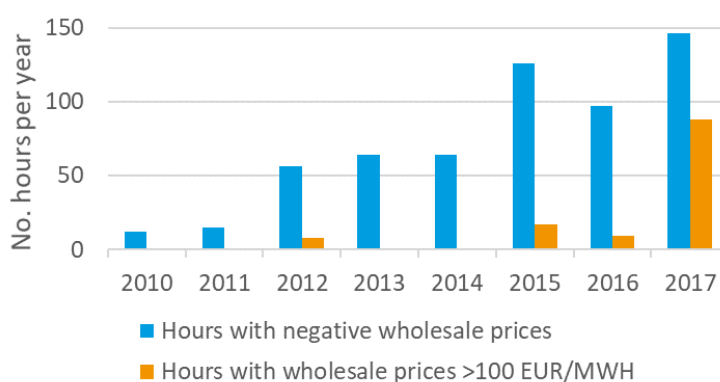

Figure 3 Extreme price events in the German electricity wholesale market. Data from [17]

Optimise position in imbalance market

Balance Responsible Parties (BRPs) are parties such as energy suppliers who are responsible for balancing supply and demand in their energy trading portfolio. Energy can be traded in the imbalance market after the wholesale market has closed to make final adjustments close to real time. A BRP can deploy flexibility to balance their own supply and demand, or to submit offers to turn generation up or down in the imbalance market which other BRPs can purchase.

Imbalance markets are in principle highly valuable; in contrast to wholesale markets where there may be a single opportunity each day to arbitrage between the maximum and minimum energy price, in balancing there will be surpluses and deficits of energy which need to be resolved on a much more frequent basis. A flexibility asset could be called to modulate its output much more frequently than with daily arbitrage. However, a challenge for this market is the difficulty in predicting the direction of the imbalance, with many in the industry of the view that it is essentially unpredictable, in which case it would be better to replace a market with a flat tariff charge levied per unit of imbalance energy used. A second challenge that is emerging in deregulated markets, is that assets designed to respond to frequency response opportunities, also have the capability to provide services to imbalance markets, and prices in these markets have come down as a result.

In the past, households have been assigned a standard profile for the purposes of balancing requirements, since there was no way of knowing when energy was used. This may change with the introduction of domestic smart meters, increasing the value for the energy supplier (or related BRP) of influencing a household's energy profile. [18]

Maximise auto-consumption within a community

Microgeneration enables consumers to generate their own electricity, but the generation profile will not exactly match the demand profile and is therefore unable to completely cover the consumer's energy needs. In communities where self-sufficiency is valued, a VPP can be used to balance local microgeneration and demand. [19] This may be useful on an island, [20] or to create a "power island" which can be isolated from the grid in the event of a power cut. This mode of operation also decreases transmission losses and prevents network upgrades. [5]

A VPP can also be used in this way when the members of the community are not in the same location, provided there is a grid connection. This allows energy suppliers to provide "peer-to-peer" energy which is entirely sourced from microgeneration and can save money for consumers. [21] [19]

Table 1 Summary of European balancing services

Service	Activation time	Sustain time	Implementation	European market project
Frequency Containment Reserve (FCR)	~30 sec	~15 mins	Dispatched automatically using droop-based freq. controllers	FCR Cooperation
Automatic Frequency Restoration Reserve (aFRR)	30 sec – 15 min (varies by country)	15 mins to hours (varies by country)	Dispatched automatically by control signal from TSO	PICASSO
Manual Frequency Restoration Reserve (mFRR)	30 sec – 15 min (varies by country)	15 mins to hours (varies by country)	Dispatched manually when TSO sends a message/phone call	MARI
Replacement Reserves (RR)	>15 mins	Hours	Dispatched manually	TERRE

1.2.2 Balancing services

The Transmission Systems Operator (TSO) is responsible for balancing the electricity system in real time after commercial markets close. The TSO fulfils this responsibility by procuring flexibility through mandatory requirements, agreements or markets. The types of services, their regulation and requirements (e.g. time taken to respond) varies between countries in Europe, and particularly between synchronous areas within Europe. [22] The European Network of Transmission System Operators for Electricity (ENTSO-E) has a generic categorisation which approximately maps onto country specific services[1]. The categories are detailed in Table 1. Europe-wide markets for these services are at various stages of implementation and the projects are also listed in Table 1. [23] On a national level, some system operators (e.g. National Grid in the UK) are working towards lowering barriers to market entry for aggregated DERs, as current testing requirements often make participation in these markets unviable for small aggregated DERs. [24] As mentioned above, an aggregated size of at least 1 MW is required to provide most balancing services in Europe, with some services requiring larger sizes (e.g. Germany requires 5 MW minimum size for Frequency Restoration Reserve (FRR)). [8] A 1 MW

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[1] A good summary of how services in EU member states map to these categories can be found in ref. [22], Table 3-1.

service aggregated from residential flexibility sources requires thousands of individual assets (accounting for derating of the portfolio to guarantee service provision). While assets can be added together to create a single unit, the testing regime, commercial frameworks and auctions are designed to deal with very few assets, and the 1000s that may be required from residential sources are essentially uneconomic due to these limits, though some effort is being made to rectify this. In Great Britain, National Grid is investing heavily in innovation aimed at unlocking the potential of residential-asset based response (including the Residential Response project). [25]

The Australian Energy Market Operator (AEMO) launched a VPP demonstration program in July 2019 to test VPP provision of ancillary services. [26] Tesla have been providing services within this program since September, [27] through a VPP trial in South Australia which so far has around 900 housing trust homes participating, each with solar panels and a 5 kW Tesla Powerwall 2 battery (maximum capacity of 4.5 MW). [28] In Phase I they have demonstrated the technical capability to provide Frequency Control Ancillary Services (FCAS) requiring proportional response to grid frequency outside a dead band of ±0.15Hz, and regulation frequency services, showing response to set points at 4s time steps. [29] On 9th October 2019, the Kogan Creek coal power station in Queensland tripped, reducing supply by 748 MW and the Tesla VPP responded to the frequency drop along with other ancillary service providers to successfully return the system to normal, showing that these services can be provided by a battery VPP in a real event. [27]
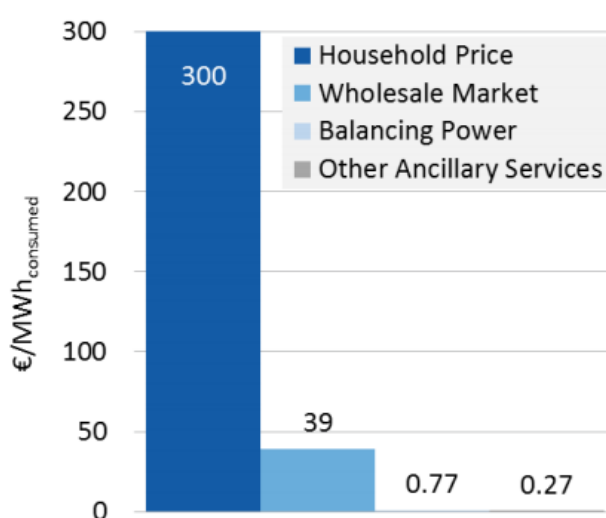

Figure 4 Annual revenues for different markets scaled by the total annual power consumed (German market data, 2014). Balancing power is a small market in comparison to wholesale electricity and retail markets. Reproduced from [30].

FCR is the most challenging to provide and therefore the most valuable service, however the market is very small. Markets for slower balancing services (aFRR and mFRR) are larger (see Figure 6) but are still small in comparison with other opportunities. Figure 4 shows that due to the small market size, balancing power and other ancillary services are cheap compared to the overall costs of the power system and were equivalent to 0.25% of the electricity retail price in Germany in 2014. [30] The wholesale market may therefore provide a more reliable long-term opportunity.

1.2.3   Network services

Increasing microgeneration and the electrification of heat and transport could hugely increase the required capacity of the distribution network (and in some cases the transmission network) if unmanaged. Flexibility can be used as a short-term solution while upgrades are planned and implemented or to prevent the need for an upgrade entirely. [2] It can be used to manage capacity so that new connections can be facilitated and to avoid congestion by reducing peak-time demand. [3] In order to provide this service, a VPP must have access to enough DERs in a congested area. A VPP for which location is important has sometimes been referred to as a "Technical VPP". [6]

Methods for network operators to procure these services are not well established and may be prohibited in some countries. Research is underway to design markets for local flexibility with projects including NODES [2] in Norway and an EPEX spot project in Germany [31]. In the UK, Distribution Network Operators Western Power Distribution and UK Power Networks are trialling flexibility marketplaces, with auctions for flexibility where prices reflect congestion and so are time and location dependent, which will be discussed further in Section 2.2.1.

A second challenge relates to the coordination of responses between distribution level and transmission level markets. These may not always be aligned, for example high renewable output might require the TSO or a wholesale market to incentivise additional load on the system, but if this comes at peak demand times then the DSO may request demands to modulate down. An example of this TSO-DSO coordination is the Energy Network Association's Open Networks Project in the UK. [32]

1.2.4   Capacity services

Generation capacity must be sourced to meet long term demand predictions to ensure security of supply in the future. In some countries, a capacity market or capacity payments are used to ensure this need is met. The responsibility for procuring capacity may lie with the Transmission System Operator (TSO) or with energy suppliers. [3] Alternatively security of supply can be ensured with strategic reserves, where capacity is kept out of the wholesale market until a trigger is activated. [3] Under the EU clean energy package, capacity renumeration mechanisms are to be a last resort with preference for reserves. [33] Flexibility can be used to reduce a supplier's capacity obligations or to enter markets for capacity or reserves where rules allow. [3] Capacity services could provide a source of revenue for VPPs if market rules allow. However, no evidence of

VPPs providing these services has been found in this literature review, so this function will not be discussed further.

1.2.5   Providing multiple services

VPPs can often stack multiple services to maximise revenue. Services can be provided at different times, by different subsections of the aggregated portfolio, or by double serving. [15] Double serving could occur by providing a service and a corresponding energy transaction to different parties simultaneously, though stacking the provision of balancing services by double serving is usually prohibited in European countries. [15] This may change in the future, for example in the UK, National Grid are working on allowing more services to be stacked. [24]

1.3   Revenue streams associated with these functions in European Markets

Revenues available from mCHP fuel cells have been simulated for a variety of cases. This section summarises the calculated value of the flexibility when providing a range of services and discusses the value of these services more generally. Although the predicted values for the services above are calculated from a range of different scenarios and services provided, all fall approximately in the range of 20 to 90 EUR per flexible kW_e per year. The actual value of flexibility will largely depend on the state of the energy system and available markets in the local area. In Figure 5, markets are scored according to how successfully demand side flexibility is monetised in all value streams. [34]

High   Medium   Low
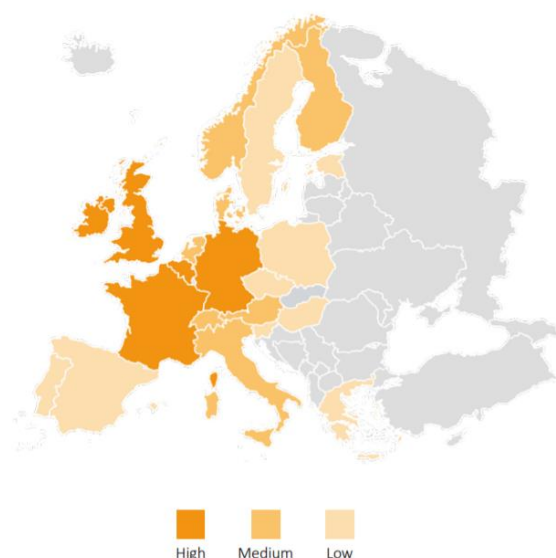
Figure 5 Monetisation of demand side flexibility in value streams. Reproduced from [34].

For comparison, the average retail electricity price in the EU is around 0.21 EUR/kWh [35], meaning self-consumption of electricity could reduce electricity bills by up to 1840 EUR per kW_e per year (if the fuel cell is run constantly at full capacity and all electricity is consumed). Maximising self-consumption in the home is a function of a Home Energy Management System (HEMS) not a VPP, since aggregation is not required. However, the communication and control technology required for a VPP is capable of performing this function in addition to VPP functions, which will affect the size and direction of flexibility available to the VPP (when it is best used in the VPP and when it is best used within the home). The design of the heating system will also influence the flexible capacity available.

The market size of the possible revenue streams open to flexibility is an important consideration. Small high-value markets will experience more competition, whereas larger markets may represent a more secure long-term opportunity. The value and market size of various services in three European countries previously analysed by Element Energy (Spain, Germany and Great Britain) are shown in Figure 6.

Figure 6 Volume and value of markets in Spain, Germany and Great Britain. From Element Energy analysis of publicly available market data, 2018. © Element Energy

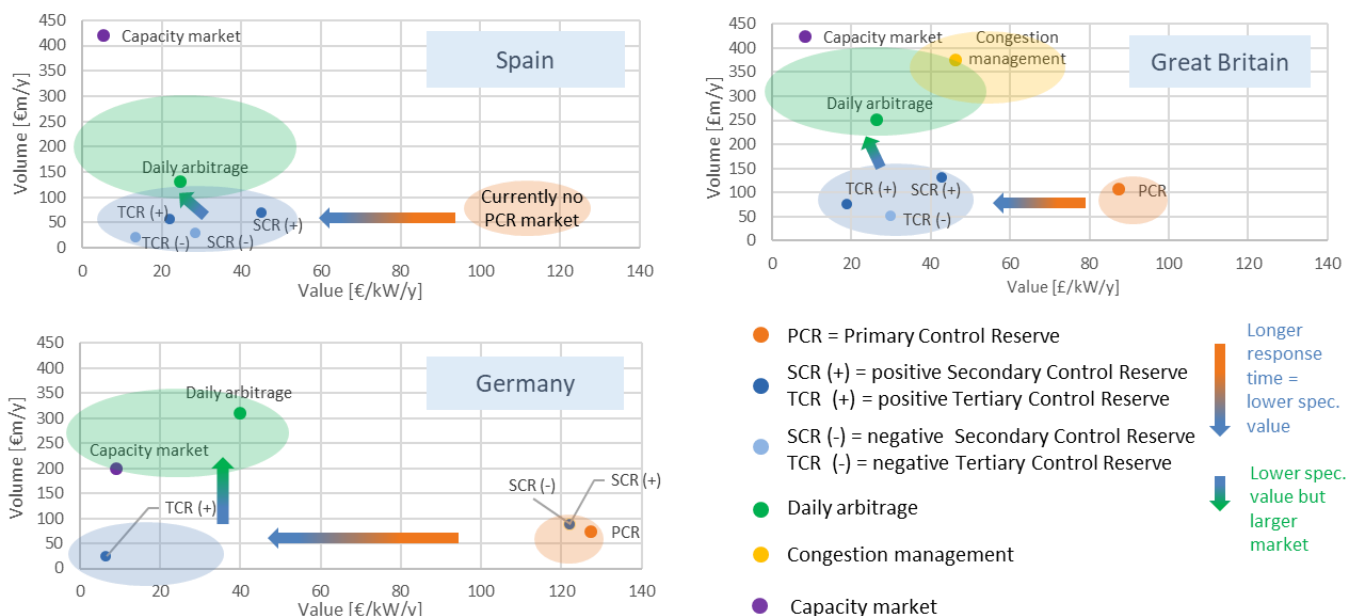### 1.3.1 Energy services

A simulation of a VPP containing 200,000 domestic mCHP fuel cells with an electrical output of 1 kW$_e$ and a hot water store of 100 litres calculated revenues of around 70 EUR per household per year. This was achieved by providing balancing for wind generation on a 15 minute timescale and response to fluctuating prices based on the Dutch day-ahead energy market (APX). [6] This revenue is equivalent to 5% of the cost of running a conventional boiler, which provides a small additional benefit to the 30% energy bill savings achieved by switching from a conventional boiler to a mCHP. The size of the thermal store was found to be important - increasing the size of the hot water tank to 500 litres increased the revenues by a factor of three. The revenues for providing flexibility services were much higher than for Stirling mCHP units which only achieved 5 EUR per household per year due to the higher heat-to-power ratio. [6] These revenues are country specific and depend on the level of wind generation and degree of energy market price fluctuation. A project investigating the value of using flexibility to balance wind power in the context of providing demand response using domestic smart appliances (not mCHP) concluded that where 30% of total installed generation capacity is wind power, the value of flexibility can range between 20 and 90 EUR per year depending on whether generation in the region is highly flexible or inflexible. [36]

Revenues available from trading in the imbalance market have been estimated at 5% of fuel costs based on data from a Belgian case study of aggregated mCHP devices. [37]

As the percentage of electricity from variable renewable generators increases, price fluctuations may also increase unless solutions to mitigate this keep pace, such as energy storage, use of flexible generation or demand resources, and interconnectors. Dispatch modelling for the UK electricity market by Element Energy shows high volatility in 2030 due to an increasing proportion of variable renewable generation with prices above £80/MWh for 60% of the time and less than £10/MWh for the remaining 40% as shown in Figure 7. Similar results are included in the ENTSO-E Ten-Year Network Development Plan (TYNDP). [38] Models for other European countries in 2050 show prices over 100 EUR/MWh for as much as a third of the time, with the most volatile markets being those with over 60% share of generation capacity from wind. [39] These price curves would mean that electricity generation from mCHP is most valuable when variable renewables are not generating and wholesale prices are high, whereas at times when renewables are generating, electricity prices may be lower than the marginal cost of mCHP generation.
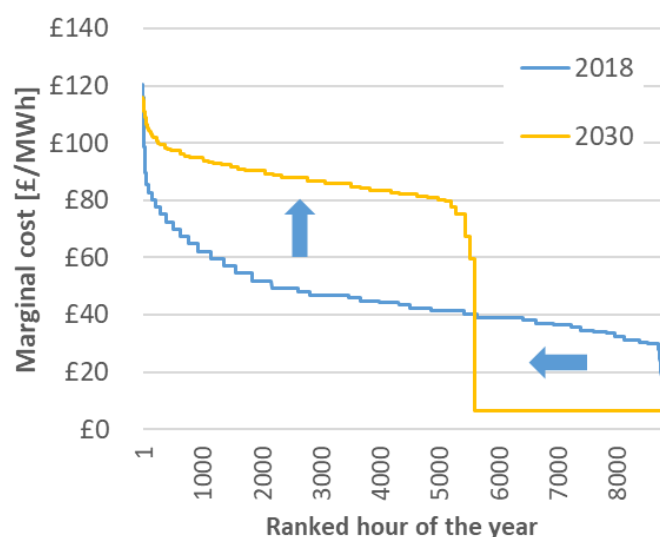
Source: EE Dispatch Model
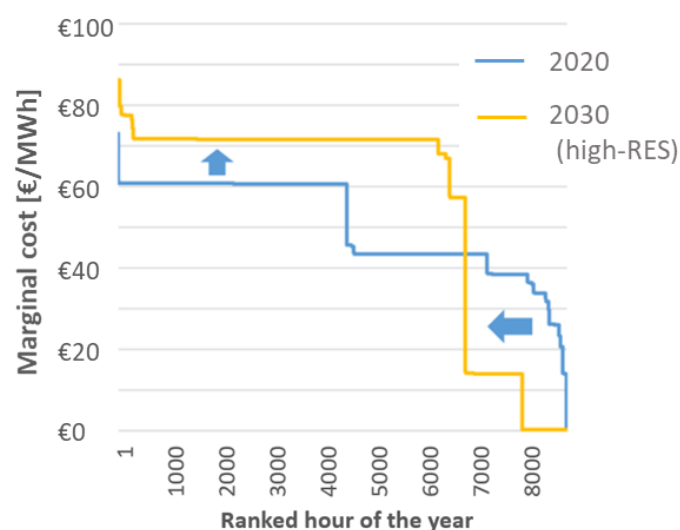
Source: ENTSO-E TYNDP

Figure 7 Left: Short run marginal cost of electricity generation as modelled by Element Energy's electricity dispatch model of GB in 2018 and 2030 © Element Energy. Right: Marginal cost of electricity modelled for the ENTSO-E Ten-Year Network Development Plan (TYNDP) [38].

1.3.2 Balancing services

A 2009 simulation based on field measurements of larger CHP units found that providing balancing services to the TSO created value of 55 EUR per flexible kW in a UK market and 20 EUR in a Spanish market. These values were predicted to increase to 75 and 55 EUR respectively by 2020. [7] No estimates for domestic mCHP were found.

In general, the faster the activation time, the higher the value of the service, though the value varies between countries. The market volume of the faster acting services is small and may therefore be subject to high competition. With the introduction of batteries, the Firm Frequency Response (FFR) market in the UK[2] and the Primary Control Reserve (PCR) in Germany (both corresponding to FCR) have seen a significant reduction in value. In Germany 2018, 230 MW of the 600 MW PCR capacity was provided by batteries following their introduction in 2014. Over this time period, prices of this service have fallen by 40% [40] to around 8 EUR/MW/hour. The Vehicle to Grid Britain (V2GB) project, which determined the value of system savings from smart and V2G EV charging in UK markets, found that providing frequency response is currently a high value revenue stream. [41] However, it is much lower now than recent estimates due to competition from batteries

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[2] The UK Firm Frequency Response has several categories approximately equivalent to FCR and aFRR

and is expected to continue to decrease in the future to the point where it no longer dominates the revenue stack for V2G assets (2030). Prices of FFR in GB have fallen from £15/MWh to £5/MWh over a three-year period, as shown in Figure 8. Prices may be high in highly regulated markets, but deregulation that allows mCHP to participate will also open the market to batteries, and similar price drops are expected to result.

In future, system inertia will reduce with an increasing proportion of renewables, which increases the need for FCR. However the quantity of FCR needed to stabilise a grid is smaller when provided with batteries – in the UK, 100 MW of batteries can replace 700 MW of thermal generator flexibility, since batteries respond much faster, which further reduces the opportunity in these markets. [42] Increasing the number of countries within a synchronous area over which these services can be shared also reduces the total quantity needed, since the chance of simultaneous frequency loss events is small. The largest markets are likely to be found in small synchronous areas with high variable renewable penetration. The revenue available also varies significantly with asset availability. For high-value system critical services such as frequency response, the asset needs to be available to modulate its demand/generation for a majority of the time. [41] This has implications for heating-related assets, with daily and seasonal modulation of output. Fuel cells running at a constant output to provide hot water with an adequately sized thermal store can be available all year and are likely to offer the best opportunity for providing balancing services. Despite falling prices, the largest revenues for balancing services are still likely to come from FCR provision. However, since the success of batteries has saturated these markets, and as battery technology continues down an aggressive price curve, there is a lower opportunity for fuel cells and other technologies to gain market share. Analysis of revenues from frequency-controlled grid services is within the scope of PACE Task 4.2.
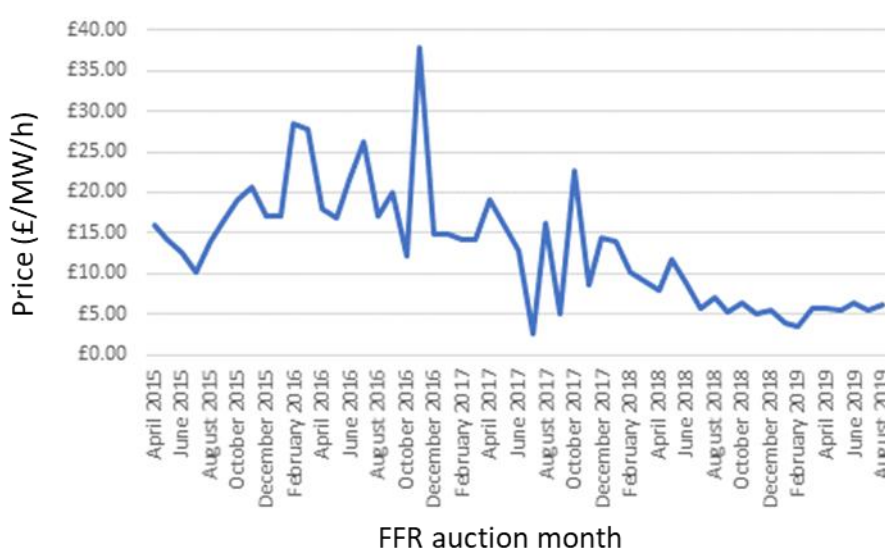

Figure 8 Auction data for FFR provision in GB (FCR equivalent) from Element Energy analysis.

1.3.3   Network services

Revenues for providing network congestion are very dependent on the state of the local grid, and general conclusions are hard to draw. [7] These services are particularly valuable in places where transmission line capacity requires energy to be "redispatched", for example in Germany where wind generation in the north must be curtailed whilst gas generation in the south is increased. Redispatch costs are currently around 1 billion EUR in Germany, meaning there is a large opportunity here. [43]

The Vehicle to Grid Britain project found that congestion avoidance on distribution networks could provide high value revenues in areas where there is a market mechanism to reward flexibility that avoids congestion. As the value of response services goes down, in the right location, congestion avoidance could be an important revenue stream. The study concluded a typical value of £50/kW/year for congestion avoidance, however there are caveats. Revenues from congestion avoidance are location specific, and revenue can range from a very high value to zero. Also, the highest value areas experiencing the most acute congestion are the most likely to be reinforced in the traditional way, following which the value of flexibility could drop to zero. [41]

1.3.4   Multiple services

A VPP providing multiple services could earn more revenue than a single service. Vehicle to Grid Britain found that stacking of revenues is required for profitability. [41] In PowerMatching City, the total benefits of flexibility in the Dutch consumer market have been estimated at between 1 and 3.5 billion EUR when used to both defer grid investment and optimise trading in energy markets. [18] These estimates are based on field measurements undertaken in the PowerMatching City project. [18] Based on measured flexibility, a Stirling micro CHP unit running in heat-led mode was calculated to have a flexibility value of 21 EUR per year (compared to 28 EUR for a heat pump and 58 EUR for an electric car) in a Dutch market. [18] As mentioned above, rules ensuring efficient whole system operation are still under development (Open Networks Project in the UK [32]) and this may limit stacking of revenues in order to avoid conflicts.

When providing multiple services, choosing the best strategy of which services to provide and when can help to maximise profit and spread risk. This could be considered when estimating likely revenues from a VPP.

1.3.5   Competition from other technologies

To secure a place in flexibility markets, VPPs using fuel cell mCHP must be economically competitive with both traditional solutions and other DERs. [5] Traditional solutions for balancing include spinning reserve capacity in thermal power stations to provide a fast response, and pumped hydro storage to provide a larger sustained response. [5]

Larger DERs such as non-domestic CHP plants or demand response from industrial energy users are likely to be able to provide the same services at lower cost owing to the larger scale. Batteries are also starting to be

deployed at utility scale for energy arbitrage and balancing services, which is affecting the value of these services as discussed in Section 1.3.2. Although demand for flexibility is likely to increase as decarbonisation takes place, the availability of flexible energy resources is also likely to increase. For example, low carbon transport will be either electric or hydrogen-based, meaning there will be the opportunity to provide flexibility services using vehicle-to-grid technology or electrolysers for hydrogen production. Analysis of future revenues available for mCHP fuel cells must therefore consider the effects of supply side competition.

1.4 Enabling technologies

Several technologies have come together which support the introduction of VPPs to the home. These include the presence of DERs in the home, the ability to communicate and control appliances in the home via the internet, and the ability to measure when a home is using electricity with smart meters.

1.4.1 Distributed Energy Resources (DERs) in the home

Historically households have been consumers of electricity but in recent years distributed energy resources (DERs) have started to make an appearance in the home. Government incentives and falling costs have led to a rise in home energy generation, particularly from roof mounted photovoltaic panels. The cost of batteries for household energy storage are also decreasing. [44] Energy consuming appliances with the potential to participate in demand side response are also increasing in the home. For example, the market share of electric vehicles (battery and plug in hybrid) increased to 2.5% in Europe in 2018 and as high as 8% in Sweden. [45] Electric vehicles are typically charged using 7 kW chargers for many hours at a time, which gives a large opportunity for providing flexibility, unprecedented amongst residential electricity assets.

Together, these resources put much potential value into the hands of consumers, and has led to the term "prosumers", a combination of the word "producer" and "consumer", to reflect the new ability of households to produce as well as consume electricity. [13]

1.4.2 Increasing connectivity and the "Internet of things"

High speed internet connections and mobile internet are now widespread across Europe, and having an internet connection to the home is the norm. [46] This existing infrastructure paves the way for VPPs to communicate with DERs at low cost. In addition, more home appliances from washing machines to electric vehicles are being made with the ability to connect to the internet and communicate their status or be controlled remotely through a user's smart phone, referred to as the "internet of things" (IoT). [36] This provides an easy route to control energy usage, with smart home systems (e.g. Nest [47]) and energy management systems beginning to appear. [36] Home energy management systems (HEMS) can control household appliances and DERs but do not aggregate or sell flexibility, but if a HEMS is already in place it may be easier to implement a VPP.

1.4.3   Europe-wide roll out of domestic smart meters

The EU aims to replace 80% of electricity meters with smart meters by 2020. [48] This is part of wider legislation towards implementing electricity markets that encourage more renewable distributed generation and more flexible demand. The intended outcomes for consumers are summarised by the European Commission as follows: [49]

- Consumers will be able to participate actively, individually or through communities, in all markets, either by generating electricity and then consuming, sharing or selling it, or by providing storage services.
- For the first time, consumers will have the right to request a smart meter and a dynamic price contract that allows them to be rewarded for shifting consumption to times when energy is widely available and cheap.

Progress towards this goal has been relatively slow, with 37% of meters replaced by 2018. The situation varies hugely by country. Some countries such as Sweden have already completed the switch to smart meters, and Finland, Italy, Estonia, Malta, Spain and Denmark have reached 80% roll-out. [50] Germany has opted out of the European program based on a negative cost benefit analysis, and has chosen to only install smart meters for households with high electricity consumption. [51]

Smart meters are necessary for VPPs that rely on dynamic pricing for control. [18] For VPPs which operate by directly controlling each appliance, the energy use of the appliance can be monitored separately, which may provide sufficient evidence that the demand or generation has been altered in response to a signal.

1.5   Distributed Energy Resources (DERs) used within a VPP to date

Many technologies are suitable for use in a VPP. In the industrial and commercial sectors, there are operating companies that aggregate DERs, optimise energy trading and provide services to the TSO. [52] [53] [54] A selection of these companies are shown in Table 2. For example, Next Kraftwerke is a German VPP operator claiming a total aggregated capacity of 7 GW in June 2019. [54] The DERs used to provide these services include large energy consuming appliances whose load can be shifted or temporarily interrupted, [55] and on-site generation such as back-up generators and CHP. The VPPs primarily operate by retrofitting existing DERs with the company's own hardware for secure communication and control. [54] [52] In Denmark, electric boilers and CHPs are used for district heating and can provide ancillary services and day ahead market optimisation. [34]

VPPs operating in the domestic sector are less developed, since the flexible capacity of each DER is smaller and therefore less attractive. However, there are a number of companies emerging which will be discussed in

Section 2.2, along with several demonstration projects looking into domestic demand response, energy management and grid integration. [56] [57] For example, tiko is operating a VPP of 6500 homes in Switzerland with an aggregated capacity of 40 MW. [58] The DERs used in domestic VPPs include home batteries, EVs (with or without vehicle to grid capability), PV panels, heat pumps and electric storage heaters. A selection of domestic VPPs are outlined in Table 4. These DERs may be aggregated with larger energy resources to enhance the services provided. [59]

Table 2 Selection of companies developing Virtual Power Plants for the industrial and commercial sectors

Company	Type	Country	DERs	Size	Ref.
Next Kraftwerke	VPP technology provider	Germany	VRE, large batteries, flexible power plants, large CHP, industrial DSR	7 GW	[54]
Energy&Meteo Systems	VPP technology provider	Germany	VRE, large batteries, flexible power plants, large CHP, industrial DSR	-	[60]
Limejump	VPP technology provider	UK	Industrial and commercial assets (demand response, on-site storage and generation e.g. CHP/ back-up generator)	1 GW	[53]
KiwiPower	VPP technology provider	UK	Industrial and commercial assets (demand response, on-site storage and generation e.g. CHP/ back-up generator)	1 GW	[52]
Energy Pool	VPP technology provider	France	Industrial and commercial assets (demand response, on-site storage and generation e.g. CHP/ back-up generator)	-	[61]

1.6 Uptake of fuel cell mCHP

Although many types of DER have been considered for use in a VPP, no fully operational VPPs reviewed here have incorporated mCHP fuel cells. For aggregators to be interested in investing in control strategies for fuel cells, there needs to be a critical volume available for aggregation that would add value to other DERs. This is likely to be at least 1 MW_e aggregated capacity, or approximately 1000 units. [62] Even for vehicle-to-grid technology where there has been a lot of interest from aggregators, the business case is unlikely to be viable until there is a higher volume and lower equipment costs. [63] Factors that affect whether mCHP will see large scale uptake may therefore affect whether a VPP is viable. These factors include the addressable market size, customer acceptance, and national support schemes.

1.6.1 Addressable market size

Estimates of the potential market size for fuel cells are shown in Figure 9. The primary market (shown in blue) is the potential fuel cell capacity in MW_e that could replace older gas boilers or be installed in new builds, assuming each dwelling installs a fuel cell with capacity of 1 kW_e. The conversion market (shown in grey) is the capacity that could replace other heating systems, which in the UK and Germany is primarily oil-fuelled heating. These estimated market sizes are an upper limit and do not take into account factors that may make a fuel cell unsuitable. [64] Some of these factors are

- Suitability of building to accommodate the size and weight of the unit
- Specification of the building's space heating system
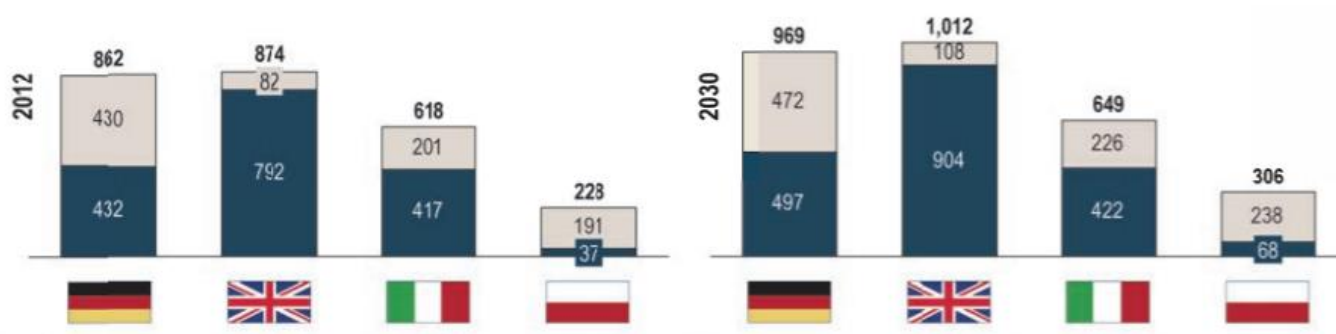- Availability and quality of a natural gas source

Figure 9 Addressable market in 2012 and 2030 for fuel cells in dwellings with 1-2 families. The primary market size (new builds and gas boilers due for replacement) is shown in blue and the conversion market (switching from other fuels) is shown in grey (units of MW_e). Reproduced from [64].

In the demonstration project "EnergieKoplopers", existing heating systems were often located on the second floor of the building, and the size and weight of the mCHP unit meant installation was not always possible. [13] The specification of the existing space heating system can also be an issue. For example, in the UK the radiator systems generally operate at higher flow and return temperatures than the FC system, and there is limited space in homes for a buffer tank. [5] Available space should be considered when determining the optimal configuration of the system in PACE Task 4.2. The availability of a local gas network is also a requirement, meaning that countries with low gas coverage such as France are unlikely to see high uptakes. The gas quality must also be sufficient, as in some regions the natural gas can contain sulphur which is harmful to fuel cells. [5] These factors should be considered when analysing the addressable market size of fuel cells in a region, and could complement the economic case for mCHP uptake which will be modelled in PACE Task 3.2.

A minimum aggregated size of 1 MW$_e$ is likely to be needed to contribute to grid stability, or approximately 1000 units. [62] This is much less than the addressable market size, though the actual likely market size in these countries is still to be determined. Countries where electricity prices are high in comparison to gas prices will make in-home generation from fuel cells more attractive.

1.6.2 Customer acceptance

The desirability of fuel cells should also be considered in assessing the likely market size. The ene.field trial reported that consumers were satisfied with the level of comfort and heating provided by the fuel cell. [62] In EnergieKoplopers, where fuel cells were used for hot water provision, participants reported that their fuel cells provided a greater level of comfort in the winter, but in the summer the fuel cells heated the room they were located in too much and were noisy due to fans starting up to prevent the cell overheating. [13]

If market conditions are right for CHP technology, fuel cells are expected to be able to compete with other technologies. They are likely to have lower initial and maintenance costs than Stirling engines, are less noisy and offer much better part-load efficiencies. [5] They are also more suited to use in a VPP which could provide additional revenue. [6]

1.6.3 National support schemes

The cost of a fuel cell is still much higher than traditional heating technologies. [5] If this continues, uptake is likely to be low. For example, a 2015 simulations of changes to residential heating in the UK towards net-zero carbon emissions show no uptake of mCHP fuel cells due to their cost. [65] Installation costs should also be considered, with typical installations taking 4-6 days of labour, though this is expected to decrease with experience. [5] However, price is expected to drop with economies of scale, and this has been seen in Japan, which is a world leader in mCHP fuel cells. Doubling of production of PEMFCs under the name ene-farm has seen prices fall by 16%, as shown in Figure 10. [66] Korea has seen similar economies of scale, although the market is less developed. [66] Prices are now reaching levels at which government subsidies are not required. However, the availability of subsidies was essential to increase the market size to this level.

In Europe, Germany has been the most successful market for fuel cells to date. [62] This is largely due to funding from national support schemes. Support schemes may also be required to train installers so that this does not present a barrier to market expansion. [62]
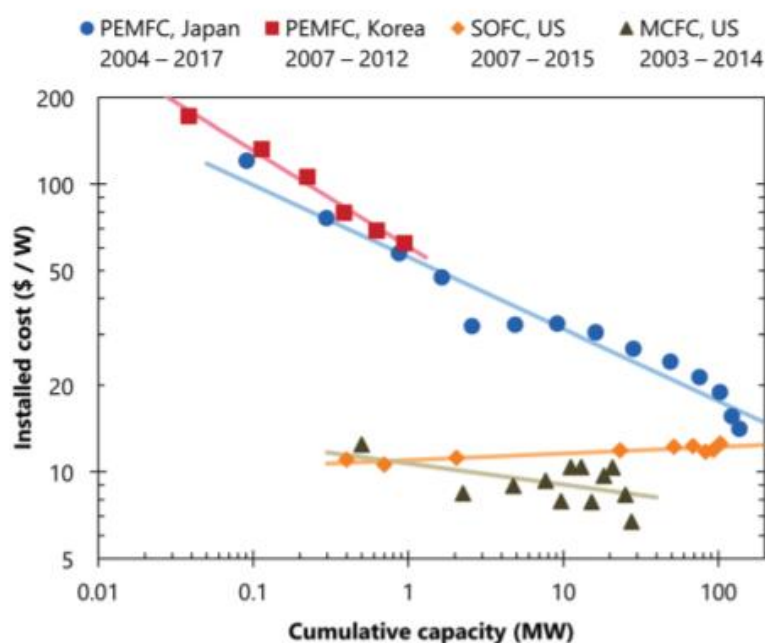

Figure 10 Learning curves for residential PEMFCs in Japan and Korea, and larger (~200 kW$_e$) fuel cells in the US. Reproduced from [66].

2 Virtual Power Plant implementations

The projects explored in this review are outlined in this section. This includes VPP demonstration projects involving mCHP units and several commercial companies implementing VPPs in the domestic sector.

2.1 Overview of mCHP VPP Projects

A number of funded demonstration projects have investigated the feasibility of using mCHP fuel cells in a VPP. The projects are summarised in Table 3 and briefly described below. Further information and conclusions from these projects will be discussed in the relevant section of this review.

The earliest projects demonstrating the use of mCHPs for providing flexible generation (EU-VPP [10], Callux [67] and DMKV [68]) showed that remote control was possible and that mCHP fuel cells can change their electricity output in response to a signal. This proved that the technology has the potential to provide flexibility in a VPP and paved the way for other demonstration projects to include them in a VPP comprising several types of DER. Results from these projects will be discussed in Section 4 which focusses on the technical requirements of mCHPs for use in a VPP.

One of the earliest projects which began to look at commercial partnerships and the value of flexibility is PowerMatching City, a project demonstrating a smart grid in a neighbourhood of 40 houses in Groningen, Netherlands. No fuel cells have been deployed in this project, however a number of homes are heated using Whispergen Stirling mCHP units with an electricity output of 1 kW$_e$ and a top-up boiler. [69] The project aimed to test the PowerMatcher operating system's ability to match sustainable generation to demand and avoid network congestion in a real community. PowerMatcher has now been provided open source and is being used in several other demonstration projects. [11] One of the recommendations from the project was that a new market model should be developed for distributing flexibility between stakeholders, and that a single market party is required to collect and sell this flexibility. These recommendations have been implemented in the Universal Smart Energy Framework (USEF) flexibility market design. [70]

EnergieKoplopers [13] is a project based in the Netherlands with the aim of testing the USEF flexibility market model [70]. DERs (listed in Table 3) from 203 households were aggregated and the flexibility sold to an energy supplier (Essent) to optimize their trading position on the wholesale (APX) and imbalance markets[3], and to a Distribution System Operator (Alliander) to reduce network congestion. These transactions took place according to the USEF model. The households participating in the VPP were located in the "Stad van de Zon" district of Heerhugowaard, [13] which is a neighbourhood where almost all houses have solar PV roofs, generating as much energy overall as is used by residents. [71] The local network experiences congestion for

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[3] Trading did not occur in live markets. Market prices were simulated for the year 2025 by the energy supplier RWE.

exporting electricity at midday when solar generation is at its peak, and in the evening there is congestion for importing electricity, when PV generation is low and demand is high, making it a suitable testing ground for network congestion avoidance. [13] In the project, 14 mCHP fuel cells with 1.5 kW$_e$ electrical capacity were installed. Five were installed in houses and nine were installed elsewhere (due to installation not being suitable). [13] The VPP used PowerMatcher for scheduling DERs and was linked to the fuel cells through BlueGen-net, a platform for controlling fuel cells made by Solid Power. The project concluded that the flexibility market was able to create value for all players.

Duurzaam Ameland is an island-based project aiming to implement a fully sustainable energy supply for the island. [20] 45 mCHP fuel cells have been installed on the island along with other DERs such as heat pumps and electric vehicles. Part of this project will be to implement a VPP on the island for optimizing energy trading in the wholesale and imbalance market and for peak shaving. [72] The VPP will use PowerMatcher and BlueGen-net in the same way as EnergieKoplopers. [72]

Other programs relevant to this review include ene.field and ene-farm, two large scale rollouts of domestic mCHP fuel cells in Europe and Japan respectively. One output of the ene.field project is a position paper on the use of fuel cell mCHP in a VPP, based on fuel cell manufacturer's views. [5] Learnings from both have been drawn on in this review.

2.1.1   Services provided

EnergieKoplopers and PowerMatching City demonstrate four of the functions outlined in Section 1.2 between them, namely

- Optimize wholesale market revenue
- Optimize imbalance market revenue
- Provide network congestion avoidance
- Maximise auto-consumption within a community

These functions were successfully demonstrated using mCHP fuel cells alongside other DERs. It is not yet known which services the VPP in Duurzaam Ameland will be providing. The remaining projects did not provide services as they were demonstrating remote control only. In EnergieKoplopers the fuel cells were automatically controlled 35% of the time to provide these services, which was a higher percentage than other technologies in the VPP. [13] The value of these services to the various market actors is discussed in Section 3.1. Balancing services have not been demonstrated in these projects and revenue from capacity markets has not been explored.

The commercial partnerships explored in these projects will be discussed in Section 3.

Table 3 List of projects demonstrating VPPs with mCHP

Title	Country	House -holds	DERs	Tested Capabilities	Years	Ref.
EnergieKoplopers[4]	The Netherlands	203	▶ 183 houses with PV, ▶ 95 with PV-switch, ▶ 49 with heat pump ▶ 45 with electric boiler ▶ 5 with mCHP FC ▶ 9 with "virtual mCHP"[5]	▶ Wholesale market optimisation ▶ Imbalance market optimisation ▶ DSO congestion avoidance	Phase 1: 2015-2016 Phase 2: 2016-2018	[13]
PowerMatching City	The Netherlands	40	▶ Stirling mCHP ▶ Heat pumps ▶ EVs ▶ Solar PV ▶ Batteries ▶ Smart appliances	▶ DSO congestion avoidance ▶ Wholesale market optimisation ▶ Maximise auto-consumption	2007-2015	[18]
Duurzaam[6] Ameland	Ameland island, The Netherlands	Up to 1600 (whole island)	45 mCHP fuel cells, mostly in non-domestic premises	▶ Wholesale market ▶ Imbalance market ▶ Peak shaving	2007-present (VPP project in progress)	[20]
EU-VPP	Germany	31	31 PEM mCHP fuel cells	Demonstration of remote control	2000-2008	[10]
Callux	Germany	500	mCHP fuel cells	Demonstration of remote control	2005-2015	[67]
DMKV (Danish Micro Combined Heat and Power)	Denmark	10	mCHP fuel cells	Demonstration of remote control	2006-2014	[68]

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[4] EnergieKoplopers is Dutch for "Energy Frontrunners"
[5] The mCHP FC could not be installed in the house so was located elsewhere but controlled according to the heating demands of the household
[6] Duurzaam is Dutch for "Sustainable"

2.2   VPP companies in the domestic sector

There are a growing number of aggregators operating in the domestic sector, summarised in Table 4. None currently incorporate mCHP, but can offer insights into what has been achieved with other DERs. Industrial scale VPPs, which often include large Stirling CHP plants in their portfolio such as those in Table 2, will not be discussed as the challenges and business models differ from residential VPP implementations.

Table 4 Companies developing Virtual Power Plants for the domestic sector

Company	Type	Country	DERs	Ref.
Tiko	VPP technology provider	Switzerland	Batteries, home appliances, heat pumps, electric heaters, EVs, PV	**[59]**
Peeeks	VPP technology provider	Netherlands	Batteries, home appliances, electric boilers	**[73]**
LichtBlick (provided by Peeeks)	Energy supplier	Germany	LichtBlick Batteries, PV, EVs, heat pumps	**[74]**
Powervault	Battery manufacturer	UK	Powervault Batteries	**[75]**
Sonnen	Battery manufacturer/ energy service provider	Germany	Sonnen Batteries, PV, EV charger, immersion heater	**[21]**
Moixa	Battery manufacturer	UK	Moixa Batteries, PV, EVs	**[14]**
OVO	Energy supplier	UK	Batteries, EVs (V2G), storage heaters	**[76]**

2.2.1   Services provided

All of the services discussed in Section 1.3 are demonstrated by this selection of companies. The majority provide multiple services, which increases the total revenue generated. The types of services are discussed below.

Energy market trading

Optimising energy trading is performed in several contexts. Energy suppliers use tiko technology to optimise trading in the wholesale and imbalance markets. [59] The UK energy supplier OVO has partnered with Dimplex to offer Quantum night storage heaters which are scheduled to charge overnight at times when electricity is cheapest on the wholesale market. [76] Powervault's batteries can be used alongside PV panels to perform

arbitrage for customers with time-of-use tariffs. [75] These functions offer value to the energy supplier, or to the consumer via the time-of-use tariff.

Sonnen's VPP is made up of domestic PV and battery installations, with the aim of maximising auto-consumption within the SonnenCommunity. Lichtblick's EnergieSchwarm shares this aim. [21] This enables these companies to supply electricity to their customers using only-customer owned DERs which means they can offer lower tariffs than a conventional energy supplier. [21]

Balancing services

Providing balancing services to the TSO is a common objective for home battery VPPs. Powervault uses its batteries to provide grid services through their GridFLEX platform. [75]. LichtBlick provides services including PCR in Germany using 317 SchwarmBatteries (in November 2019) and Eneco provides PCR using customer's Tesla Powerwall and LG Chem home batteries, both using Peeeks technology. [73] Tiko's VPP white label technology is used by several companies to provide grid services. Tiko technology is currently providing Frequency Control Reserve (FCR) using domestic batteries, and automatic Frequency Restoration Reserve (aFRR) using a combination of electric heating loads and hydroelectric power. [59] Sonnen has partnered with tiko to provide Primary Control Reserve (FCR equivalent) in Germany, and claims that to do this its customers' batteries are used for a few minutes each week. [21]

Aside from these European examples, Tesla are currently aggregating 900 5 kW Powerwalls together with solar PV in a VPP in Southern Australia to provide balancing services to the Australian Energy Market Operator [28]. The VPP has successfully responded to a frequency drop caused by a coal power station outage and contributed to restoring the system to normal operation [27].

Network services

Providing local network management is in the early stages of commercial development. The distribution system operator (DSO) UK Power Networks has recently offered contracts for 18 MW of flexibility through a new platform from piclo [77], totalling £450,000 for providing constraint management in eight locations. [78] Powervault and Moixa have both won contracts to supply these services using home batteries, and Moixa's contract is to provide 50 kW using 50 batteries. OVO is running a trial with Western Power Distribution, a DSO in the UK, to provide network management services by offering free Sonnen batteries to households in a particular location in Lincoln, UK that is experiencing congestion. Part of the battery's capacity will be reserved for local network services between October and March when congestion is a problem. [79] Sonnen themselves are also running a trial in Germany aimed at using the flexibility of batteries to provide redispatch [80], the process of lowering power output in one location whilst increasing power output in another in order to reduce network congestion [81].

3 Case Studies of Commercial Partnerships

This section outlines some of the key players acting in a VPP and the relationships between them. An overview of the roles of market actors and their relationship is shown in Figure 11. Project recommendations from relevant demonstration projects are included for each market actor in Section 3.1. Section 3.2 discusses partnerships explored in these projects and examples of partnerships used in VPPs operating in the domestic sector.

3.1 Market actors

Flexibility in generation or demand originates with the prosumer and is valuable to a number of market parties – the Balance Responsible Party (BRP), Distribution System Operator (DSO) and Transmission System Operator (TSO). The aggregator is responsible for unlocking the value of the prosumer's flexibility and allowing parties requiring flexibility to use it, as illustrated in Figure 11. Multiple roles can be filled by the same party, for example an energy supplier could fill the role of the BRP and the aggregator. The role of the TSO was not discussed in the demonstration projects reviewed here (since balancing services were not provided) and will not be included.

Figure 11 Partnerships in a flexibility market according to USEF. Reproduced from [3].

3.1.1 Role of the consumer

Since the consumer is usually the owner of the DER, their participation is vital to the implementation of a VPP. Any successful VPP must therefore ensure that consumers are rewarded appropriately and are not impacted negatively by the control of their devices. [5] [18] [36] Since domestic VPPs are a new opportunity, the question remains as to whether consumers are willing to participate and whether participation offers genuine benefits. [36] [13]

Consumer attitude to costs and Payments

In the EnergieKoplopers project, [13] consumers were found to perceive any up-front cost of control hardware negatively, even if they could make the money back in future payments. Dynamic pricing was also viewed negatively due to uncertainty in how much they would benefit, and transparent billing was valued highly. Bonus flexibility payments of €30 per year were seen as a "nice benefit" but were not an important driver in choosing to participate in the VPP. Surprisingly the main driver for participation was found to be the ability to contribute to a sustainable energy system. These conclusions were drawn from interviews with 40 consumers in the Netherlands during the project which ran from 2017-2019, and therefore may not reflect consumer attitudes across the EU. Consumer attitudes to sustainability and cost of energy are likely to vary by region and over time. In PowerMatching City, an earlier project running from 2007-2015 also in the Netherlands, participants were found to choose an energy supplier that focused on cost savings over one that promoted sustainable energy consumption in the community. [18]

Amongst domestic VPP companies, incentive levels vary. All propositions to the consumer offer a clear incentive, either as an annual fixed payment or a zero-cost tariff. Moixa is offering a fixed incentive of £50 per year for three years, and an extended smart battery warranty[7]. In return, customers' spare battery capacity is used to provide network services in limited areas. [14] Powervault is another battery manufacturer who enables their customers to participate in a VPP providing network services and balancing services. Customers are paid a fixed income of £240 per year for participating[8] [82], and if their energy supplier offers a time-of-use tariff they can also make savings from arbitrage. [75] Sonnen and LichtBlick offer zero-cost electricity tariffs when using home solar plus storage to participate in the VPP and provide balancing services.

Consumer attitude to control

The comfort of the prosumer can be directly impacted by the control of their heating system. [1] In EcoGrid EU, a large smart grid trial, some participants initially complained of a loss of comfort owing to the control of their heating system. However once initial issues had been sorted, automatic control was perceived as being neutral to moderately positive [1]. Systems where the consumer was given a greater ability to adjust the

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[7] As advertised in November 2019
[8] In July 2018

temperature settings were perceived more positively than those with less control options. The majority of consumers in EnergieKoplopers were willing to have control hardware installed in their house, and automatic control was preferable to manual control [13]. However, the consumers wished to have the ability to override the settings if they considered it necessary [13]. Automatic control was also found to be preferable for consumers in PowerMatching City since it involves less effort [69]. In fact, the VPP provider Peeeks has found that increased comfort due to automated control may be the main driver for participating in a VPP, as the payments available are not large enough to convince a consumer of the value [83]. The growth of the smart thermostat market including products, such as the Nest thermostat, which use machine learning to optimise the heating schedule shows that consumers are interested in automated control [47]. A driver is the reduction in bills through avoiding heating during unoccupied times. This is part of wider growth in smart home systems.

Trust in the organisation and the technology providing control is key to consumer willingness to participate, and was cited as the top priority in choosing a VPP company by consumers interviewed in the EnergieKoplopers project [13]. The project found that trust is built in part by the company displaying a good knowledge of the consumer's appliances, being able to simply explain the reason for control, and providing more detailed information if requested [13]. For the VPP companies listed in Section 2.2, the company dealing with the customer has an existing relationship with them, either as their energy supplier or battery provider, which may increase trust. Technology providers offer a route to energy suppliers or DER manufacturers setting up VPPs with lower initial costs but do not deal with customers directly.

Providing that trust is established and comfort maintained, these studies suggest that consumers are likely to be willing for their appliances to be controlled within a VPP.

3.1.2   Role of the aggregator

The role of the aggregator in a directly controlled VPP is to enable consumers to offer the flexibility of their DERs to those who would benefit from it. [3] They are responsible for overseeing the communication and control of these assets. They also use forecasts (e.g. weather) and knowledge of consumer use patterns to determine when flexibility will be available. [13] A large aggregated portfolio of DERs not only has a larger flexible capacity but also provides more predictable and available flexibility. [13] This flexibility can then be offered by the aggregator as a product to other market players, with the aggregator taking a cut of the revenue for the service it has provided. [3]

The risks faced by the aggregator include IT malfunctions which prevent the DERs from being monitored or controlled, and inaccuracies in forecasting. In EnergieKoplopers, a third of the flexibility sold was not delivered due to inaccurate forecasting and IT problems (see Figure 12). [13] However, the delivery of flexibility was measured as changes to the net load, not the controllable load, and the aggregator was responsible for forecasting both the net load of the consumers and the available flexibility. The available flexibility was very well predicted and was not the source of the problem. A recommendation from the project was that the responsibility for forecasting uncontrollable domestic load is spread more fairly between the players. [13]

The uncontrollable load is particularly difficult to predict for the purposes of providing services to the DSO, since only a few hundred households may be connected to a transformer where congestion is experienced, and this small number makes predicting the consumption profile more challenging. In PowerMatching City, forecasting of transformer loads was carried out by the DSO who was able to make measurements at the transformer, which should enable more accurate predictions. [18] Derating must be higher when providing local network services since a single unit failing represents a higher proportion of the units available to relieve congestion at that location.

If delivery of flexibility had been measured as changes to the controllable load rather than the net load, and the amount of flexibility sold had been adequately de-rated, the aggregator could have delivered more flexibility. However, IT problems affecting the whole system would still result in non-delivery.
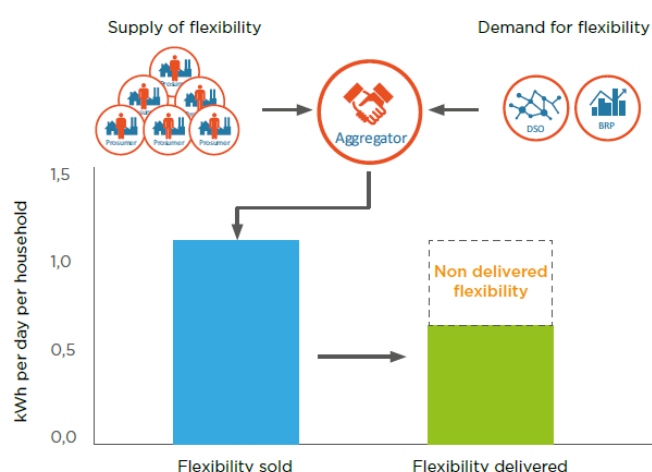

Figure 12 In EnergieKoplopers, the aggregator delivered 2/3 of flexibility sold. Reproduced from [13].

3.1.3   Role of the Balance Responsible Party (BRP)

Balance responsible parties can either be retail energy supply companies or serve several energy suppliers, and these agreements vary between countries. [13] Flexibility is of value to BRPs for two reasons. Firstly, the BRP can use flexibility to shift demand to times of day when they can buy cheaper energy on the wholesale market. Secondly, they can optimize their position in the imbalance market either within their own energy portfolio or by submitting bids (see Section 1.2.1).

The energy supplier Essent took the role of BRP within the EnergieKoplopers VPP. [13] By buying flexibility, the BRP was able to increase the average value of their energy portfolio, as shown in Figure 13. However, the portfolio was also exposed to more risk, mainly due to the aggregator failing to correctly forecast and deliver flexibility, and in extreme cases the energy portfolio could have negative value. In addition, when other players

(e.g. the DSO) requested the BRP's customers to turn up their demand, the BRP is required to meet this demand by buying energy, which also increases risk for the BRP. [13] With a more experienced aggregator, and improved trading strategies from the BRP, this can be improved. The use of flexibility in wholesale trading has been profitable for large aggregators.
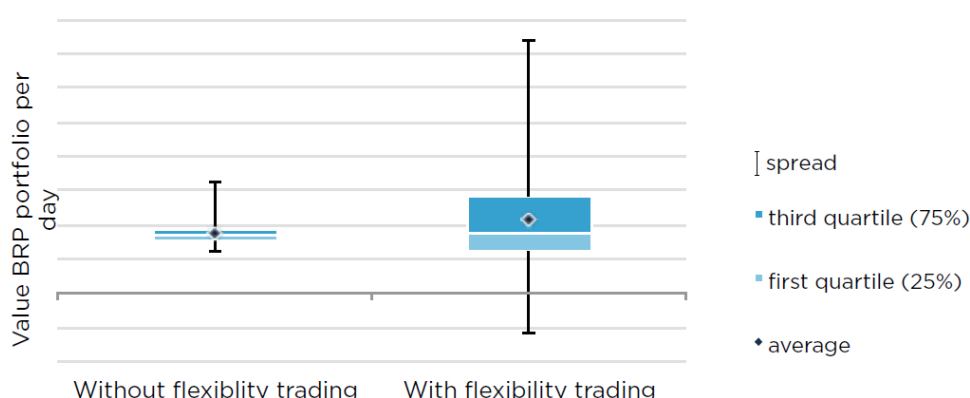

Figure 13 Flexibility trading was found to increase the value and the risk of the BRP's energy trading portfolio in EnergieKoplopers. Reproduced from [13].

3.1.4 Role of the Distribution System Operator (DSO)

The DSO is responsible for operating the distribution network, such as ensuring there is sufficient capacity for the connected load, and managing congestion. [3] Increasing microgeneration and the electrification of heat and transport poses a challenge to DSOs since there is a danger that network capacity upgrades will not keep pace with increasing load. [4] The European Commission's "Clean energy for all Europeans" package entitles DSOs to use flexibility available on their grid for congestion management (Electricity Directive Article 31) [84] and mandates DSOs to choose the most cost efficient method of grid reinforcement, whether that is physical infrastructure or flexibility (Electricity Directive Article 32). [4] Consequently, the value of flexibility to a DSO is in deferring grid reinforcement costs, and policy will soon be in place to support this.

In EnergieKoplopers, the DSO Alliander found that flexibility was effective at preventing congestion [13]. However in the trial case it would have been cheaper for the DSO to invest in grid reinforcement at a cost of €150/household/year at 4% interest. [13] The analysis concluded that using flexibility to prevent congestion is profitable for dealing with occasional peaks, but not when larger capacity is needed. [13] NODES, a trial of a local flexibility market platform also suggests that DSOs are likely to be using flexibility for a few hours to a few hundred hours a year [2]. Since grid reinforcement have a relatively long lead time, DSOs require long term agreements (>5 years) regarding availability, volume and price of flexibility. [13]

Flexibility can also increase congestion if it is being used by another party (e.g. the BRP) during congested periods, though the load changes are brief. [13] For the DSO to avoid grid reinforcement and therefore benefit

from flexibility, there must be a mechanism to enable the DSO to prevent this from happening. [13] In the PowerMatching City smart grid, transformer loads can be measured, allowing forecasts at a specific grid location to be made and enabling the DSO to acquire flexibility at that location before congestion occurs. [18] In the USEF market model, this congestion can be prevented by the DSO having the opportunity to procure flexibility after the BRP has completed their orders. [13]

3.2 Commercial Partnerships

Commercial partnerships from two demonstration projects, EnergieKoplopers and PowerMatching City, are reviewed here, followed by partnerships used in the companies listed in Section 2.2.

3.2.1 EnergieKoplopers

EnergieKoplopers uses the Universal Smart Energy Framework (USEF), [13] a market-based coordination mechanism for trading energy flexibility which is being implemented in a number of demonstration projects. [70] The commercial partnerships are represented well by Figure 11. In the first phase of the trial, the energy supplier was the aggregator as well as the BRP (Essent). In the second phase the aggregator is a separate company (SymPower). [13] In the EnergieKoplopers implementation, consumers are given fixed energy tariffs with bonus flexibility payments. The aggregator predicts the flexibility available from consumer appliances, sells this to the BRP and DSO, and then delivers the flexibility by controlling consumer appliances. The aggregator takes a cut of the revenue and divides the rest between the households as a bonus payment. [13]

The arrangements for trading within the USEF model are shown in Table 5. In the "contract" phase, agreements are established between all market parties. For each trading window, three phases must occur. First the aggregator forecasts the available flexibility and sells it to the BRP, referred to as the "plan" phase. Secondly, the DSO determines whether the predicted energy profile will cause network congestion and has the opportunity to procure flexibility to resolve this, referred to as the "validate" phase. There may be multiple iterations of these phases to reach an optimal solution for the BRP and DSO. In the "operate" phase, DERs are controlled to provide the sold flexibility. The BRP and DSO may have the opportunity to procure additional flexibility closer to real time to solve issues during this phase. Finally, payments are made for the delivered flexibility in the "settle" phase. In EnergieKoplopers, no iteration took place between "plan" and "validate", and this sometimes led to the BRP's flexibility orders causing the network load to exceed the DSO's target limits. In the project, the BRP and DSO were found to have opposite flexibility requirements (requesting flex-up and flex-down at the same time) 16% of the time. At these times a mechanism for resolving this conflict is required, and the market mechanism described by USEF should be suitable, but market dynamics were not investigated in EnergieKoplopers due to the limited number of parties involved. [13]

Table 5 USEF flexibility trading phases and their implementation in EnergieKoplopers. From [13].

USEF phase	USEF description [85]	EnergieKoplopers implementation
Contract	"In the contracting phase, various contractual relationships need to be established for USEF to function properly."	▶ Participant contract ▶ Aggregator-DSO agreement ▶ Aggregator-BRP agreement
Plan	"In the planning phase, the Aggregator examines its portfolio of clients, each with its individual needs and flexibility preferences. Energy demand and supply are forecasted for the upcoming period, usually a calendar day. Both the BRP and the Aggregator carry out an initial portfolio optimization. During this phase, the BRP may procure flexibility from its Aggregators. The Plan phase results in an Aggregator plan (A-plan) agreed upon by the Aggregator and the BRP."	Flexibility is traded with the BRP for arbitrage on APX Day Ahead market and imbalance market.
Validate	"In the validation phase, the DSO determines whether the forecasted energy demand and supply can be safely distributed without limitations. If the prognosis predicts congestion, the DSO may procure flexibility from the Aggregators to resolve it. It is important to note that there can be multiple iterations between the Plan and Validate phases"	Flexibility is traded with the DSO to reduce the solar peak and the evening peak. In the project, there were no iterations between the Plan and Validate phases.
Operate	"In the operation phase, the actual assets and appliances are dispatched and the Aggregator adheres to its plan. When needed, the DSOs and BRPs can procure additional flexibility from Aggregators to resolve unexpected congestion or to solve imbalance issues."	The PowerMatcher controls the smart appliances. In doing so, the sold flexibility is delivered. During Operate, the DSO can buy additional flexibility if needed.
Settle	"In the settlement phase, any flexibility the Aggregator has sold to the BRPs and DSOs is settled. This settlement comprises contracted and delivered flex as well as contracted flex that was not delivered"	Once a month, it is calculated how much flexibility was sold and delivered for what price. The profit of the Aggregator is equally shared amongst the participants.

3.2.2   PowerMatching City

In PowerMatching City, customers were offered a dynamic tariff to incentivise turning appliances up or down (this is an example of an indirect VPP). [18] The tariff was set to represent the interests of an energy supplier and a DSO through the PowerMatcher operating system. The energy supplier essentially filled the role of aggregator by collecting the required data for the PowerMatcher system. A home energy management system controlled some consumer devices automatically according to the price signal and suggested good times for customers to use appliances such as the dishwasher which were not controlled directly. The project recommends that one party (e.g. the energy supplier) acts as an aggregator for the purpose of collecting and redistributing the flexibility.

The customer's energy bill is generally made up of an energy component (usually a flat rate per kWh) and a fixed component for use of the network. In the trial, customers paid for network use based on actual usage instead and were able to receive a discount on this component for providing flexibility to the DSO, but were never charged more than the standard fixed rate.

A similar approach is used in the EU EcoGrid smart grid, which gives the consumer a dynamic (5 minute) price and a price forecast made up of an energy component and a locational network use component [1]. In this model, the DSO is offering a discount on a consumer's energy bill rather than buying flexibility from an aggregator. Likewise, the energy supplier does not buy flexibility from an independent party but incentivises consumers to turn demand up or down through a tariff. The tariff is set to represent the requirements of the supplier and DSO, and the available flexibility from the prosumer. This is illustrated in Figure 14.
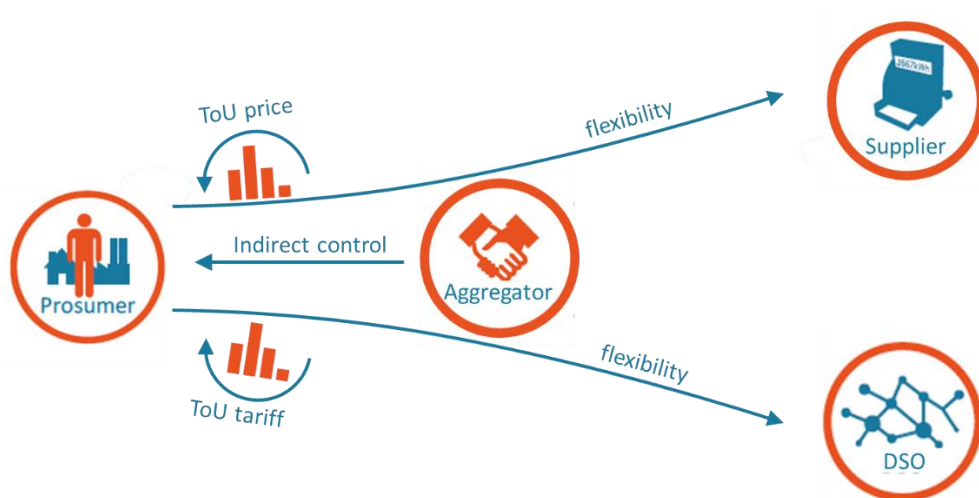

Figure 14 Commercial partnerships for a VPP using indirect control. Icons reproduced from [3].

3.2.3   Examples from VPP companies

The commercial partnerships of the companies discussed in Section 2.2 follow the model outlined in Figure 11, with the role of aggregator being filled by either an energy supplier or a battery manufacturer. These parties may operate the VPP with or without using a third-party technology company. The model used in PowerMatching City where time-of-use tariffs are set by the aggregator to control appliances has not been replicated commercially by any of these companies.

These companies can be grouped into three types –

- Battery manufacturer: offers payments to battery owners who participate in a VPP
- Energy supplier/service provider: offers low tariffs to groups of customers owning DERs and storage who participate in a VPP
- Technology company: offers a VPP as a service to other parties

The battery manufacturers Moixa and Powervault offer fixed incentives for providing network services in limited areas, and Powervault also provides balancing services. [14]**.** For Powervault owners, if their energy supplier offers a time-of-use tariff they can also make savings from arbitrage [75]. Aggregation is not necessary for this function but an aggregator is likely to have the necessary capabilities to provide it (see Figure 3 of ref [3] for an illustration of this).

The model used by energy suppliers Sonnen and LichtBlick is to offer customers who own PV and batteries a zero-cost electricity tariff, up to a maximum annual consumption. [21] To get this tariff, customers must allow their spare battery capacity to be used to provide grid services. Sonnen also offers a low-price electricity tariff for customers who join the Sonnen Community but do not provide grid services (currently available in Germany, Austria, Switzerland and Italy). They are able to offer a higher export tariff and lower import tariff than a conventional energy supplier by "sharing" energy between members. [21]

Tiko does not deal with households directly but provides a VPP service to energy suppliers. This allows energy suppliers to improve their energy trading and attract more customers by offering lower tariffs or providing enhanced energy management services to the customer with the additional data and control required for the VPP. Peeeks also follows this model, providing software-as-a-service to LichtBlick and Eneco. [73]

In addition to these models, Sonnen has recently announced a subscription model which offers customers a PV system and battery for a monthly fee equivalent to their existing electricity bill. This removes the barriers to customers who cannot afford the upfront costs of these assets. Customers can also get an electric car with smart charging for an additional monthly fee. Participation in the VPP is required as part of the subscription,

which generates revenue for Sonnen. [86] This model could be explored for mCHP fuel cells, where the upfront cost of the unit is prohibitive.

Although the DER manufacturer taking the role of aggregator is a common model for home batteries, this possibility was not considered in the demonstration projects discussed in this section. One advantage of this model is that the manufacturer is in the best position to understand how the DER will respond to providing services and how this might affect its lifespan, and can also use it as an added incentive for purchasing their product. Although they may not have the relevant expertise to implement a VPP, they may be able to use white labelled technology from another provider, such as Sonnen partnering with tiko. If trading flexibility is to be an important revenue stream in the business case for buying a fuel cell, manufacturers could follow a similar model. However, fuel cell manufacturers have not been interested in this role so far. [5]

3.3 Summary

Overall, commercial partnerships described by Figure 11 are beginning to be established between consumers, aggregators who may also be BRPs, and TSOs. Selling flexibility to DSOs has also been demonstrated in trial projects and can be part of the wider concept of a smart grid.

There are several ways to incentivise consumers, but consumers were found to prefer fixed benefits to time-of-use tariffs and this is also reflected in the offerings currently available from commercial VPP companies. The consumer's trust in the aggregator was found to be important, and commercial aggregators all have an existing relationship with the consumer as a DER manufacturer or energy supplier. When flexibility is measured based on changing the total load of households rather than just the controllable load, this makes delivery too challenging for the aggregator. Sub-metering of assets controlled by the aggregator may therefore be required to prove that flexibility was delivered rather than relying solely on household smart meters.

VPPs operating in the domestic sector sell flexibility to the TSO for balancing purposes through existing mechanisms. Where the aggregator is also a BRP, flexibility is used for energy market trading. Providing flexibility to a DSO is limited as procurement of these services is not well established. Demonstration projects have looked into how DSOs can benefit from flexibility and found that it is profitable to use flexibility for incidental peaks but not for increasing capacity as a permanent alternative to network upgrades. USEF provides a framework for a flexibility market but this may require further testing, particularly with regards to market dynamics and prices when multiple parties are involved.

4 Technical requirements of mCHPs in a VPP

This section will discuss the ability of mCHP fuel cells to participate in the services and markets discussed in Section 1.2, which have different criteria for participating.

Currently aggregated domestic generation may not be eligible to participate in energy markets or services in all European countries, though this is expected to change with the introduction of the European Commission Clean Energy Package, which is expected to open all markets to aggregated generation and DSR. When providing balancing services, the response time is a key criterion, since services requiring the fastest activation times are usually of higher value. The response time and control signal required are outlined in Table 1. Standards for providing network congestion avoidance have not yet been developed. The response time required will depend on the ability to predict congestion ahead of time. The response time of fuel cells is discussed in Section 4.1.

Other requirements include the availability of flexibility when market actors require it and the ability to successfully communicate and control the fuel cell, which are discussed in Sections 4.2 and 4.3 respectively.

4.1 Response time of fuel cell mCHPs

Proton-exchange membrane fuel cells (PEMFCs) are the dominant technology for mCHP and operate at around 80°C [66]. The fuel cell must reach operation temperature before electricity can be generated, and the start-up time can be 45 minutes or more [6]. A smaller number are solid oxide fuel cells (SOFCs), which can have start-up times exceeding 12 hours [66]. Once the fuel cell is "hot", the power output can be modulated within seconds [5]. This ability makes mCHP suitable in theory for providing flexibility on all relevant time scales, including frequency control, though this has not been demonstrated in practice in any of the projects reviewed here.

Load profile following has been demonstrated at a minutes to hours timescale [67] [10] as shown in Figure 15. Prequalification tests for FCR and aFRR vary by country and usually require demonstration that the unit can follow both step profiles and continuous profiles within a permissible response range [22]. Tests to these standards have not been demonstrated in the projects reviewed here. The profiles shown in Figure 15 are likely to be sufficient for energy and imbalance markets, and fuel cell mCHPs have been demonstrated in VPPs providing flexibility on a 15 minute timescale for imbalance markets [13]. However the start-up times dictate that the fuel cell must already be hot to be available for both grid-balancing services and energy markets, either by remaining on all the time or by receiving sufficient notice of windows for which they must be available [5].
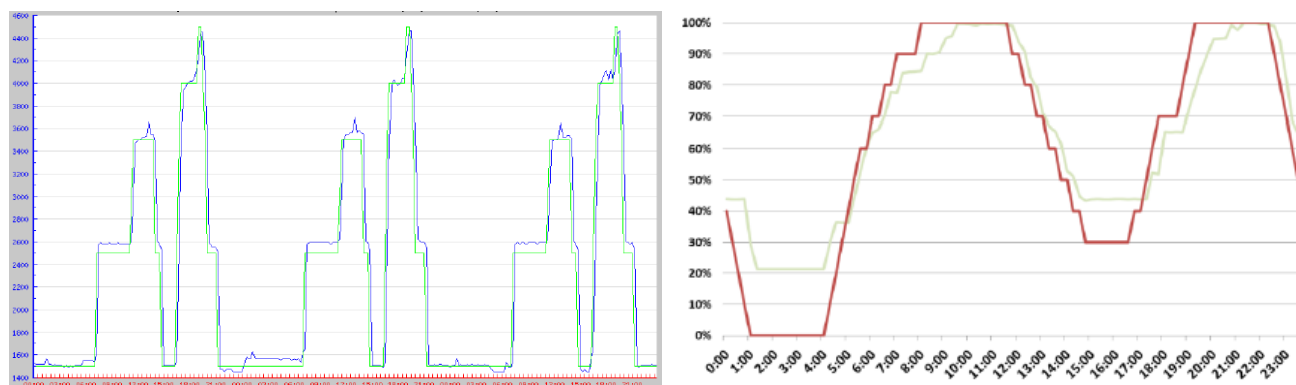
Figure 15 Load profile following of fuel cells in the EU VPP and Callux projects on a timescale of hours. Left: Green = requested, blue = output. [10] Right: Red = requested, green = output [67]

4.2 Availability of flexibility

4.2.1 Influence of operation mode

The CHP unit can be run in several modes such as following the heat or electrical load of the house, following the grid, or maintaining a constant output. In addition, the fuel cell can be sized to provide both hot water and space heating, or only hot water. These choices influence their ability to provide flexibility [5]. Installing an appropriately sized thermal store (illustrated in Figure 16) means that the fuel cell does not have to follow the heat load of the house. This allows the electricity production (and therefore heat output) to be shifted to different times of day without negatively impacting the temperature of the house or hot water supply. Conventional boilers providing space heating do not usually have a thermal store except the thermal inertia of the building, whereas storage tanks for hot water are relatively common [6].

In EnergieKoplopers the 1.5 kW$_e$ fuel cells were used to provide hot water only. The normal operation was to run the fuel cell with a constant electricity output and the residual heat (fuel to heat efficiency of 30%) was used to heat a 200 litre hot water tank [13]. In most experiments, the fuel cell ran with a high electricity output in normal operation and generation could be turned down for a specified length of time in response to a signal e.g. during the midday solar peak. [87] In one experiment, the electrical output of the fuel cell was zero under normal operation and could be increased (referred to in the project as flex-down of demand) during the evening demand peak. While running the fuel cell at less than its full capacity enables generation to be increased at times of peak demand, there is also less electricity generated in total and therefore less revenue from sale or self-consumption of electricity. Loss of efficiency is not an issue when operating with lower outputs, as the part-load efficiency of a PEMFC is the same as its full-load efficiency. [6] These considerations should be balanced when assessing which mode of operation provides the best business case.
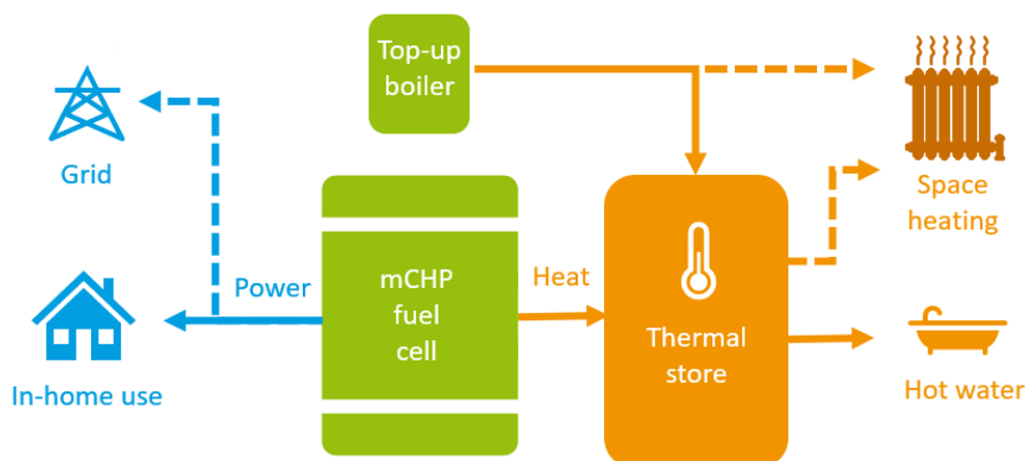
Figure 16 Example of a heating system with a mCHP unit, conventional boiler and thermal store. Based on systems in literature (e.g. ref. [5]). © Element Energy

Top-up boilers are commonly used alongside mCHP fuel cells as shown in Figure 16. In hot climates or in passive or very low-energy buildings, space heating may not be required, meaning a fuel cell could be operated in this way to provide hot water with no additional heating technology. [88] However, in countries where winter heating is necessary, using the fuel cells only for hot water requires that an additional heating system is used for space heating, which is usually the majority of the heating demand. Across the EU, space heating represents 64% of household energy consumption, whereas water heating is 15% [89][9].Fuel cells can be sized to meet a proportion of space heating demand, but sizing them to meet peak heating demand is currently too expensive.

The electrical efficiency is tending to increase with each generation of mCHP, which would allow more electricity generation for the same heat demand, making fuel cells more attractive as generators. [5] In this case the fuel cell could be purchased by a consumer as an electricity generator which provides hot water as a by-product, rather than as a replacement heating system. The most economical way of using the top-up boiler, fuel cell and thermal storage together to match heat demand and enable flexible generation in a VPP has not been studied in the projects outlined in this review, and is part of the scope of PACE Task 4.2.

[9] Breakdown by EU country is also available from reference [89]

4.2.2 Seasonal availability

By nature, CHP produces heat and electricity at the same time. The availability of electricity is therefore dictated at least to some extent by the heating demand of the building. Depending on the climate, the demand for space heating in European countries may vary enormously through the year, with no heating required in the summer and high demand in the winter. Hot water is more constant throughout the year, with only a small seasonal variation due to the difference in cold water inlet temperature [90]. In EnergieKoplopers where fuel cells were used to provide direct hot water, the available flexibility of the fuel cell was relatively constant throughout the year [13] as shown in Figure 17. If the fuel cell is used for space heating as well as hot water, the available flexibility (turndown modulation) will be larger in winter, but much reduced in summer, since the electricity output will be limited by the low demand for heat [5]. While demand turn-up is possible in summer, the intentional dumping of heat is already contrary to CHP Quality Assurance guidelines and would be unlikely to be acceptable to this mode of operation. The high value of electricity means that it is likely to be more economical to run the fuel cell with a low heat to electricity proportion so that more electricity can be generated whilst still utilising the heat produced. Any additional heating demand may be met with the top-up boiler. Sizing the fuel cell to provide space heating may be beneficial if the extra electrical capacity available in the winter can generate sufficient revenue to justify the extra cost of a larger system.

The seasonal requirements of power system services vary. In colder climates, the highest electricity prices typically occur at peak times in the winter months, meaning the higher output of fuel cells which are sized to provide space heating during these months is well suited to trading in energy markets or the imbalance market. Electric heating will further increase demand during cold periods, and one study has found that if 50% of households own mCHP units, this would offset demand from 20% of households owning heat pumps [66].
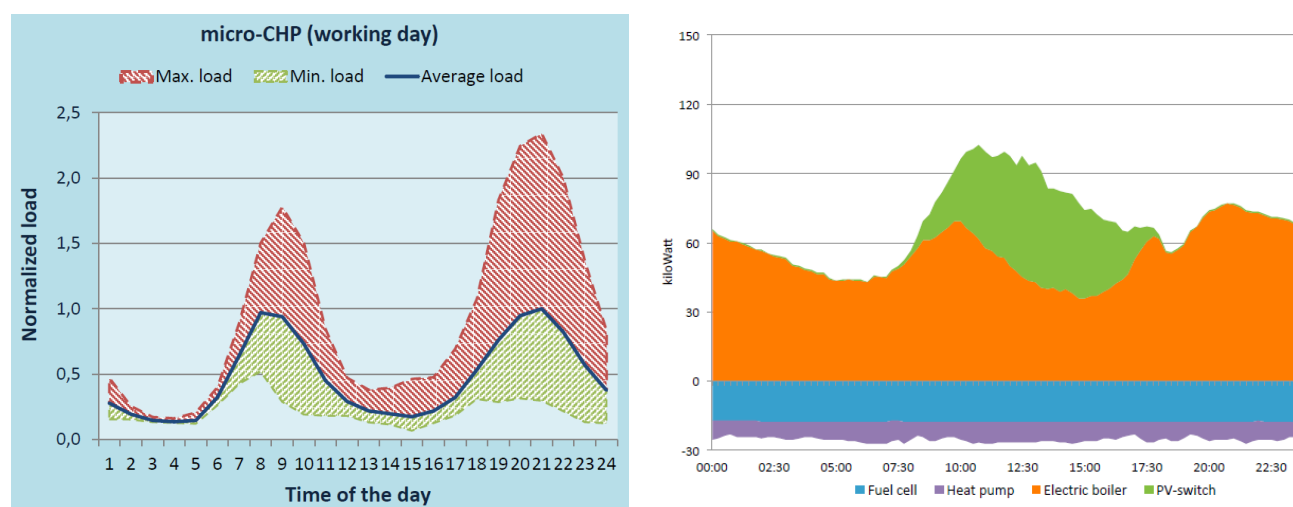

Figure 17 Left: Available flexibility of a Stirling mCHP providing hot water and space heating (red = increase generation, green = reduce generation). Reproduced from ref. [18]. Right: Available flexibility of a fuel cell mCHP providing hot water only (blue). Reproduced from ref. [13].

Widespread introduction of electric heating (either direct resistance heating or with non-hybrid heat pumps) would significantly increase peak loads on the power system, likely leading to unprecedented investments required in generation and distribution system capacity increases as discussed in Section 1.2.3. Heat producing flexible technologies such as m-CHP units offer the potential to delay or avoid these investments. Relative to these, m-CHP units could offer significant system savings due to their peak output correlating with system demand peaks. Analysis of these system savings is within the scope of PACE Task 4.3. However, it is not clear whether markets and regulation will be capable of rewarding these flexible units for such avoided capacity investments. At the very least, networks would have to be allowed to charge domestic customers based on the network capacity they use. A more sophisticated method is to reward customers who do not contribute to congestion at peak times, either via a dynamic tariff or by flexibility payments, both of which are discussed in Section 3.2.

The capacity requirements for fast acting frequency regulation (response) services is greater when renewable output is high and demand is low. This is because renewables displace large thermal generators from the generation merit order. As a result, overall system inertia is smaller, and a larger capacity of response services is required. [91] In central and northern European climates, lowest electricity demand (and so greatest demand for regulation services) is in the summer [92], which is challenging for heat-producing flexible devices. As discussed in 1.3.2, DERs need to be available for the majority of the time to achieve high value from balancing services, meaning fuel cells sized for hot water provision which have a relatively constant availability can offer a higher proportion of their capacity for this service than fuel cells sized for space heating which will have a much lower flexible capacity in the summer.

4.2.3   System availability is improving

Failure of mCHP units, resulting in the unit being offline for some time, is a risk to delivering the promised flexibility. Callux and SOFT-PACT report availabilities of between 90-96% whereas a more recent trial (ene.field) reports an average availability of almost 98% [62]. Since many units are aggregated in a VPP, the sale of flexibility is not dependent on a single asset and an aggregator can reduce the risk of undelivered flexibility by selling less flexibility than the total portfolio capacity [13] [6]. The appropriate derating factor to apply to the flexible capacity of fuel cells may need further investigation, which could be considered within PACE Task 4.2.

4.2.4   Degradation

PEM fuel cells have a degradation rate of around 1% per year and a lifetime of 10 years, and SOFCs between 1-2.5% with a lifetime of 3-10 years [66]. Degradation must be considered when calculating the available flexibility within a VPP. Since this degradation is predictable, it should not present a risk to delivery of flexibility if it is accounted for, but will reduce the total flexible capacity over the lifetime of the unit. The reduction in capacity due to degradation should be included in the economic value analysis in PACE Task 4.2.

It is possible that using the fuel cell to provide flexibility may accelerate degradation. For example, the voltage loss in PEMFC vehicles is reported to be between 23.91 and 0.16 µV per start/stop cycle [93]. Improvements in the operation procedure can largely prevent this degradation [93], and it has been reported that a SOFC mCHP system degrades at the same rate with rapid load variations compared to steady-state operation [94]. In EnergieKoplopers, the fuel cell manufacturer required that control signals were sent via a dedicated platform built by the manufacturer, which was able to check the output instructions sent by the aggregator and adjust the operational tolerances to prevent incorrect settings and safeguard the manufacturer's warranty. If it is necessary for the manufacturer to alter instructions, this should be clearly communicated to the aggregator to avoid non-delivery of sold flexibility.

4.3   Communication and control are built in by manufacturers

One of the biggest costs to implementing a domestic VPP is the installation and maintenance of control hardware in people's homes. [95] When combined with the introduction of smart meters, fuel cells may be able to avoid this cost, since they are typically manufactured with the ability to communicate and to control their settings via the internet. [5] For example, Viessmann fuel cells come with a built in energy manager, [96] and Solid Power uses Bluegen-net, a dedicated platform to control and monitor the fuel cell used in EnergieKoplopers. [13]

If all fuel cell manufacturers use a different communication protocol or API, this will create additional work for the aggregator if they wish to communicate with fuel cells from several technology providers. Several projects have recommended creating standardized interfaces and protocols for communication and control for both fuel cells and all demand response appliances in order to reduce costs of setting up and maintaining the VPP. [13] [18] [67] The fuel cell communication protocols should also be investigated to ensure they are secure enough for the purposes of a VPP. [62] Standardization is likely to encourage adoption of mCHPs in domestic VPPs, but may not be essential if aggregators are willing to interface with multiple technology providers.

4.3.1   Monitoring specifications for system services

Providing high value (e.g. regulation) services from small-scale residential assets is novel and presents a number of challenges to stakeholders. For example, in the UK, the specification of frequency and power meters required for entering the Frequency Response market, is appropriate to large, multi-MW systems, but is not affordable for small scale (kW) residential assets. Commissioning tests and FR asset management requirements are ultimately not applicable to portfolios of small flexible units. The System Operator (National Grid) has commissioned numerous research projects to determine how to improve market access to these assets. For example, the Residential Response project is evaluating new ways to test and manage large portfolios of residential DSR assets, lowering prohibitive costs to these new providers while ensuring reliable performance for the ESO. [97]

4.4 Summary

In summary, fuel cells should be able to respond fast enough to provide all functions discussed in Section 1.2. However, their ability to meet all technical requirements to provide services to the TSO remains to be demonstrated. Fuel cells have been shown to be remotely controlled through fuel cell manufacturers' platforms, but interfaces may benefit from being standardised to improve ease of use for the aggregator. When calculating the flexible capacity that a fuel cell could provide, the setup of the heating system and operation mode should be considered. Hot water systems provide constant flexibility throughout the year, whereas space heating systems provide more during winter, which is suited to the requirements of energy and imbalance markets. More work is needed to determine which system design offers the best business case for overall energy savings and flexibility revenue.

5   Recommendations for implementation of a mCHP VPP

VPPs using DERs in the home are commercially active, and demonstration projects have shown that mCHPs are able to provide flexibility in a VPP. Implementing a mCHP VPP is achievable, but there are several barriers which could hinder progress. The barriers to implementation include revenue risk in volatile and undeveloped markets that do not always fully support participation from aggregated DERs, technical and cost barriers for deploying hardware in homes, and the lack of large-scale uptake of mCHP in many countries. Revenue and hardware related barriers are general to any VPP. For example, the Vehicle to Grid Britain project found that the main three barriers to V2G implementation were high hardware costs, revenue risk in volatile energy markets and the consumer's response to the proposition. [41] Recommendations associated with these barriers are discussed in this section.

5.1   Supportive regulation and accessible markets can help VPPs

For VPPs to be viable, markets must allow aggregated DERs to participate on equal ground with large scale generation. [22] In addition to this, a recommendation from EnergieKoplopers was that in order to provide services to the DSO, the DSO must be allowed to use flexibility to defer infrastructure upgrades, and there must be consistent treatment of capex and opex in order to show that this is a cost effective solution. [13] [7] The "Clean Energy for All Europeans" package addresses these issues, and member states are expected to adopt these policies by 2021. Further recommendations to support aggregated DERs are outlined in the European Smart Grid Task Force's final report on demand side response. [98] These policies could be considered in PACE Task 3.3 in order to unlock the economic value of avoided grid extension (assessed in PACE Task 4.3) and ensure revenues from participating in a VPP (assessed in PACE Task 4.2) are achievable under future energy policies.

In addition to these policy changes, establishing flexibility markets could help by providing an easy point of entry for aggregators to provide services to multiple players. [13] Markets or standard agreements for providing flexibility services to DSOs are particularly needed as this is a new opportunity. [2] EnergieKoplopers recommended that the USEF market model continues to be explored to investigate market dynamics and price formation. Market actors should have a clear assessment framework to determine whether purchasing flexibility will pay off in particular circumstances. USEF should also be developed further to explore how the risks of forecasting can be spread more fairly between market actors, as the aggregator had too much forecasting responsibility in EnergieKoplopers. [13] This is not within the scope of PACE but could be considered in other European projects, and the fuel cells deployed within PACE could be used in a field trial of a VPP, focussing on markets.

5.2 An attractive proposition to consumers is needed

On the consumer side, consumers need to be convinced of the value of participating in the VPP (as discussed in Section 3.1.1). EnergieKoplopers recommended that there should be no investment costs or financial risks involved in participation and that a fixed incentive is more likely to be attractive than a dynamic tariff as consumers are generally risk averse. The proposition should also have a compelling story, simply explaining the concept and how it contributes to a sustainable energy system. It was also recommended that trust in the company is important and can be improved by providing excellent customer service including a good knowledge of the consumer's appliances and being able to simply explain the system and reason for control (a customer portal was helpful for this). Customers should also be able to override the automated control if they wish [13].

5.3 Technical challenges of operating VPPs in a domestic setting must be overcome

Communication with domestic devices can be challenging. If malfunctions occur in the home, this can be a large cost to the aggregator who may have to visit the site to fix the problem. In EnergieKoplopers, appliances were not available for 10% of the time due to IT malfunctions. The project recommended that reliability and ease of use are important for unlocking flexibility and ensuring the prosumer has confidence in the technology. [13] EU EcoGrid also found that the most common technical reason for not being able to provide flexibility was missing data or lost connectivity between the home gateway and the server. [1] When the system did not function properly this also produced a negative reaction from participants. [1] These issues are likely to improve with more experience, but standardisation of control and communication protocols would also help to simplify the process. The roadmap to progress a fuel cell VPP in PACE deliverable 4.6 could consider the case for standardisation of the communication protocols used by mCHP fuel cells with reference to existing open DSR standards (see Section 5.4).

The suitability of the optimisation algorithms should also be carefully considered. PowerMatcher works well at small scale and should be scalable since intensive tasks are divided between different computation clusters, but the complexity of the algorithms meant that, at very large scale (in EU EcoGrid), the time from measuring data in households to updating the broadcasted price signal that controls devices was too long. [1] In the final phase of the EcoGrid project the time was reduced to 10 minutes, which is adequate for energy markets but not for balancing services. Other commercial VPPs have demonstrated balancing service provision using many domestic DERs, showing that this is possible with the right choice of protocol and algorithm. [59] Future field trials could include a commercial aggregator with proven capabilities in this area to avoid these problems.

Frequency response (FCR) is controlled locally to avoid latency issues, but the hardware specifications make this difficult to achieve cost effectively on a domestic scale. If frequency-controlled grid services are shown to be an important revenue stream in PACE Task 4.2, the possibility of building this hardware into the fuel cell could be considered in the PACE D4.6 roadmap.

5.4   Standardisation can decrease the costs of implementing a VPP

The set-up process for a VPP currently requires installation of hardware at each household. PowerMatching City showed that costs were reduced by using existing internet infrastructure and cheap built in electronics compared to installing separate connections and computers. However, the cost was still too high for a viable business case. The recommendations from the project were to use a standardised framework along with standardised interfaces and protocols across Europe, in order to benefit from economies of scale. [18] EnergieKoplopers recommended hardware and IT standardisation to keep costs low, and recommended that there should be no investment costs to the consumer as far as possible. [13] There are several frameworks for standardisation such as OpenADR (Open Standard for Automated Demand Response) [99]. The Universal Smart Energy Framework (USEF) also provides a standardized device interface which has provision for several control strategies which cover direct and indirect VPP implementations. [85] In the second phase of EnergieKoplopers, a platform was developed that multiple aggregators could join to trade flexibility and open standards were used throughout the chain. [100] Adopting open standards widely and developing a "plug-and-play" method of implementing the VPP would greatly reduce costs.

5.5   Summary

There are several barriers to implementing a VPP involving mCHP fuel cells, but none that cannot be overcome. Energy markets and service provision should be opening up to aggregated DERs in the near term. Consumers are willing for their DERs to be controlled providing they understand the value and trust the company. Companies are operating VPPs in the domestic sector commercially in some countries, showing that technical challenges can be overcome with experience. Standardisation of communication and control protocols is likely to help reduce the cost of implementing a VPP and reduce the number of technical problems that could occur when linking a variety of DERs. Aggregators will need to know that there are a significant number of households that wish to participate in a VPP with mCHP fuel cells before being willing to invest in control strategies. Manufacturers may be able to help this case by making fuel cells as simple as possible to incorporate into existing VPPs, or by running a VPP themselves.

6 Conclusion

From reviewing demonstration projects and other literature, fuel cell mCHP units are found to be capable of providing energy services and network services through flexible generation. The response time is fast and could theoretically be used to provide balancing services, but this has not been demonstrated and it remains to be seen whether the load following performance is good enough to pass prequalification tests. In addition, there is unlikely to be a large opportunity for FCR provision due to competition with batteries. Use of mCHPs in VPPs that use flexibility to optimise trading in wholesale and imbalance markets and to avoid network congestion has been demonstrated successfully in field trials using simulated markets. Revenues from these services have not been demonstrated but are likely to be in the region of 20-90 Euros per flexible kW per year based on previous simulations, though this will depend on the country and the services provided. When considering the available flexibility of a mCHP, the design of the heating system, the operation mode of the fuel cell and the reliability of the VPP technology should be taken into account. This will be explored in PACE Task 4.2.

The main benefit of owning a mCHP fuel cell is likely to be the reduction in electricity bills due to self-consumption, which does not require aggregation. Self-consumption can be optimised with the use of a Home Energy Management System (HEMS). Revenue from a VPP may be able to offer a moderate additional income for mCHP owners, if a business proposition that is attractive to all parties can be developed. To be attractive to consumers, there must be no or low investment barriers, trust in the aggregator and technology, and a clear incentive (either monetary or contributing to sustainability). The aggregator must have easy access to markets for selling flexibility to other parties and should not be exposed to an unfair share of the demand forecasting risk. The cost of connecting to and controlling the DERs must also be low and the reliability high, which can be improved by standardisation. Flexibility is bought by Balance Responsible Parties for energy trading, and Distribution System Operators for network congestion avoidance which provides revenue. To access these revenues, market rules must allow aggregated DERs to participate in energy markets and the DSO must be allowed to use flexibility from DERs to avoid network congestion. Alternatively, these parties can provide revenue to the prosumer through time-of-use tariffs, but this may be a less popular offering amongst consumers. In this case, DSOs must be allowed to charge domestic customers based on the actual capacity they use and to vary these charges based on when the network is congested. Network congestion prevention with domestic sized assets is challenging due to limited scope for aggregation at a congested location. Going forward as renewable penetration increases, the largest opportunities for a VPP are likely to be in energy services, with the possibility of additional revenue from balancing services if these can be demonstrated. Possible revenues will be assessed in PACE Task 4.2.

Further work to establish flexibility markets and their dynamics is required and to implement standard communication and control protocols for DERs to provide services. The ability of fuel cells to provide balancing services could also be investigated further. From reviewing VPP companies operating in the domestic sector, the energy supplier or fuel cell manufacturer are the most likely candidates for the role of aggregator. This could be achieved via a third-party technology provider. If fuel cell manufacturers wish to secure revenues

from flexibility in the economic case for purchasing a fuel cell, they could investigate business models where participation in a VPP is offered alongside fuel cell ownership, or could partner with energy suppliers to offer energy as a service.

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