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Energy in Buildings and
Communities Programme

# Impact of Microgeneration Systems on the Low-Voltage Electricity Grid

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## October 2014

## A Report of Annex 54 “Integration of Micro-Generation and Related Energy Technologies in Buildings”

Edited by

| | |
|---|---|
| M. Sasso | (Università degli Studi del Sannio, Italy) – Subtask B Leader |
| Evgueniy Entchev | (National Resources Canada, Canada) – Operating Agent |
| Peter Tzscheutschler | (Technische Universität München, Germany) – Operating Agent |

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**Authored by:**

| | |
|---|---|
| Nick Kelly | (University of Strathclyde, UK) |
| M. Sasso | (Università degli Studi del Sannio, Italy) |
| G. Angrisani | (Università degli Studi del Sannio, Italy) |
| C. Roselli | (Università degli Studi del Sannio, Italy) |

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Ken Darcovich (Subtask A Leader), Evgueniy Entchev, Peter Tzscheutschler (Operating Agents)

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# 1 Overview

The primary function of Annex 54 is the analysis of microgeneration performance in buildings. Within the context of Annex 54, the term 'microgeneration' relates to a broad range of low-carbon technologies that can provide heating, cooling and/or power to buildings and communities. These include fuel cells and engine-based polygeneration systems, heat pumps, PV, micro wind power and biomass. Microgeneration technologies can be deployed individually or in combination (so-called hybrid systems).

Whilst the primary use of microgeneration is to service the energy demands of a building or a community, microgeneration technologies could also play a role in wider energy networks such as communal heating schemes or (more typically) local electrical networks. However, the widespread participation of microgeneration in an energy network presupposes that those networks have evolved to accommodate and best utilise the microgeneration resources. Currently, this is rarely the case and microgeneration technologies tend to be connected piecemeal to existing networks, which have been designed to transport power, in one direction, from large central generators to the end user at the end of the network.

The role of this report is to set the operation of microgeneration in buildings within this wider operational context. The report therefore focuses on connection into electrical networks and develops two main themes. First, the impact of microgeneration on existing electrical systems is explored. Second, the report looks ahead as to how microgeneration could be best utilised in energy networks – this will encompass approaches to control, related technologies such as energy storage (including hybrid vehicles) and demand-side control.

The report draws on studies undertaken by Annex 54 partner organizations, papers presented at recent Microgen conferences [1,2] – organized by Annex members – and work done within the Highly Distributed Energy Futures (HIDEF, 2013) consortium, a group of University partners who were the UK representatives on the Annex.

# 2 Microgeneration and the Grid

Building-integrated microgeneration is an emergent technology and as such does not yet make a significant contribution to the overall energy supply. However, the deployment of a range of microgeneration technologies is proceeding apace, though unevenly, throughout the developed world. For example, the most widely deployed microgeneration technology is currently PV; in the EU it is estimated that approximately 70 GW of photovoltaic capacity has been installed to date [3], of which almost half has been installed in Germany [4]. Micro-wind is also rapidly expanding where there is a viable resource. For example 22 MW of micro wind turbine capacity [5] is now installed in the UK as part as a rapid upsurge in microgeneration.  In Japan, micro-CHP has gained a foothold in the domestic market with approximately 100,000 residential engine-based units installed and approximately 30,000 PEM fuel-cell-based units installed since 2009 [6]. However, the deployment of micro-CHP and polygeneration in other countries has been less spectacular. For example, in the UK, micro-CHP installations account for less than 1% of total installed microgeneration capacity (1.7 GW) [7].

Figure 1 shows the cumulative installed PV capacity in Europe between 2000 and 2011.

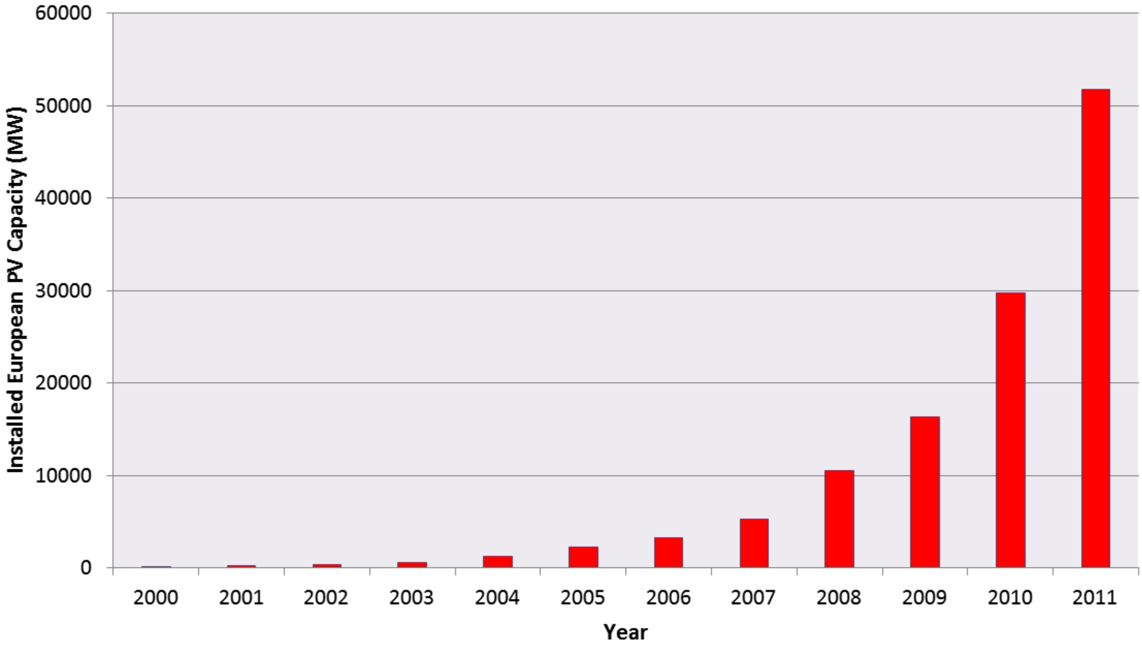

**Figure 1 growth of PV capacity in Europe [8]**

The emergence of a heterogeneous mix of microgeneration technologies, connecting into the existing power infrastructure poses challenges for the provision of a stable and secure power supply. However, as will be discussed later, microgeneration also offers considerable opportunities for a reduction in carbon emissions associated with electricity supply, the co-location of thermal and power supplies and the de-centralization of energy supplies.

## 2.1 Characteristics of Contemporary Electricity Generation

Electricity networks are displacement systems – the supply of electrical power must balance the power demand at any point in time; failure to do so would result in a collapse in supply.  In the developed world, the general form of power system that has evolved to facilitate the requirement for and instantaneous power balance is based around a small number of large, central power stations, producing three-phase, alternating current (AC) at high voltage with individual power generation capacities typically exceeding 1 GW. These larger stations tend to be nuclear, coal or gas powered, however very large hydro power stations also exist (for example China's 3-gorges Dam project has an installed capacity of 22.5 GW [9]). These few power sources provide the power to supply many millions of smaller loads.

In order to maintain a supply and demand balance, power stations are brought on and off line over time or, where practical, their output is modulated to match a largely unregulated demand.

To illustrate this, Figure 2 shows the variation in demand over a winter day in Spain along with the mix of generation that meets the demand.

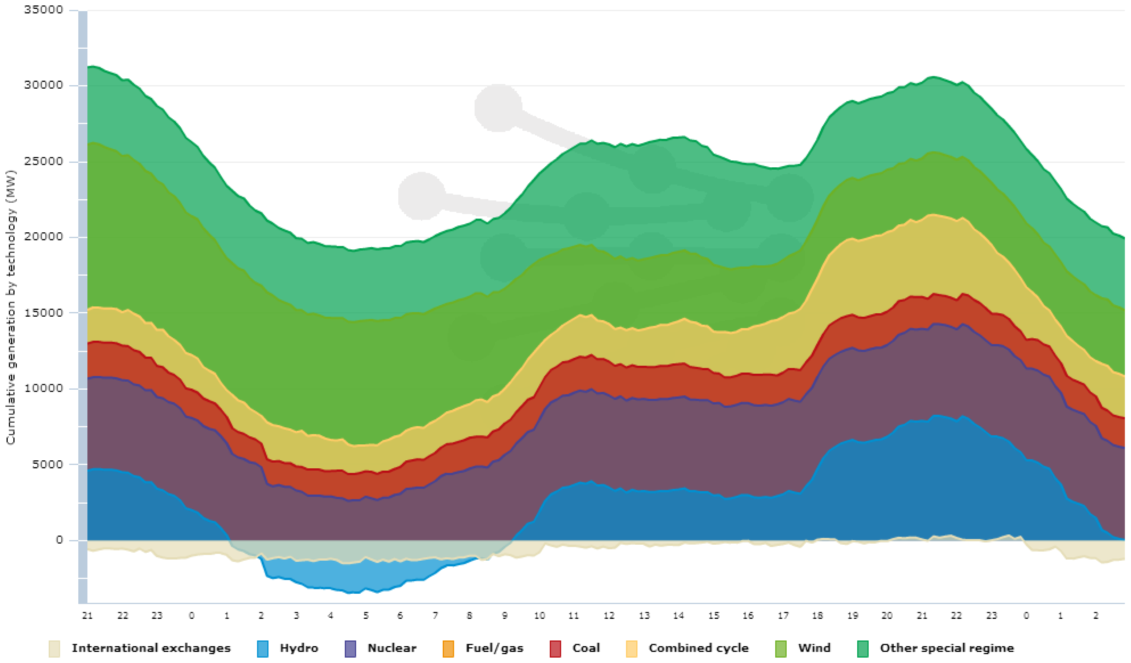

**Figure 2 variation in Spanish winter demand and the associated generation mix [10]**

It is notable that larger nuclear power and coal power stations generate almost continuously at a steady rate (providing so-called base load), whilst gas power and hydro power stations are modulated to match supply and demand; the reasons for this relate to both the nature of the basic power source - it is technically challenging to modulate the output of a nuclear reactor; and also financial - the high capital cost and long lead-in time of nuclear power plant requires that it accrues maximum revenue from generation.

The electrical transmission and distribution system has evolved over time to facilitate the efficient transport of large volumes of electrical energy from a few large generators to a large number of power consumers - a so-called ‘few-to-many’ system [11 Fig. 3]. Large generators typically produce power at a few tens of kilovolts (kV), with power being transmitted at hundreds of kV and eventually supplied at a few hundred volts to the majority of end-users. The flow of power in such systems is characteristically mono-directional, with electrical power cascading down from high to low voltage levels.

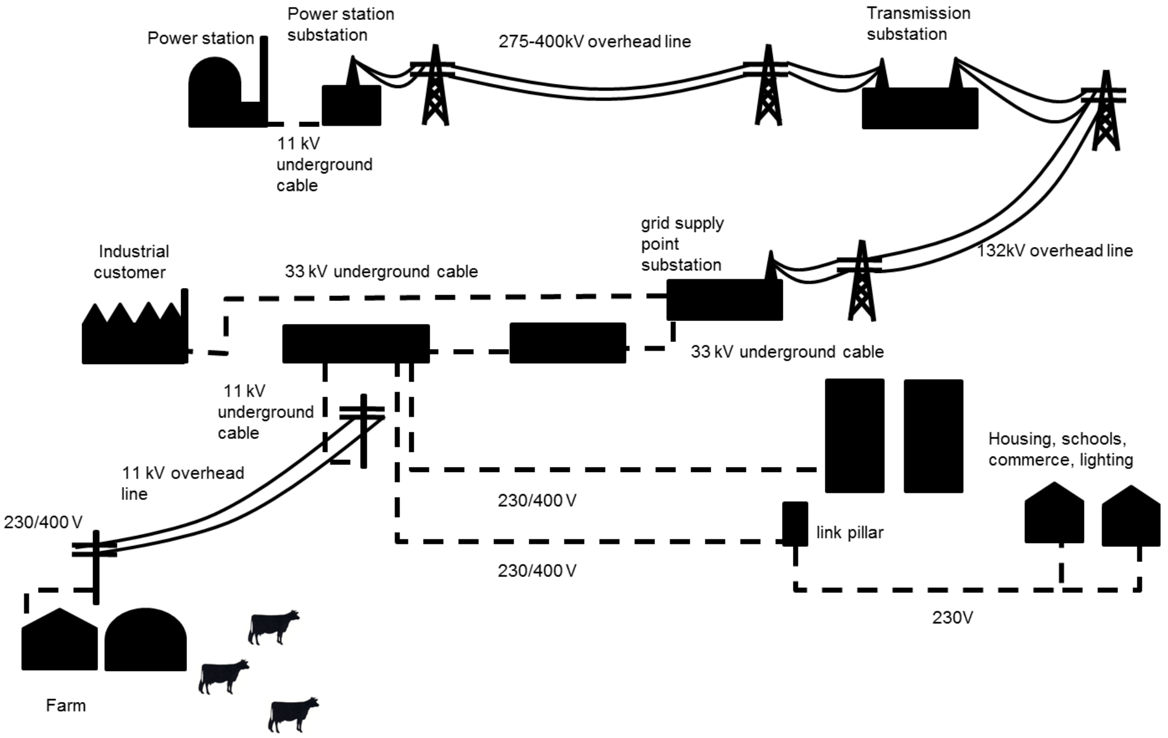

**Figure 3 typical ‘few-to-many’ network topology**

## 2.2 The Challenge Posed By Microgeneration

With the evolution of embedded generation (e.g. wind turbines and cogeneration) and more recently, many different varieties of microgeneration, the few-to-many model of a power system is changing. Future power systems may instead feature a ‘many-to-many’ topology [11], featuring a large number of smaller generators. Microgeneration technologies typically couple into the electricity distribution network at low voltage levels; this has the potential to change the mono-directional power flow characteristics of conventional power distribution - if the penetration of microgeneration is high enough in a particular section of a power system the potential exists for power flows to be reversed i.e. bulk power to flow from low to higher power regions of the electricity network.

The co-ordination and operation of a power system featuring variable direction power flows and large numbers of heterogeneous generators poses significant technical challenges. For example, microgenerators produce electricity at many different voltage levels, different AC frequencies (sometimes unregulated frequency), or produce DC power. These different technologies need to be interfaced with the electricity network. However, whether an electricity system conforms to a ‘few-to-many' or 'many-to-many' topology, a balance between supply and demand still needs to be maintained and power supplied to end users with high reliability and (at least in the medium term) at a near-fixed frequency and with dependable voltage levels.

## Dispatchability

Viewed within the context of a stable electricity supply, microgeneration technologies fall into two broad categories: *dispatchable* and *non-dispatchable*. These categories also apply to larger-scale generation. A *dispatchable* generator can be tuned off or have its output modulated as demand changes; the output of a *non-dispatchable* generator cannot be controlled (other than connecting or disconnecting the generator). Table 1 categorises some common, thermal/electrical microgeneration technologies.

The dispatchability or otherwise of microgeneration is complicated by the fact that the primary function of these technologies is not to supply electricity to the electricity network. Rather, they exist to service local demands (electicity, heating, cooling). Consequently, whilst a technology such an engine-based cogeneration may in theory be modulated to service some requirement in the electricity system, the demands of the local load may negate that option. For example, a cogeneration system servicing a heat load may be unable to turn off as requested by an electricity network operator as the heating set point in the load may not have been achieved. This contrasts to (for example) with a gas power station, the only function of which is to service the requirements of the electricity network.

**Table 1: categorizing microgeneration technologies according to their dispatch characteristics**

| *Dispatchable* | *Non-dispatchable* |
|---|---|
| Engine-based polygeneration | Photovoltaics (PV) |
| Polymer Exchange Membrane (PEM) fuel cell | Micro-wind turbines |
| Micro-turbine | Solid Oxide fuel cell (SOFC) |
| Micro-hydro | Wood-fueled cogeneration |
| Heat pump[1] | |

It should be noted that, the integration of microgeneration with thermal or electrical storage may engender dispatchability in an otherwise non-dispatchable technology. For example, PV coupled to a

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[1] Heat pumps are special case in that they are a local source of heat but act as a significant load on the electricity system. However, the ability to modulate heat pump demand enables them to act as dispatchable load on the electricity network.

large storage battery becomes a dispatchable power source and the output of the battery can be switched on or off or perhaps modulated over time.

## Interfacing

In conventional power stations the generators are typically synchronous machines, producing AC power synchronised to the grid frequency at approximately 10 kV. Microgeneration technologies are far more heterogeneous producing DC or AC power, single and polyphase, operating at different voltage levels and at different (sometimes variable) frequencies. Table 2 illustrates the variety of power characteristics from microgenerator sources (sourced from a variety of manufacturer's technical specifications).

**Table 2 Electrical characteristics of some micro power sources**

| Device | Power characteristics | Illustrative Voltage | Frequency |
|---|---|---|---|
| PV | DC | 12 V | n/a |
| micro-CHP | DC or AC (single or 3-phase) | 100-400 V | fixed (e.g. 50 Hz) |
| Fuel cells | DC | 100-400 V | n/a |
| Small wind turbines | DC or AC (single or 3-phase) | 100-400 V | fixed or variable |

All of these different technology types need to be interfaced to the LV electricity network, operating with country-specific voltage and frequency limits. In the case of those technologies producing fixed-frequency, sinusoidal AC power this is relatively straightforward, i.e. a small induction generator driven by a motor operating at synchronous speed (i.e. 50/60 Hz) simply draws reactive power (VAr) from the network in order to produce electrical power (W). However for other technologies and situations the interfacing is less straightforward. For example, the interface to a PV system will typically incorporate DC-DC conversion featuring maximum power point tracking (MPPT) and boosting the voltage to network levels; this would be followed by DC to AC conversion. Maximum power point tracking involves dithering of the output current of a PV array in order to find the optimum DC current and voltage levels.

Power electronic interfaces (PEI) would typically be required for the majority of microgeneration technologies and would also be required when interfacing storage technologies such as batteries to the network. A general interfacing topology for microgeneration technologies is presented by [12], Fig. 4 that illustrates the possible stages required to feed power from microgeneration to the grid or feed power from the grid into local storage. In Section 5 the design and use of a storage PEI is proposed as a means to support the operation of the LV network.

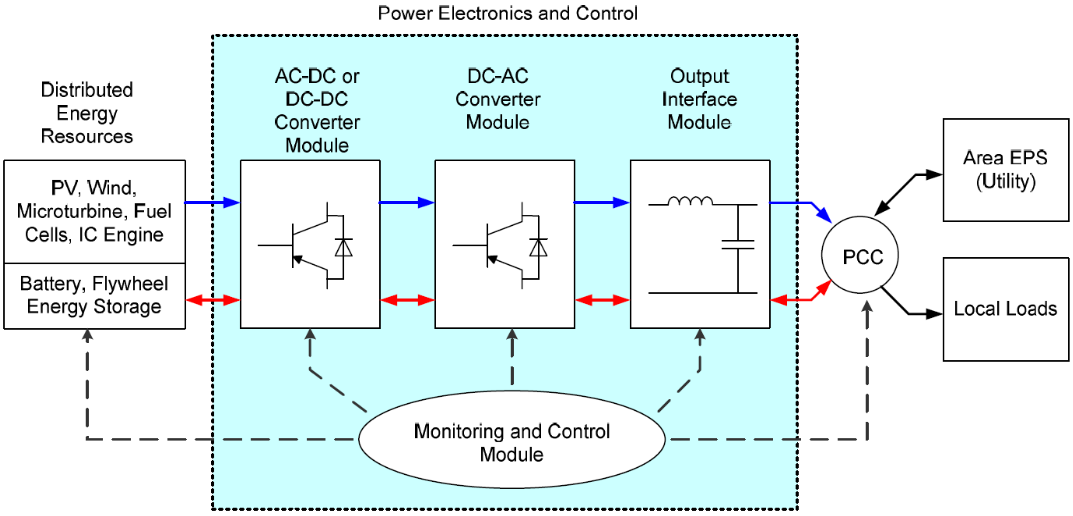

**Figure 4 General interface topology for microgeneration (PCC – point of common coupling) [12]**

# 3 Impact of Microgeneration on Existing Networks

As evidenced in Section 2, the connection of microgeneration to the existing electricity network is growing at a rapid rate and in a largely uncoordinated manner. Regulations for the connection of microgeneration apply, but these tend to only deal with safety and power quality issues. For example, in the UK there are regulations with regards to the size of microgeneration along with the quality of the interface. For generation below 3.7 kW the installer merely has to inform the distribution network operator (DNO) and ensure that the device's interface complies to the G83/2 or G59/2 (ENA, 2013) standard with regards to harmonic content, power factor and automatic disconnection on loss of mains power (G83). Europe wide, the EN 50160 [13] standard dictates the power quality for consumers and covers frequency, voltage levels, and harmonic distortion. In G83/2 and G59/2 there is no restriction with regards to the exchange of power (i.e. timing of exchange and quantity) with the local electricity network.

## 3.1 Power Flows

The potential impact of the uncoordinated growth of microgeneration on power flows in the electricity network, particularly the low voltage electricity network (LV) is considerable. All electrically connected devices such as PV, micro wind, CHP and heat pumps have the potential to increase LV power flows: for power generating technologies such as PV this stems from their ability to export power to the network, with heat pumps, the increased power flow stems from increased electrical demand.

### Reverse Power Flows

As was mentioned previously, the power system was developed for mono-directional power flows. The addition of significant quantities of generation to the low voltage network has the potential to the reverse the conventional flow of electrical power such that it flows back up through the voltage levels.

Sulka and Jenkins [14] modeled the power flows associated with 150 dwellings equipped with micro-CHP and observed strong reverse power flows at times of peak heating demand in the morning. Burt et.al. [11] also observed reverse power flows at medium and low voltage levels in a study of a mixed industrial/residential development. However, these reverse power flows were only observed with microgeneration penetrations approaching 100%.

In their PV study, Thomson and Infield [15] noted that distribution system losses were reduced as PV penetration increased; reducing the power transported in the LV network and the PV met part of the domestic load. However, larger PV installations could negate this effect if this resulted in significant reverse power flows, again increasing the power flows in the LV network.

### Increased Power Demand

Rodgers et al [16] indicate that the typical demand of a heat pump seen in the UK (3-6 kW) is typically higher than the allocated capacity-per-property in LV transformers. Munuera and Hawkes [17] looked at the potential impact of widespread heat pump deployment on the UK domestic electrical demands. This study indicated that a 50% penetration of heat pumps would more than double the maximum demand seen in the LV network. Wilson et al [18] analyses UK daily electricity and gas usage data and concluded that even a partial shift of demand from gas to electricity would result in a significant strain on the electricity network, Fig. 5.

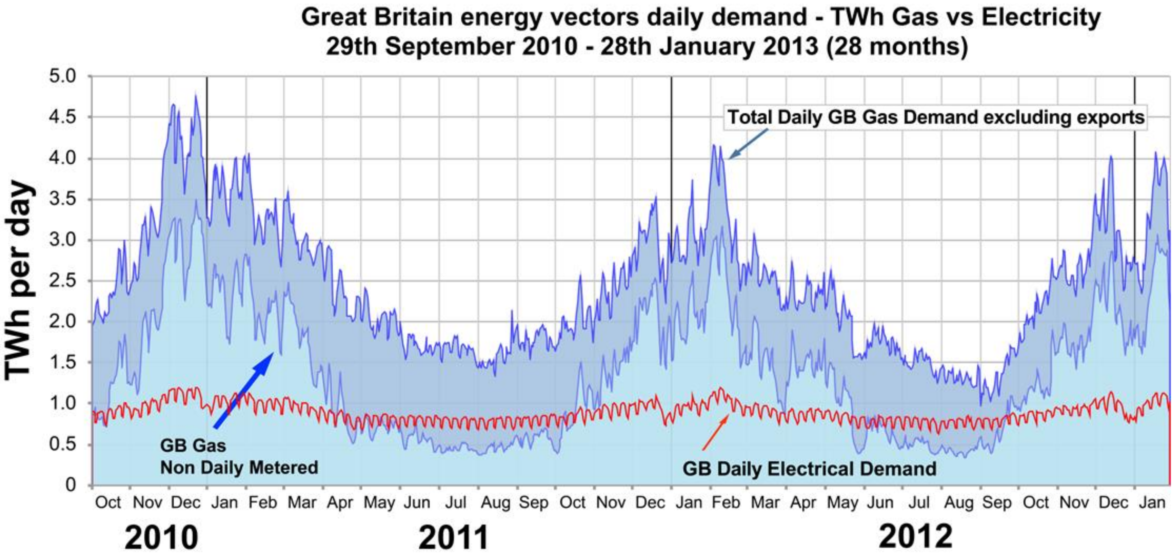

**Figure 5 UK daily metered gas and electricity use [18]**

However, the diurnal timing of microgeneration power flows will determine their ultimate network impact. For example, if the power generation of microgeneration devices was co-incident with local electrical demand, the power flows in the LV network would be reduced. Similarly, if heat pump demand was co-incident with the output from power generating microgeneration then overall power flows in the LV network would reduce. As discussed later, both Rodgers et al [16] and Kato and Suzuki [19] use co-incidence of supply and demand to mitigate the impact of microgeneration on the LV network.

## 3.2 Voltage Variation

One of the key impacts of microgeneration is on the voltage prevailing in the local network. The injection of power into the network from microgeneration technologies has a tendency to increase voltage; the connection of additional load would (such as electric vehicles or heat pumps) have the opposite effect. EN 50160 stipulates that voltage should be maintained within +/- 10% of the nominal value for 95% of the time [13]. In the UK the nominal voltage level is 230 V. Thomson and Infield [20] analyzed the impact of integrating a variety of micro-CHP technologies into an existing calibrated model of a UK suburban low voltage network. At high penetrations (i.e. microgeneration integrated into all dwellings) the authors observed that there was the potential for unacceptably high voltages (i.e. exceeding 253 V) from the perspective of both the consumer and the DNO. Figure 6 shows an example of the impact of microgeneration on the occurrence of different voltage levels.

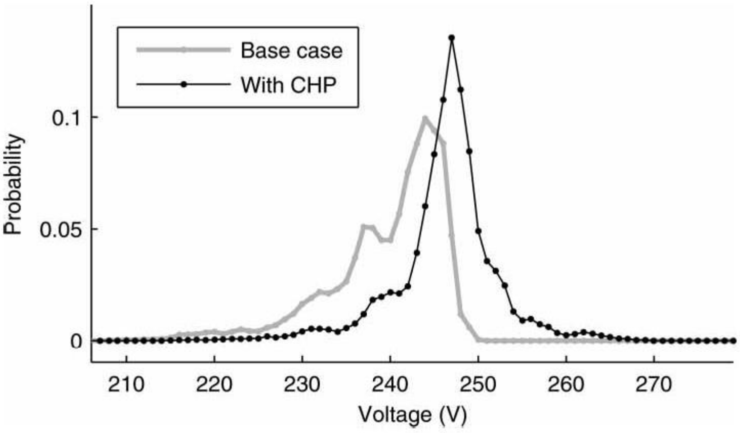

**Figure 6 Voltage at customer connection points for an LV network with and without CHP (CHP penetration 100%) [20]**

The same authors [15] also examined the impact of PV on a typical section of UK urban network indicating that the installation of 2.1 kW PV arrays on approximately 30% of dwellings resulted in the occurrence of voltage limit breaches.

## 3.3 Harmonics

Ideally in an AC power system the current and voltage waveforms delivered to a load would be pure sinusoids with a single (fundamental) frequency *f*. However, in real power systems both waveforms are distorted (figure 7). The harmonic distortion of a waveform relates to how far away it is from a pure sinusoidal form.

A pure sinusoid has a total harmonic distortion of 0%. By contrast – the alternating current and voltage are square waves will have a total harmonic distortion of 50%. Any alternating voltage or current waveform (distorted or otherwise) can be formed by the combination of a series of pure sinusoids of frequencies which are an integer multiple of the waveform fundamental frequency. The total harmonic distortion (THD) is the Euclidian norm of the non-fundamental waveform magnitudes divided by the fundamental waveform magnitude. EN 50160 stipulates that the THD in the electricity supply should not exceed 8%.

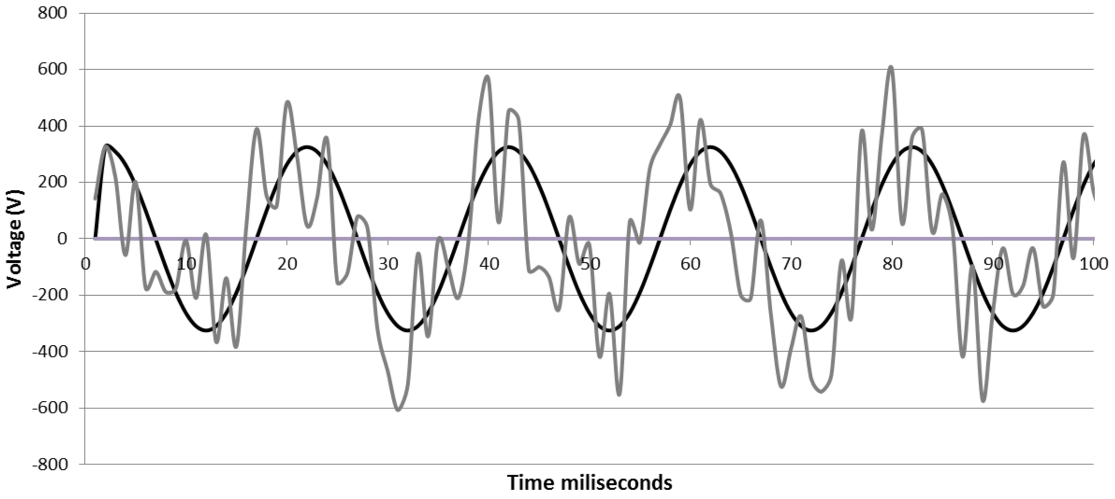

**Figure 7 Distorted and undistorted voltage waveforms**

In Japan, the total harmonic distortion associated with microgeneration inverters must be less than 5% [see section 3.3] and the power factor must be greater than 0.85. Further, devices must include protection to ensure that they cannot operate in islanded mode [21].

Badea et al [22,23] analysed the power quality associated with a hybrid microgeneration system featuring a 9 kWe Stirling engine unit and 2 kWe PV system; the output of both was stored in a battery, which was interfaced to the LV network via an inverter before being supplied to the load within a building or exported to the network. Interestingly, the authors analysed the power quality associated with the load and the output from the inverter and the load. This showed that whilst the power output from the generation has low harmonic distortion and sinusoidal current the power associated with the load had harmonic content breaching EN 5160 limits and non-sinusoidal, imbalanced currents; this was due to nonlinear loads such as lighting and electronic appliances reflecting highly distorted voltage waveforms back into the supply; this hints that with well-designed power interfaces, microgeneration would not degrade the quality of the power supply.

# 4 Accommodating Microgeneration in Current Networks

The connection of a large number of microgenerators within an existing electricity network, along with storage, demand side management and possibly electric vehicles, along with possible coupling to local heat networks fundamentally changes the form of the 'few-to-many' electricity system as explained earlier. Further, the potential piecemeal appearance of significant quantities of dispatchable and non-dispatchable generation at lower voltage levels poses challenges with regards to the safety and the security of the electricity supply. Consequently, significant research effort has been expended on developing new concepts with regards to how future energy systems could operate to maximise the potential benefits and mitigate the possible impacts of microgeneration. This section looks at mitigating these potential impacts and then looks further ahead to best maximising the potential of microgeneration in future, distributed electricity networks.

## 4.1 Mitigating Microgeneration Impacts in Networks

### Demand Side Management

The introduction of significant quantities of non-dispatchable generation such as PV, places more of an emphasis of demand side control in order to maintain stable network operation, particularly in networks of semi-autonomous micro-grids. Darby [24] highlighted at different forms of load management including passive demand reduction through the implementation of energy efficiency measures; active end-user participation through time-of use tariffs or dynamic pricing; and fully automated control of demand. In a study of automated control and variable pricing projects McKenna et al [25] found that the use of these techniques provided no guarantee of load management. Indeed, the authors describe the response of consumers to both variable pricing and automated control of appliances as 'complex'. The field trials highlighted both demand reduction *and* demand increases to variable pricing along with variable pricing 'fatigue', where the demand response to a price signal diminishes over time. In short, the authors conclude that neither load automation nor price-based control will provide definitive demand management and that significantly more research is required.

Kelly et al [26] looked at the use of thermal buffering to allow demand side management of a population heat pumps. In this detailed simulation study the authors employed substantial thermal buffers (up to 1200 L) to time-shift the operation of domestic air source heat pumps to electrical off peak periods. However, the load shifting resulted in a significant energy penalty of up to 60%. Further, when analyzing the performance of a population of air source heat pumps (ASHP), with their performance constrained to off-peak periods of operation the net result of load shifting was an *increase* in peak electrical demand rather than a reduction, the principal reason being that the load acted to reduce demand diversity (figure 8), albeit using a crude time-based tariff for load shifting.

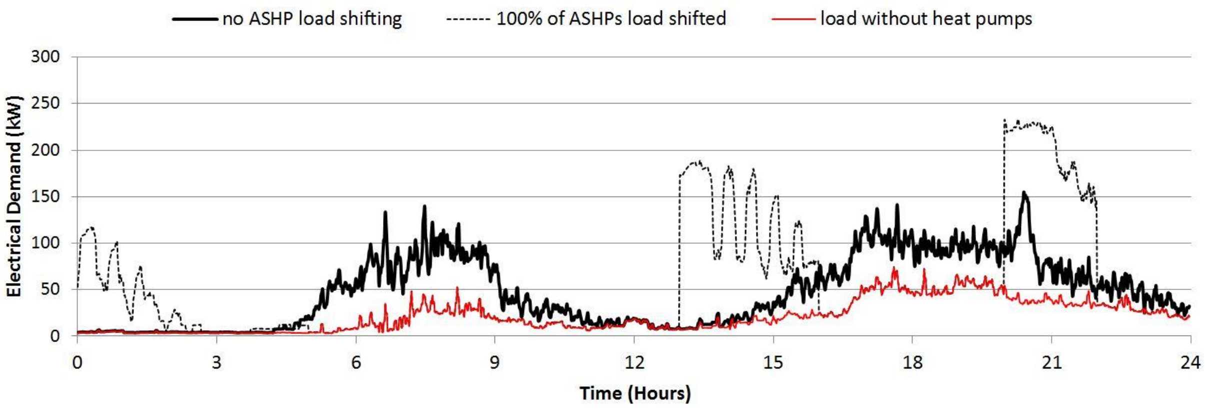

**Figure 8 Tariff-based load shifting of a population of heat pumps [26]**

Cooper et al [27] also looked demand side management of heat pumps using a calibrated, simplified model; in this case the demand side management strategy consisted of reducing the set point temperatures of a population domestic heat pumps, by up to 3 °C as the demand of the heat pumps plus dwellings approached the rating of the local supply transformer. The authors noted a deterioration in performance when thermal buffering was coupled to ASHP, but an improvement in the performance of micro-CHP devices such as Stirling engine (also noted by other authors e.g. Haeseldonckx et al [28])

## Co-operative Device Management

To mitigate against voltage rises from high penetrations of domestic PV, Kato and Suzuoki [19] explored the re-scheduling of domestic heat pump water heater loads (integrated with thermal storage), to absorb exported power at forecast times of high solar radiation intensity. The authors demonstrated that this was an effective mechanism for voltage regulation. However, the efficacy of the load management was strongly liked to accuracy of the short-term weather forecast.

Rodgers et al [16] investigated the potential synergy between micro-CHP and air-source heat pumps (ASHP), in a collection of dwellings. Both of these technologies need to provide heat at approximately the same point in time (typically morning and evenings) and so the potential exists for the increased electrical load of the ASHPs to be part met by the micro-CHP. Without the micro CHP the authors found that a typical LV supply transformer suffered over load with only 15% of the dwellings equipped with a 2.3 kWe heat pump. However, with ICE micro-CHP (2-4.7 kWe) installed in 25% of the houses the other 75% could support heat pumps without overloading the transformer.

Brandoni et al [29] look at both the use of heat pumps and electric vehicles to balance supply and demand in a microgrid along with micro-CHP. The authors point out that the potential for deployment of heat pumps is limited as the CHP is meeting much of the heat or cooling load. The deployment of EV's is preferred as there is no overlap with regards to the provision of heating. The wider impact of EV's is discussed later.

# 5 Microgeneration and Future Networks

Whilst the previous section demonstrated that microgeneration could be ‘accommodated’ in existing networks, there are emerging models of future, more distributed power systems that attempt to best utilise microgeneration with regards to primary fuel savings and improving security of supply. In these future more distributed electricity networks the burden of providing system support services such as frequency control falls more heavily on  microgeneration and demand [30]; this required the co-ordinated action of a large number of devices acting as so-called ‘virual power plant’ (VPP). The co-ordination of a large number of smaller generators in order to maintain supply demand balance, voltage quality and a secure supply is an immense control challenge, requiring new paradigms of electrical systems control. However there are also potential benefits including a reduction in the requirement of inefficient, central ‘spinning reserve’, i.e. large thermal generators energised and synchronized with the grid, but not producing power, which are required to deal with unexpected disturbances in the electricity network [30].

Many different visions exist as to how a population of micro generators could co-operate most effectively within a future power system.

## 5.1 Smart Grids and Virtual Power Plant

The most widely researched future network concept that is compatible with the co-ordinated operation of microgeneration, distributed storage and demand management (together often referred to as distributed energy resources) is the ‘smart grid’. Many similar definitions of a smart grid abound. For example, The European Technology Platform [31] define a smart grid as:

*“A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.”*

Steck [32] investigates the VPP concept and demonstrates the ability of micro-CHP (along with thermal storage and back-up boilers) to participate in an electricity market using a variable price signal. The control of the CHP includes day-ahead scheduling and use of the device to provide frequency support. The author’s study indicated that this combination of control and service provision provided the greatest level of revenue, at the expense of slightly increased fuel use in the CHP.

In a further study Steck [33] analyses the performance of a linked pool of micro-CHP devices and their performance in providing network services, particularly network balancing (using a variable electricity price). Again this study indicates that CHP can operate (with thermal storage and back up heating) both to cover heat demands and provide grid services. For the population of CHP devices, the difference in total operating time between basic heat load tracking control and the provision of balancing power is less than 10% in the simulated cases, where the demand is provided by a number of non-domestic loads.

Zapata et al [34,35] and Donceel and Van Engeland [36] study three different strategies for operating micro-cogeneration devices (micro-CHP) in a virtual power plant (VPP). The first strategy analyzes the case where the micro-CHP and a photovoltaic system supply two households in order to increase self-consumptions of electricity by aggregating them in a VPP. Three different scenarios are analyzed. In the reference scenario (NO VPP) both dwellings produce their electricity independently. In the second and third scenarios the dwellings are aggregated in a VPP. The major difference of the latter is that in the second scenario (50% PV) the PV installation generates 50% of the total annual electric consumption of the house, whereas in the third scenario (100% PV) it produces 100% of its annually integrated consumption. The study also compares the performance of two different internal combustion engines cogeneration devices – one with on/off regulation and a second machine able to modulate. The results show that using the VPP arrangement the local use of generated electricity increases largely. Finally, the total operational cost for all scenarios is calculated. All VPP scenarios give better results than working in an individual approach. Additionally, the use of micro-CHP that is able to modulated gives more economical advantages.

The second strategy [34] aims to reduce the physical imbalance of a VPP integrated by several CHP and PV installations. The VPP operator bids electricity to the day-ahead market using the forecast for solar irradiation. In real time, the imbalance due to deviations between the forecast delivered and the real output has to be settled in the balancing market. Thus, in order to compensate for these errors, the operation of the CHP is rescheduled.

In the third strategy Donceel and Van Engeland [36] study the possibility to integrate micro–CHP in the Belgian balancing market. For this aim a small aggregator consisting of 13 MCHP is simulated. The imbalance reduction methodology assumes that the CHP aggregator is part of a Balance Responsible Party (BRP). By rescheduling its production, it tries to reduce the imbalance cost of the BRP. The model makes use of a two stage linear programming. In the first stage, a day-ahead (DA) schedule is optimized in order to submit the bids on the spot market. In the second stage, the optimization performs imbalance reduction.

The 'cell' concept (described by Anderson et al [37]), is an extension of the concept of the smart grid, in which an energy network is compartmentalized into cells, each of which includes a variety of distributed energy resources (DER) and is capable of internal and external actions. Internal actions could include voltage and load management. An example of an external action would be co-operation between cells of system frequency. The cell concept was developed in an attempt to reduce the control complexity faced in a future energy system featuring microgeneration, energy storage and demand side management (DSM). The authors expand the principle of the cell to encompass multiple energy streams and sources a so-called 'energy hub' (e.g. [38]).

The concept of 'energy-hubs' as the linkage points between co-located, distributed energy networks is explored by Carbone et al [39, Fig. 9], where the authors attempt to optimize the energy flows in a multi-carrier networks against a large number of objectives including demand-supply matching, provision of network support and minimization of cost.

Sasaki and Wada [40] describe the operation of a demonstrator smart energy network, comprising both a 'smart-grid' and a co-located heat and cooling distribution network. The network was constructed between three office buildings a nursing home and a smart-house demonstrator building. The demand of this collection of buildings comprised cooling (offices), space heating and hot water (all buildings) and electricity (all buildings). To meet this demand a heterogeneous collection of microgeneration technologies was employed including PV, solar thermal collectors, small scale CHP, reversible heat pumps and absorption chillers, along with back up chilling and heating (supplied from the gas and electricity networks). The authors describe the testing of a heat and power dispatching controller, which prioritized renewable and low-carbon resources first. The system was tested over and the demonstration results compared to the provision of heat, cooling and power separately. The authors demonstrate that the integrated energy network reduces carbon emissions by over 25% compared to conventional alternatives.

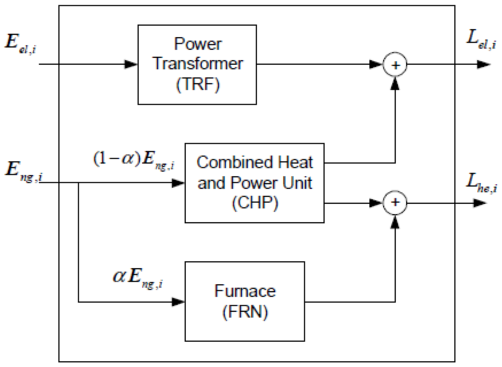

**Figure 9: an energy hub, with gas and electrical input streams and heat and power output [39]**

Angrisani et al [41,4] analyze a system consisting of a natural gas-fired micro-CHP unit, a heat storage and a peak boiler. The system provides thermal and electric energy to two end-users, the former is an office, where the generation system is located, and the latter is a residential building connected to the former through a district heating micro-grid. In order to analyze the influence of climatic conditions, two different geographical locations in Italy are considered, also characterized by different natural gas and electricity tariffs. In order to obtain more stable and continuous electric and thermal loads and to increase the operating hours per year of the micro-CHP unit, a load sharing approach is used. The operation of the micro-CHP is governed by a control system, aimed to optimize a thermo-economic objective function. The physical models representing the components, the thermo-economic objective function and the buildings have been implemented in a widely used commercial software ("TRNSYS") for whole building simulations. The models are calibrated and validated through data obtained from experimental tests carried out in the laboratory of the University of Sannio (Benevento, Southern Italy). The results of the simulations highlight the potential benefits of the thermal load sharing approach. In particular, this study shows that a MCHP unit connected by means of a thermal micro-grid to different users in "load sharing mode" can obtain a high number of operating hours as well as significant energy (Primary Energy Saving in the range 9.9-14.0%) and environmental (avoided $CO_2$ equivalent emissions in the range 17.9-25.2%) benefits with respect to an appropriate reference system, even in Mediterranean areas, where the climatic conditions are not always suitable for cogeneration.

## 5.2 Control and Communication Mechanisms

In order to co-ordinate the operation of micro-generation, storage and demand, considerably more information is required regarding the state of energy networks than is the case in conventional power systems, where frequency and bulk power flows are monitored, but typically little is known about the state of the low voltage network. Further, load data is typically available at very low resolution (i.e. monthly aggregate metering, [43]) with a chronic lack of data with regards to the temporal and spatial use of energy, particularly in the LV network.

### Smart Metering

Smart metering is being rolled-out across Europe driven by pan-national and national legislation (e.g. 2006/32/EC Energy Services Directive), initially as a means to substantially improve the availability of data on the performance of energy networks at the point of end-use. However, as Arpino et al [44] point out, the concept of smart meters includes bi-directional communications, with the smart meter being able to actuate local devices such as loads and microgeneration. The authors identify 4 uses for smart meters (some of which overlap): a) accounting, billing, and end-user management; b) performance monitoring; c) optimization and control of energetic systems; d) fault detection. Key to unlocking the potential of smart metering is the ability to transmit significant volumes of data to and from the meter. The authors also review a range of different communications protocols from wired systems through to Wi-Fi and discuss the pros and cons of each. However, one of the key messages to emerge from this and other papers is that whilst smart metering has the potential to provide an infinitely richer volume of data for use in the control and operation of future electricity networks, this in itself presents a significant challenge - the theory (and to an extent the technology) behind smart metering and smart grids is extant, however significant work still needs to be done in terms of handling, processing and (most importantly) acting upon the huge volumes of data that would emerge from a smart-grid-type system of any scale.

### Distributed Control

Ainsworth et al [45], describe the application of highly distributed, agent-based control to the load management in a low voltage network. With this approach different components within the power system (e.g. substations, appliances, microgeneration, etc.) become entities within a distributed control network capable of negotiation towards a single or multiple goals. The authors demonstrate the application of the approach in reducing peak demand within a simulated system featuring hundreds of dwellings.

Gräßle et al [46] investigate the use of a hierarchical observer-controller (OC) control architecture to control the operation of a buffered micro-CHP plant operating in a low-carbon home, which also features an electric vehicle. The micro-CHP, vehicle (battery), CHP thermal store and heat emitters in the building each have their own dedicated OC controller which collects local data and passes filtered information back to a high level OC controller. The high level controller operated the CHP and charging/discharging of the battery based on market price signals and user defined constraints, such as required temperatures within the dwelling, availability of hot water, etc. The author’s control approach also makes use of a forecast of the end-user’s likely heat and electricity demand over the following 24-hours. The authors simulate the performance of their controller against heat-led operation of the micro-CHP. Whilst the fuel use and operating time of the micro-CHP is similar in both cases, the OC controller achieved a near 50% reduction in imported electricity costs, mainly due to the vehicle battery discharging to cover electricity demand during periods of high electricity costs.

### Multi-objective Control

One of the many control challenges posed by the deployment of microgeneration is the requirement to satisfy the needs of the end user whilst providing a service to the electrical network. Allison and Murphy [47] explore the use of multiple-input, multiple-output control algorithms (MIMO), commonly used in the aerospace industry, to the problem of controlling a micro-CHP device plus thermal store with the objective of both maintaining thermal comfort in the building and minimising the use of electricity from the electrical network. The authors demonstrate that the technique can be successfully applied, but did not compare the performance of the MIMO controller against more conventional alternatives.

## 5.3 The Role of Storage in Future Networks

In the development and operation of smart grids, the integration of both thermal and electrical storage will be critical as it provides the capacity for heat-led microgeneration to operate flexibly in time, rather than responding instantaneously to local demand; this offers the potential for microgeneration to service both the local demand and also to operate in a manner that is beneficial to the local energy network. Gräßle et al [46], state that the combination of thermal and electrical storage with microgeneration greatly simplifies the 'problem' of operating microgeneration to meet local demands and the needs of the wider energy network. Additionally, coupling storage and microgeneration offers the potential for microgeneration prime mover size and cost reductions. The combination of microgeneration and storage technology is commonly termed 'distributed resources'.

### Thermal Storage

Thermal storage in microgeneration systems can take many forms. For example rock bed stores have sometimes been combined with solar thermal collection systems and the ground surrounding a building effectively becomes a heat store when reversible ground source heat pumps are used to heat and cool a building during summer and winter respectively [48]. However, the most common medium for thermal storage (for both cooling and heating systems) is water given its high heat capacity and density.

Thermal storage allows dispatchable technologies such as engine based micro-CHP and fuel cells to effectively decouple from the thermal demand of the local load that they serve – the thermal store (buffer) meets the thermal demand whilst the microgeneration has more freedom to interact with the electricity system (Figure 10). With renewable microgeneration such as solar thermal collectors, storage such as hot water tanks can reduce short term temporal fluctuations in resource.

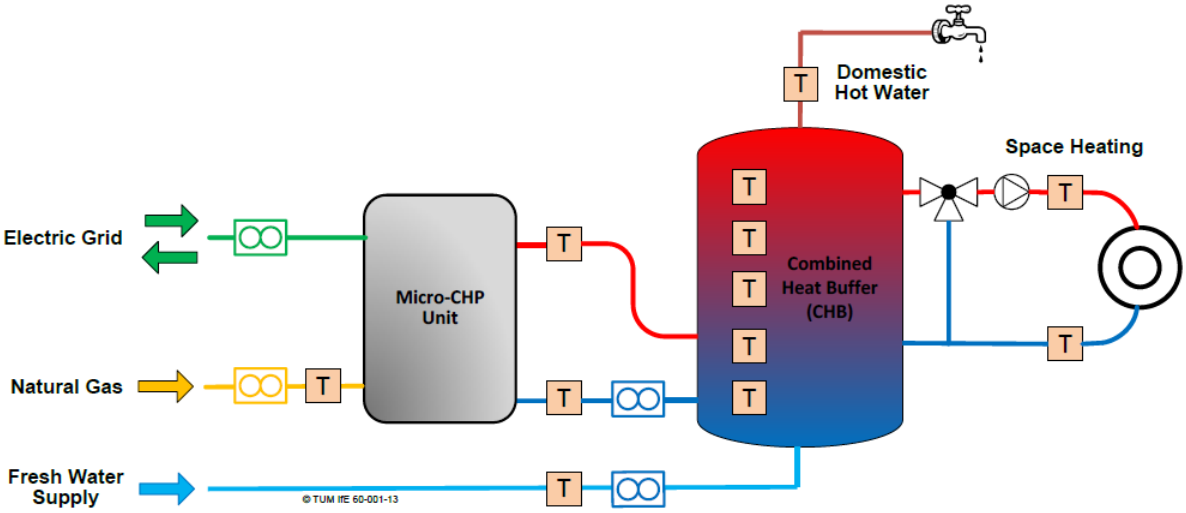

Figure 10: a micro-CHP device with a thermal store [49]

Buffering also offers opportunities with regards to reducing the size of microgeneration required to service a specific load. For example, consider the case of a micro-CHP system servicing a thermal load. Without buffering, then the micro-CHP device would need to be sized to cover all or part of the peak demand of the system. With a thermal store then the output of the store plus the micro-CHP device covers the thermal demand. The thermal store can be charged over time and consequently the size of the micro-CHP can be reduced as it does not have to cover an instantaneous peak heating demand.

Buffering has its disadvantages in that storage can use up valuable living space within a building and also introduces additional standing losses and costs, often causing deterioration in the performance of the microgeneration system (e.g. [26,27]).

As mentioned previously, Kato and Suzuki [19] combined heat pumps, water storage and PV in order to re-schedule the operation of the heat pumps in order to absorb surplus power from the PV.

Hong et al [50] and Kelly et al [26] investigated the use of hot water buffering tanks and buffering tanks enhanced with phase change material (PCM) to allow heat pumps to operate flexibly in order to meet a domestic demand, whilst avoiding peak demand on the electricity network. Hong et al [50] investigated both thermal storage sizing and the potential for flexible operation. Without thermal buffering, the operation of the heat pump could be delayed by up to 90 minutes before thermal comfort in the dwelling was affected and hot water temperatures became unacceptably low. Heat pump operation could be set back by up to 6 hours, but only if 500-700 L of thermal buffering was added and only if the insulation of the dwelling was improved to near-passive-house standards.

Kelly et al [26] examined the use of phase change material in thermal buffering (making use of the model developed by Padovan and Manzan [51]) for heat pumps in UK dwellings with average levels of insulation. The authors looked at both hot water storage and hot water storage augmented with variable numbers of phase change modules. Heat pump operation could be set back to off peak periods using a 1200 L tank, without affecting comfort temperatures in the dwelling and whilst still delivering acceptable hot water temperatures. A 500 L tank (with 50% of the volume comprising inorganic PCM) gave the same performance. The authors also noted that the combination of thermal storage with the heat pump significantly increased the energy consumption (in the worst case by over 50%), carbon emissions and running costs – this was due to the increased standing losses and deterioration in the coefficient of performance of the heat pump when used with a buffer tank. Rodgers et al [16] also noted that indirect heating with a heat pump resulted in a significant increase in energy use. Borg and Kelly [52] noted an energy penalty associated with cold water buffering when tri-generation was used to service the needs of a Maltese apartment block, again this was due to the addition of standing losses (in this case parasitic heat gains).

Lipp and Sanger [49] investigated the operation of a micro-CHP and integrated buffer/water storage tank test rig. Their study focused on the quantity of storage potential employed in flexible operation of the CHP unit during normal and set back operation – this indicated that less than 50% of the total storage capacity of the tank was used. One of the conclusions of the authors was that measurement of storage tank thermal charge needs to be improved to better utilize the available tank capacity.

## Electrical Storage

In a similar manner to thermal storage, a battery can temporally decouple the electrical output of the microgeneration system from the instantaneous electrical demand, for example exporting power to the electricity network when export prices were highest. Alternatively, the battery could be used in much the same way as a thermal buffer, assisting the microgeneration device to better follow the (electrical) demand and potentially allowing a smaller capacity device to be used at a higher and more efficient load factor.

Johnson et al [52], explore the use of a 150 Ah Lithium-ion battery along with a domestic, 1 kWe PEM fuel cell micro-CHP system operating with variable electricity (TOU) tariffs. The PEM device was coupled to the heating network via a thermal buffer. The authors simulate several cases, including where the fuel cell runs continuously to meet space heat and hot water loads, whist charging the battery and/or meeting the electrical demand. With the battery restricted to operate only at times of high electricity import, the total energy costs for the dwelling could be significantly reduced (depending upon the price paid for electricity exported to the network). The authors also examine the use of a battery on its own, charging at times of low electricity priced and discharging to the network at times of peak electricity demand. The authors conduct a basic financial analysis indicating that the losses associated with charging and discharging the battery outweigh any potential opportunities to take advantage of TOU electricity pricing.

Darcovich et al [53,54] explored the use of Lithium Ion batteries with a Stirling Engine cogenerator. The use of the battery allowed the Stirling unit to run continuously, rather than operating in start-stop mode. This would increase the efficiency of the battery and also reduced the variability of import/export with the local electricity network.

Darcovich et al [54] also analysed the sizing of batteries for use with both a 4.6 kWe micro-CHP and 2 kWe PV array when installed within a 132 $m^2$ Canadian detached residence. The authors looked at both the financial viability of battery use and also the physical impact on the battery of using it as and energy buffer. The authors conclude that a Lithium-ion battery size of around 6 kWh with a charge/discharge power of 2 kW provided a good match to the demand of the building and the

PV/micro-CHP combination. Interestingly, the authors also conclude that the operation of the CHP alone provided the best financial return. Whilst the addition of the PV and battery improved the financial return, this was at the expense of significant additional capital cost. Further, Darcovich et al [54] explored the effect of use on the lifespan of the battery. When the battery was used on its own to shift domestic power draws away from maximum time-of-use (TOU) prices, without microgeneration, the lifespan was projected to be approximately 30 years. When used aggressively to maximise the revenue from the micro-CHP plus PV system there was an increase of approximately 60% in battery cycling, which would significantly shorten battery life, but set against improved financial performance.

## 5.4 Electric Vehicles

Plug-in and Hybrid Electric vehicles (PHEV) pose a potential problem to future networks in that their widespread adoption could significantly increase domestic electrical demand, if vehicle charging was done at home. Possible consequences of extensive PHEV deployment could include low voltages and cable overloading in the LV networks.

Shao et al [55] look at the widespread deployment of both EVs and heat pumps within the Danish LV electricity network. In their analysis the authors look at power flows and voltages against different scenarios: when EV charging and heat pump operation against managed operation of EVs and heat pumps (with thermal stores). The author’s analysis shows that unconstrained operation of heat pumps and EVs results in both violations of power flow in LV supply lines and also in the voltage supplied to end users, with frequently unacceptable low voltages. These problems appear to be eliminated when the heat pumps are subject to congestion management and their operation is delayed at times of peak EV charging, however network power flows are still significantly increased.

Ribberink and Entchev [56] used detailed simulation to examine potential benefits from the combination of an electric vehicle, 2 kWe domestic CHP unit and thermal store when integrated into a Canadian detached dwelling. The authors examined the case of the CHP operating in heat-led mode against a number of scenarios of both EV use and electricity export tariff. The EV had a charge requirement of 26.5 kWh per 100 km. The authors conclude that the combination of the EV with the micro-CHP system increased the self-consumption of electricity and greatly reduced the volume of exports, they also identified that charging the vehicle after 10 pm provided the best financial return for the end user and best match to CHP operation.

Noda et al [57] looked at the mitigation of voltage drop associated with PHEV charging through smarter design of EV chargers and power interface technologies. Whilst real power is required from the network to charge the battery the EV charger interface could be employed to inject reactive power back into the network, thus minimizing the voltage drop as vehicle batteries are charged (Figure 11). The approach does have some potential drawbacks in that the current in the supply cables in increased compared to the case without voltage compensation, also the cost of the charger in increased due to the increased complexity if the charger’s power electronics.

However, PHEV could also be viewed as a potential resource, particularly considering that the average vehicle is stationary for 94% of the time. A PHEV can therefore be regarded as a domestic energy store, which has the potential to interact with the grid (e.g. ‘vehicle-to-grid’ operation) providing services such as voltage regulation. Used flexibly, EVs could improve the integration of microgeneration technology through for example absorption of surplus power or improving microgeneration load following characteristics.

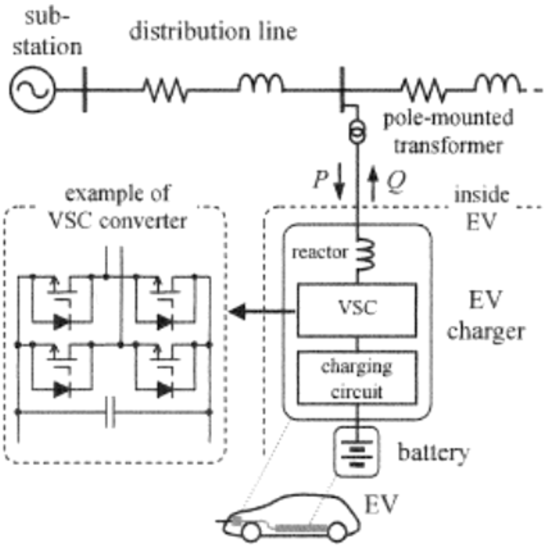

**Figure 11 Compensating for voltage drop due to EV charging [57]**

Gräßle et al [46] analysed the performance of a domestic energy management system (smart controller) which seeks to integrate both an electric vehicle and micro-CHP device. In their paper the EV can act both as a sink for surplus CHP-generated electricity and can also be discharged to help supply demand in the dwelling. The CHP unit features a thermal store so that its operation can be temporally decoupled from domestic heat demand. The performance of the domestic energy system is compared to conventional heat-led operation of the CHP device. The authors indicate that cost savings of over 40% are feasible if the CHP can be operated flexibly according to varying electricity tariffs and if the vehicle battery can be used to help cover the dwelling electrical demand.

Knapp et al [58] go beyond using just the battery of a plug-in hybrid electric vehicle (PHEV), but also look at the possibility of using the PHEV heat output for use in a dwelling. In their economic analysis the authors conclude that such an approach is financially feasible only in highly insulated houses with relatively low heating loads, mainly due to the high cost of vehicle fuel.

Brandoni et al [59] analysed the impact of micro-generation technology spread on sustainable communities, with the aim of identifying solutions for its minimization such as, for instance, the combination of micro-CHP systems with heat pumps, and the introduction of Electric Vehicles as electrical storages. The Sustainable Communities under analysis are located in Marche Region, in Central Italy and were characterised by a number of inhabitants lower than 100,000. Different scenarios have been built: i) the ‘2050 reference scenario’, deriving from not taking further policies in addition to those suggested by Sustainable Energy Action Plans; ii) the ‘potential’ scenario with a 50% $CO_2$ emission reduction target by 2050; iii) the ‘virtuous’ scenario with a 100% $CO_2$ emission reduction target by 2050, which is a 100% renewable energy scenario. Electric vehicles are, indeed, necessary to reduce transport sector emissions, shifting the energy needs from fossil fuels to renewable sources. Results show that the main reduction of the energy demand in different energy scenarios comes from the decrease in the transport sector, thanks to the introduction of EVs, which are characterized by a higher efficiency (5 km/kWh vs. 1.5 km/kWh), and in the thermal demand of dwellings, where it has been assumed to introduce combined heat and power production in addition to apply the thermal insulations to a higher share of existing buildings.

# 6 Conclusions

The aim of this report was threefold. First, the activities of ECBCS Annex 54 were to be set within the context of wider changed in energy networks, including new paradigms such as ‘smart grids’. Second, the report looked at the potential impact of microgeneration when employed piecemeal within existing energy networks, particularly on the electricity network and reviewed strategies to mitigate these impacts. Third the report looked ahead to the more cohesive integration of microgeneration into energy networks through the emergence of new energy supply and demand paradigms such as ‘smart grids’ – featuring many thousands of small generators and loads, and possibly multiple underpinning energy grids.

## 6.1 Microgeneration within the Context of Existing Networks

The growth of microgeneration in existing electricity networks has been patchy and highly country specific, with spectacular growth in PV in Europe (particularly Germany) and significant penetration of domestic micro-CHP in Japan. It was noted that the growth of microgeneration technologies connected into the electricity network at the low voltage level ran contrary to the evolution of power systems in the developed world for much of the 20th century – in which the focus was on the development of large generating stations providing power to many small loads – a ‘few-to-many’ model. Large-scale generation produces AC power at a near-fixed frequency and voltage over three-phases. In this model supply and demand are balanced through control of central generation and power is transmitted at high voltage and distributed down through the voltage levels. The emergence of microgeneration, generating at low voltages, diametrically opposed to this model and created potential problems for the smooth operation of a conventional power system. Microgeneration is by nature heterogeneous, featuring a range of technologies producing DC power, AC power (at various frequencies and over single or multiple phases). All of these technologies need to be interfaced, using power electronics, to the existing AC infrastructure.

The operation of microgeneration was viewed within the context of ‘dispatchability’, i.e. the ability of a device to be switched on or off or modulate its output according to requirements. It was noted that the emergence of large quantities of renewable technologies such as PV and small wind turbines reduces the ability of generation to accommodate demand and places more of an emphasis for control on the demand for energy. Conversely, the deployment of nominally dispatchable technologies such as micro-CHP offers opportunity with regards to the provision of support to the electricity network with regards to supply demand balancing.

The concept of ‘dispatchability’ for microgeneration is less clear cut than for central generation in that microgeneration’s primary responsibility is to the local load it serves; the provision of network support can be viewed as a secondary priority.

## 6.2 Microgeneration Impacts and Mitigation

Three primary impacts were identified with regards to microgeneration in an electricity network: 1) alteration of power flows; 2) impact on voltage and 3) impact on power quality. Focusing on power flows, the appearance of significant microgeneration has the potential to bring about reversed flow of power at lower voltage levels, with power flowing upwards from lower voltage levels. Whilst there is nothing intrinsically wrong with reversed power flows, it can pose challenges for the operation of conventional power systems that were designed for mono-directional flow. Several strategies were reviewed to mitigate the reverse power flows including shifting demand to absorb surplus power and mixing micro-generation technologies such that one would absorb the generation of the other (e.g. heat pumps and micro-CHP, or electric vehicles and micro-CHP). It was also noted that reverse power flows were seen to occur only at relatively high penetration levels approaching 100% (e.g. [20]).

Voltage levels in a power system can be influenced by microgeneration, with voltage rising as power is injected into the LV network and falling with increased load. PV and micro-CHP have the potential to bring about a voltage rise, whilst the increased uptake of heat pumps (and EVs) has the potential to bring about unacceptably low voltages. Various mitigation strategies were identified including the use of the power electronic interfaces to compensate for voltage drops and the co-location and synchronization of power consuming and producing technologies to reduce the interaction of microgeneration with the network. Problems with voltage were seen to occur only at relatively low penetration levels (e.g. [15]).

The quality of power delivered has the potential to be affected through the need for power electronic interfaces to micro-generators. Lower quality interfaces typically deliver a distorted (i.e. non-sinusoidal) current and voltage waveform into the LV network. However, it was apparent that the distortion caused by microgeneration was significantly less than that caused by non-linear loads such as lighting reflecting distorted voltage waveforms back into the LV network (e.g. [23]).

## 6.3 Microgeneration and Future Networks

Rather than piecemeal deployment and mitigation of microgeneration impacts, a more coherent approach would be the development of specific energy deliver networks, developed to accommodate heterogeneous generation sources - a smart grid being a means to integrate generation, demand and other resources (such as energy storage) in order to deliver sustainable and secure energy supplies.

Future network featuring large numbers of generation sources, potentially linked to demand management and storage required sophisticated control base of a far richer variety of operational data than is seen in today's power systems. The use of smart metering to provide this data was reviewed by Arpino et al [44] along with the means to large volumes of data between devices. Many different control strategies were in evidence with regards to the operation of smart grid type structures including centralized price-based control and more distributed control. The fundamental dichotomy between the local and networks demands on microgeneration were explored through the use of MIMO and the application of thermal storage to decouple local and network requirements.

McKenna et al's [25] review of load management indicated that as yet there is little evidence that manipulation of conventional domestic loads can provide significant flexibility in demand. Other authors demonstrate the potential for electrical load flexibility, but only in technologies that in themselves significantly increase load (e.g [50]).

Energy storage (both thermal and electrical) was seen to be a critical element in the effective deployment of microgeneration and is an element that runs throughout this report. Thermal storage is variously used to improve the performance of microgeneration technologies such as micro-CHP through the reduction of cycling and can also be deployed to reduce the size of micro-generation needed to match a specific load. Storage can be a means to integrate heterogeneous heat sources (i.e. operating at different temperatures). Further, for technologies such as micro-CHP and heat pumps, thermal storage can decouple the demand for heat and the generation or demand for electricity respectively allowing these technologies to be operated for the benefit of the electricity network whilst still meeting the needs of the end user in terms of hot water and space heating. It was noted however in many instances that thermal storage imposes a significant energy penalty in that it introduces additional losses to an energy system.

Electrical storage (i.e. batteries) also acts to improve the operation of microgeneration in that it can be used to absorb surplus generation from PV and microgeneration and then inject power into the LV network as need demands. Again it was noted that the addition of battery storage to a power system will introduce additional losses. EVs (featuring on-board batteries) were variously used to absorb surplus power from microgeneration and also to operate in support of the electrical network, although EVs unlike static batteries have the potential to impose a very significant additional load on the electricity network whilst charging.

Fundamentally, storage is required to provide the flexibility in the operation of microgeneration technologies so to enable them to actively participate in the operation of future advanced energy networks.

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# Background Information

## International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) in order to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 28 IEA-participating countries, as well as to increase energy security through energy research, development, and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

## The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates research and development in a number of areas related to energy. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, achieving this through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy-efficient technologies. The R&D strategies apply to residential, commercial, office buildings, and community systems, and will impact the building industry in five focus areas for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

## The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects but also identifies new strategic areas in which collaborative efforts may be beneficial. As the programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

| | |
|---|---|
| Annex 1: | Load Energy Determination of Buildings (*) |

Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)

Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings
Annex 60: New Generation Computational Tools for Building & Community Energy Systems Based on the Modelica & Functional Mockup Unit Standards
Annex 61: Development & Demonstration of Financial & Technical Concepts for Deep Energy Retrofits of Government / Public Buildings & Building Clusters
Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles
Annex 65: Long-Term Performance of Super-Insulation in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behaviour in Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

(*) – Completed

# Annex 54

The **Annex 54 “Integration of Micro-Generation and Related Energy Technologies in Buildings”** undertook an in depth analysis of micro-generation and associated other energy technologies.

## Scope of activities

- multi-source micro-cogeneration systems, polygeneration systems (i.e. integrated heating / cooling / power generation systems) and renewable hybrid systems;
- the integration of micro-generation, energy storage and demand side management technologies at a local level (integrated systems);
- customised and optimum control strategies for integrated systems;
- the analysis of integrated and hybrid systems performance when serving single and multiple residences along with small commercial premises; and
- the analysis of the wider impact of micro-generation on the power distribution system. To broaden the impact of the Annex’s output there will be significant effort to disseminate its deliverables to non-technical stakeholders working in related areas such as housing, product commercialisation and regulatory development.

## Outcomes

- An update on occupant related DHW and electric load profiles.
- Component models and their implementation in building simulation tools.
- Review of best practice in the operation and control of integrated micro-generation systems.
- Predictive control algorithms to maximize the performance and value of micro-generation.
- Experimental data sets for the calibration and validation of device models.
- Performance assessment methodologies.
- Country-specific studies on the performance of a range of micro-generation systems.
- Studies of the viability of micro-generation systems in different operational contexts and of the impacts of micro-generation on the wider community and the potential benefits, in particular for the electricity network.
- An investigation of interactions between technical performance and comercialization/ regulatory approaches for micro-generation.
- Compilation of case studies of the introduction of microgeneration technologies.

Annex 54 was built upon the results of Annex 42 "The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems".

To accomplish its objectives Annex 54 conducted research and development in the framework of the following three Subtasks:

### Subtask A - Technical Development

The subtask contains a broad range of activities related to models and load profiles development, data collection and micro-generation systems predictive controls development and optimization.

### Subtask B - Performance Assessment

The subtask uses simulations to develop an extensive library of performance studies and synthesis techniques to identify generic performance trends and “rules of thumb” regarding the appropriate deployment of micro-generation technologies.

### Subtask C - Technically Robust Mechanisms for Diffusion

The subtask contains work related to the interaction between technical performance, economic instruments and commercialization strategies and provision of this information to the relevant decision makers. Given the importance of micro-generation in meeting many countries’ climate change targets the subtask assesses the ability of micro-generation to enter the market and deliver on national and international energy policy objectives.

## Research Partners of Annex 54

| | |
|---|---|
| Belgium | Catholic University of Leuven |
| Canada | Natural Resources Canada |
| | National Research Council |
| | Carleton University |
| Denmark | Dantherm Power A/S |
| Germany | Research Center for Energy Economics (FfE) |
| | Technische Universität München (TUM) |
| | University of Applied Science of Cologne |
| Italy | Università degli Studi del Sannio |
| | Seconda Università di Napoli (SUN) |
| | National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) |
| | Università Politecnica delle Marche |
| Japan | Tokyo University of Agriculture and Technology |
| | Osaka University |
| | Nagoya University |
| | Tokyo Gas |
| | Osaka Gas |
| | Toho Gas |
| | Saibu Gas |
| | Mitsubishi Heavy Industry Ltd |
| | Yanmar Energy Systems Ltd |
| Korea | Korean Institute for Energy Research (KIER) |
| Netherlands | Technische Universiteit Eindhoven (TU/E) |
| United Kingdom | University of Strathclyde, Scotland |
| | Imperial College London, England |
| | University of Bath, England |
| United States | National Institute for Standards and Technology (NIST) |