



Energy in Buildings and  
Communities Programme

# Integration of Microgeneration and Related Technologies in Building

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**Energy in Buildings and Communities Programme**

**October 2014**

**Final Report of Annex 54**

Edited by

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On behalf of IEA EBC Annex 54



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## **Final Report of Annex 54**

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Evgueniy Entchev, Peter Tzscheutschler (Operating Agents)



# Table of Contents

<b>Executive Summary</b> .....	<b>9</b>
<b>1 Introduction</b> .....	<b>11</b>
1.1 Focus of Annex 54 .....	11
1.2 Structure of Annex .....	12
<b>2 Micro-Generation Technologies and Systems</b> .....	<b>15</b>
2.1 Combined-Heat-and-Power (CHP) Systems .....	15
2.1.1 Internal Combustion Engine .....	15
2.1.2 Stirling Engine .....	16
2.1.3 Fuel Cell .....	18
2.2 Renewable Power and Poly Generation.....	19
2.2.1 Photovoltaic (PV) .....	19
2.2.2 Heat Pumps .....	21
2.2.3 Batteries as Residential Electricity Storage .....	24
2.2.4 Thermal Storage .....	25
2.2.5 Chiller.....	27
<b>3 System Modelling and Demand Profiles</b> .....	<b>29</b>
3.1 Demand Profiles .....	30
3.2 Models for CHP units .....	32
3.2.1 Calibration and Validation of AISIN SEIKI ICE micro-CHP unit .....	33
3.2.2 PEM Fuel Cell Model Calibration Using Multiple Regression Method.....	34
3.3 Models of System Components .....	37
3.4 Modelling of complete systems .....	37
3.4.1 System Model with Internal Combustion Engine implemented in TRNSYS.....	38
3.4.2 System Model with Internal Combustion Engine implemented in Matlab/Simulink .....	41
3.5 Optimization Tool Using a Unit Commitment Approach .....	43
<b>4 Performance Assessment</b> .....	<b>47</b>
4.1 Methodology .....	47
4.2 Test Procedures.....	53
4.3 Review on National Studies.....	55
4.3.1 Country-Specific Simulations, Experimental and Field Test Studies based on CHP systems.....	55
4.3.2 Country Specific Simulations, Experimental and Field Test Studies based on CCHP systems .....	62
<b>5 Drivers of Commercialization and Support Mechanisms</b> .....	<b>71</b>
5.1 Landscape of Support Mechanisms .....	72
5.1.1 Feed-In Tariffs for Microgeneration .....	72

5.1.2	Grants .....	75
5.1.3	Building Regulations .....	76
5.1.4	Regulation for Smarter Energy Systems .....	76
5.1.5	Summary of Support Mechanisms .....	77
5.2	Micro-generation Economics with Support Mechanisms .....	78
5.2.1	Economic Performance Assessment with Support Mechanisms .....	78
5.2.2	Economic Performance with Support Mechanisms .....	78
5.2.3	Advanced Performance Assessment with Support Mechanisms .....	81
<b>6</b>	<b>Summary, Conclusion and Outlook.....</b>	<b>83</b>
6.1	Summary .....	83
6.2	Conclusions .....	84
6.3	Outlook to Possible Future Work.....	86
	<b>Abbreviations.....</b>	<b>89</b>
	<b>References .....</b>	<b>91</b>
	<b>Image Sources .....</b>	<b>96</b>
	<b>Background Information .....</b>	<b>97</b>



## Executive Summary

Micro-generation is a novel method for producing heat and power on site and near the end-user with high reliability, efficiency, and security of energy supply. The variety of micro-generation technology choices and applications is strongly dependent on a building's electric and thermal load profiles. Building integration of micro-generation systems is challenging because the loads are small and stochastic in nature, and the diversity is high. Given the rapidly increasing numbers of micro-cogeneration installations around the world, there is a pressing need for knowledge to enable informed choices to be made on where and when the installation of micro-cogeneration systems is appropriate. To properly integrate these systems in buildings, a significant number of operational and design issues must be investigated and resolved.

This report contains the research findings of Annex 54 of the International Energy Agency's Energy in Building and Communities Programme (IEA EBC), which was established in 2009 to further develop simulation models and performance assessment techniques affecting the integration and future penetration of micro-generation systems in buildings. The Annex 54 research encompasses the broad range of end-uses of micro-generation and the systems within it that might be deployed. The work reflects the state-of-the-art and future performance in micro-generation, including integration with energy storage and demand-side management technologies (e.g. responsive loads or dynamic demand control), virtual utility, and smart energy networks. Finally, given the ubiquitous nature of this technology and its broad societal impact, the research results are accessible to a broad audience including engineers, policy makers, and businesses.

Annex 54 successfully developed models of micro-generation units and system components, and implemented them into performance simulation platforms for state of the art buildings. A huge amount of country-specific data has been collected from laboratory and field testing, and has been used to determine demand-side profiles and to gain knowledge on micro-generation system integration and performance under variety of real life operating conditions.

The country-specific synthesis analysis performed by Annex 54 revealed generic performance trends and "rules of thumb" for the appropriate deployment of micro-generation technologies. The developed assessment methodology established common reference points for performance comparison, assessment methodology, and metrics, as

well as for the identification of generic not country-specific factors affecting the viability of micro-generation systems and their appropriate deployment in buildings and communities.

A selection of the range of support mechanisms to incentivize the adoption of micro-generation technology has been analysed. It is recognized that the supporting schemes can change quickly and, as such, the country-specific incentives and grants have been examined over the life time of the Annex. As such, the report provides a snapshot of feed-in tariffs, grants, building regulations, and the role of micro-generation and associated technologies in smarter energy systems.

# 1 Introduction

Annex 54 of the International Energy Agency's Energy in Buildings and Communities Programme (IEA/EBC) was established in 2009 to examine the "Integration of Microgeneration and Related Technologies in Buildings". The Annex was organized as a task-shared collaborative research project involving 29 organizations from ten countries. The combined on-site generation of electricity, heating, and cooling energy is an emerging technology with significant potential to deliver energy efficiency, as well as environmental benefits, through reduced primary energy (PE) consumption and lower greenhouse gas (GHG) emissions.

## Background

The starting point of Annex 54 was the work performed within IEA/ECBCS Annex 42 [1-1]. This Annex focused on the modelling of fuel cells and other micro-cogeneration systems. Some of the major outcomes included: hot water and electrical load data for use in modelling studies; calibrated models of fuel cell, internal combustion (IC) engine and Stirling engine (SE) devices; experimental protocols for the testing of devices; and empirical validation datasets and country-specific performance studies on residential micro-cogeneration systems.

Given the rapidly increasing number of micro-cogeneration installations around the world, there was a pressing need to conduct further research to enable informed choices to be made on where and when the installation of a micro-cogeneration system is appropriate. The research of the proposed follow-on Annex 54 should encompass the broad range of end-uses for micro-generation, and the systems within which it could be deployed. Furthermore, the work should properly reflect the state-of-the-art and future performance in micro-generation, including integration with energy storage and demand-side management technologies (e.g. responsive loads or dynamic demand control). Finally, given the (potentially) ubiquitous nature of this technology and its broad societal impact, the research results from the Annex should be accessible to a broad audience including engineers, policy makers, and businesses.

## 1.1 Focus of Annex 54

The focus of Annex 54 has been shifted from model development and experimentation (Annex 42) towards a more expansive analysis of micro-cogeneration and associated technologies. The scope of activities encompasses multi-source micro-cogeneration systems, polygeneration systems, and renewable hybrid systems and their integration in supply objects. Additionally, components as energy storage systems and advanced control systems are included, as well as demand-side management technologies.

Performance of integrated systems is analysed, as well as the wider effects of micro-generation on low-voltage power distribution systems.

The work focuses mainly on the simulation of numerical models of integrated micro-generation systems. The data were derived from laboratory experiments and field testing services to calibrate

models and derive load profiles. The results are performance studies into the efficiencies, economics, and environmental impact, in terms of primary energy consumption and CO<sub>2</sub>-emissions, of micro-generation technologies.

Additionally, diffusion strategies for the mass deployment of micro-generation-related technologies are examined; this activity encompasses a regulatory and market review, along with data emerging from the technical analysis.

### 1.2 Structure of Annex

To accomplish the aforementioned, the three subtasks have been defined to organize the work of Annex 54, as illustrated in Fig. 1-1:

#### Subtask A: Technical Development

Subtask A undertakes the model development and data collection activities that underpin the work of Subtasks B and C, with the emphasis on the optimized operation of micro-generation systems. This requires the development of models of contemporary micro-generation devices and controllers to maximize the energy performance for local, and possibly community, energy needs in different operational scenarios.

This work also involves the specification of boundary conditions for the modelling of micro-generation, especially the establishment of appropriate hot water and electrical demand profiles.

#### Subtask B: Performance Assessment

Subtask B uses simulation as a means to develop an extensive library of performance studies covering different technology types and combinations, including the performance in different countries and with different end-users. The simulation work initially focusses on improving/optimizing the performance of basic but realistic micro-generation system configurations in a limited set of operational contexts. Subsequent work features a wider range of system components (such as electrical storage technologies), system functions, and end-users.

A synthesis analysis is undertaken with a view to identifying generic performance trends and “rules of thumb” regarding the appropriate deployment of micro-generation technologies. This requires the establishment of common reference points for the comparison of performance, requiring agreement on a common assessment methodology and metrics, and the identification of generic demand and supply technology characteristics.

The Subtask will focus on the applications of micro-generation in individual residences, multi-residences, and small commercial buildings. However, the scope of the work also encompasses mobile energy systems such as Plug-in Hybrid Electric Vehicles (PHEV) and more conventional EVs, as well as demand-side management through other appliances.

### Subtask C: Technically Robust Mechanisms for Diffusion

Micro-generation is an emerging class of technologies, and, as such, is only partially or poorly understood in terms of market introduction. For example, early models of micro-generation support in the residential sector are closely tied with energy efficiency; however, important technical and economic tensions/synergies exist between these interventions. Given interactions such as these, there is a risk that commercialization and support strategies devised by decision makers will lead to underperforming installations. To reduce this risk, decision makers require unbiased information regarding the interaction between the technical performance of micro-generation and the mechanisms for the diffusion of these systems.

Given the importance attributed to micro-generation in meeting many countries' climate change targets (i.e. requiring substantial penetration), Subtask C will draw upon micro-scale technical analysis to assess the ability of micro-generation to enter the market, and to deliver on national and international energy policy objectives.

The Subtask begins with an analysis of the technical implications of current regulatory approaches supporting the deployment of micro-generation in OECD countries. Following on from this, case studies of micro-generation commercialization in a variety of OECD countries are developed, drawing on performance assessments emerging from Subtask B. The aforementioned tasks are undertaken with a view to identify the key characteristics of the interactions between technical performance, economic instruments, and commercialization strategies for micro-generation.

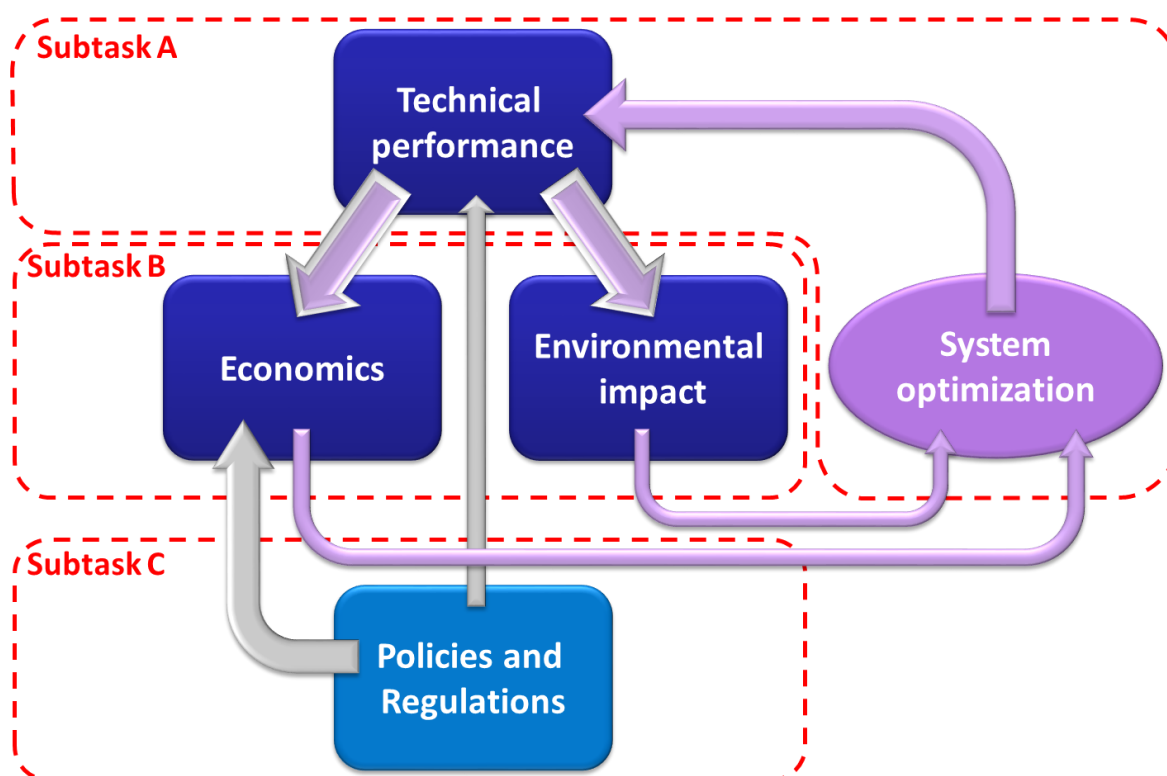


Figure 1-1: Structure of Annex 54.



## 2 Micro-Generation Technologies and Systems

This chapter delivers a short overview of the micro-generation equipment, also including a balance of plant components, investigated during Annex 54.

### 2.1 Combined-Heat-and-Power (CHP) Systems

#### 2.1.1 Internal Combustion Engine

The internal combustion engine (ICE), well known from car engines, is presently the most mature technology available for micro-CHP applications on the market because it achieves high thermal efficiency, reduction of noise and vibrations, low maintenance and long life service, while requiring a small installation space.

More specifically, these engines occupy small installation spaces, have high mechanical (25–35%) and thermal (50–65%) efficiencies, produce low noise (<60 dB(A) at 1 m) and vibrations, require little maintenance (one change of spark plugs and oil a year, corresponding to about 4000 h), and have a long life service (40,000–60,000 h, corresponding to about 10 years). Finally, owing to lean burn, NOX emissions are less than 100 ppm with a stable shaft power output at a range of engine speeds between 1200 and 3000 rpm. These features make micro-CHP systems based on ICEs a valid and interesting application that is suitable, above all, for residential and light commercial users [2-1]. Consequently, a number of Reciprocating Internal Combustion (RIC) engine-based cogeneration systems, suitable for the residential sector, are currently available on the market [2-2].

Honda and Osaka Gas have developed the Ecowill model [2-3], presented in Fig. 2-1. This is a 1-kW electrical and 2.80-kW thermal output cogeneration unit, designed for use by a single family, that has



Figure 2-1: Honda MCHP



Figure 2-2: Aisin Seiki MCHP

an overall energy efficiency of 85%. In the period 2003–2009, approximately 86,000 units were sold

## 2 Micro-Generation Technologies and Systems

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in Japan. A new model was introduced to the North American market in 2006 that is capable of supplying 1.2 kW of electric power.

In February 2002, Tokyo Gas and Aisin (Toyota group) [2-4] launched an MCHP system in Japan that has also been available on the European market since 2006; the model is presented in Fig. 2-2. The model, based on a 3-cylinder, 952-cm<sup>3</sup> ICE, provides an electric output of 6 kW and 11.7 kW of thermal power, with a total efficiency, at full load, equal to 85%.

The German manufacturer [2-5] Senertec., which has presently installed more than 32,000 units in Europe, produces a cogeneration unit with 5.5-kW electric and 12.5-kW thermal power output called Dachs, illustrated in Fig. 2-3. This unit is based on a one-cylinder four-stroke ICE that has a displacement of 579 cm<sup>3</sup> and can be fuelled by natural gas, LPG, fuel oil, or biodiesel. The total efficiency at full load is approximately 90%.

Vaillant, with the Ecopower 4.7 module [2-6], produces an MCHP system, based on a Briggs & Stratton 5HP engine, which is fuelled by natural gas or propane. The MCHP system produces 4.7-kW electrical and 12.5-kW thermal outputs for an overall energy efficiency of up to 92%. The cogenerator can modulate the electric power between 2.0 and 4.7 kW<sub>el</sub>, the range of the corresponding thermal power is 6.0 to 12.5 kW<sub>th</sub>.

Within the power range of 4 kW<sub>el</sub> onwards, other manufacturers offer systems with comparable technical characteristics to the systems described above.



Figure 2-3: Senertec MCHP

### 2.1.2 Stirling Engine

The Stirling engine was invented by Robert Stirling in 1817. It operates through the cyclic expansion and compression of a gas caused by heating and cooling. Mechanical power is captured through the movement of a piston in a cylinder, comparable to other reciprocating engines. One advantage of the process is that, owing to the external combustion outside the cylinder, solid fuels such as wood can also be used as fuel.

In modern micro-CHP units, a fuel is used to heat the process (expansion of the gas). The heat recovered from the cooling site (compression of the gas) can then be used to supply heat to a building.



Aside from prototypes, some developments have been made in pilot manufacturing and wider applications in field tests:

- Solo Stirling (7.5 kW<sub>el</sub>, 22 kW<sub>th</sub>, operated with natural gas)
- Sunmachine (3.0 kW<sub>el</sub>, 10.5 kW<sub>th</sub>, operated with wooden pellets)
- WhisperGen (1.0 kW<sub>el</sub>, 7.5 kW<sub>th</sub>, operated with natural gas)
- Microgen Stirling (1.0 kW<sub>el</sub>, 6.0 kW<sub>th</sub>, operated with natural gas)

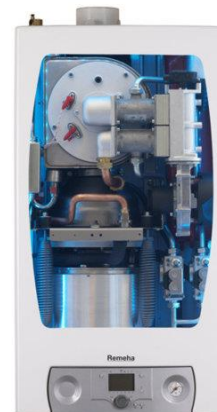
However, at present only one system, the SE produced by the Microgen Engine Corporation, is manufactured in larger quantities and is available on the market. This system is not sold directly to the final consumer but several European manufacturers of heating appliances have integrated this SE into their heating appliances, usually in combination with a condensing boiler.

Measurements made with the Solo systems demonstrated an electrical efficiency of approximately 25%. However, micro-CHP systems based on the Microgen SE have achieved electrical efficiencies of only 12–15%. In both cases, the overall efficiency, including the use of heat, is in the range of 90 to 94%.

Fig. 2-4 and 2-5 show two Stirling micro-CHP systems. Both contain a condensing boiler to service peaks in the heat demand and a control system. The left engine, produced by Senertec, also comprises a 530 l thermal storage.



**Figure 2-4: Stirling micro-CHP system  
Senertec Dachs Stirling**



**Figure 2-5: Stirling micro-CHP system  
Remeha eVita 28c**

### 2.1.3 Fuel Cell

Fuel cells offer the possibility of converting a fuel, usually hydrogen, directly into electricity by a catalytic electrochemical reaction. Heat is a by-product of this process that also can be used.

Two types of fuel cells have been proven to be suitable for cogeneration purposes:

- **Proton Exchange Membrane Fuel Cells (PEMFC):**  
This type of fuel cell uses pure hydrogen and oxygen from the air to generate electricity and heat using a polymer membrane, at temperature level of up to approximately 85°C, with electrical efficiency of approximately 35%. To convert natural gas into hydrogen, a reforming and purification process has to be implemented ahead of the fuel cell.
- **Solid Oxide Fuel Cells (SOFC):**  
SOFC usually utilize a ceramic material as electrolyte and are operated at temperatures typically above 650°C. This high temperature level can be used to develop an internal reforming of fuels, with hydrogen content in the form of natural gas. The electrical efficiency is in the range of approximately 50%.

This technology has reached the highest maturity in Japan. A fuel cell household cogeneration system, powered by natural gas and liquefied petroleum gas, was released in 2009 and has been sold under the Ene-Farm brand [2-7] to a total of 50,000 houses.

The Ene-Farm system generates power on-site to be used within the households; the resultant heat is effectively utilized for the domestic supply of hot water. Consequently, the energy utilization rate is approximately 86%. A learning function records the daily patterns of electricity and hot water use in the household; this allows the system to estimate and determine the best operation plan of when to start/stop the generation for maximum energy efficiency. In comparison with conventional power generation systems, the Ene-Farm system cuts primary energy consumption by approximately 37%, and CO<sub>2</sub> emissions are reduced by approximately 49%.

CALLUX is a field test being performed in Germany since 2008, with the goal of installing 500 fuel cell CHP systems in residential buildings. The target issues are to gain experience in operating fuel cell systems, increasing system reliability, and reducing maintenance costs. One particular focus is on data handling and communication with the fuel cell system. Consequently, the Callux-Box was developed, allowing a scheduled operation of the fuel cell systems [2-8].

A comparable project, conducted at the European level, is Ene.Field, which started in 2012, bringing together more than 50 partners from 12 countries. The aim is to install 1000 fuel-cell CHP units to stimulate cost reductions by transitioning to serial production. Policy mechanisms related to domestic micro-CHP will be analysed and commented on, and business models will be investigated. [2-9]



Figure 2-6: Panasonic Fuel Cell MCHP

## 2.2 Renewable Power and Poly Generation

### 2.2.1 Photovoltaic (PV)

Solar energy is presently the most abundant, inexhaustible, and cleanest of all the renewable energy resources. The power from sun, intercepted by the earth, is approximately  $1.8 \times 10^{11}$  MW, which is many times larger than the present rate of all energy consumption. A photovoltaic (PV) system is a device that converts solar energy into electricity directly, without any heat engine to interfere. Typical applications of PV systems in use today are for power sources, water pumping, for use in remote buildings, solar home systems, communications, satellites, and many more; the demand for PV systems is increasing every year. An example of PV application in a building is presented in Fig. 2-7.

PV modules have achieved mass production, with some 40 GW annual production capacity. A typical module has a peak power of 250 W with an efficiency of up to 19%. PV installations are counted in the millions and some installations have already reached capacities of more than  $100 \text{ MW}_p$ , with capacities of  $500 \text{ MW}_p$  being projected.



Figure 2-7: Building Integrated Photovoltaic System in Canada by Schletter and SkyFire with “turtle” roof shape [2-10]

PV applications can be classified into on-grid and off-grid applications:

1. **On-Grid Applications:**

The PV system feeds surplus electrical energy directly into the electricity supply grid. The benefits of this on-grid connected PV power generation are generally evaluated based on its potential to reduce costs for energy production and generator capacity, as well as its environmental benefits.

2. **Off-Grid Applications**

Currently, PV systems are most competitive at isolated sites, away from the electric grid that require relatively small amounts of power, typically less than 10kWp. In these off-grid applications, PV systems are frequently used in the charging of batteries, thus storing the electrical energy produced by the modules and providing the user with electrical energy on demand.

### Concentrating Photovoltaic (CPV) Systems

Most of photovoltaic panels are made of Si in mono-crystalline, poly-crystalline, or amorphous forms. Chemical composite materials (Ga, As, In) are used for very highly efficient solar cells. In order to achieve these high efficiencies of approximately 40%, multi-junction cell technology is employed [2-11]. Multi-junction cells consist of three or more layers of very thin solar cells, each of which absorbs solar irradiation at a different wave range.

Generally, multi-junction cells are installed in concentrating photovoltaic (CPV) systems, which have primary optics such as lenses or mirrors to concentrate solar irradiance onto the cells. Owing to multi-junction cells being very expensive to produce because of the advanced technology involved, it is advantageous that this concentration results in a reduction in the cell size. There are several types of lenses used in this concentration. Flat Fresnel lenses are used commonly in CPV systems. 3D-shaped lenses, for example dome shaped Fresnel lenses with the concentration ratio of 500 suns,

were developed for CPV modules in Japan. CPV modules have to be mounted on sun tracking devices with two axes in order to capture solar incident in a normal direction (Fig. 2-8). While flat PV modules can intake not only direct incident but also diffused radiation from the sun, CPV modules can only utilise direct incident radiation. Consequently, it can be said that CPV modules are suitable for areas with rich direct solar radiation. For example, CPV systems are already employed to supply electricity on a commercial basis in Arizona in the US.



Figure 2-8: CPV with dome shaped lenses

### Hybrid Solar Panels

Hybrid solar panels are designed for recovering thermal energy as well as producing electricity using one module. The efficiency of commonly used PV cells is approximately 10–15%, which implies that the rest of solar energy turns into heat. Hybrid solar panels work by collecting such heat to supply domestic hot water. Generally, these panels have a layered structure where PV cells are fixed on a metal plate to integrate the extraction of electricity and thermal energy from the same component. The heat generated in the cells is transferred to fluid flowing just behind the metal plate to produce hot water.

It is advantageous that one device can generate different types of energy at the same time, like co-generation. Considering that roof areas are a form of restricted resource in urban areas, it is attractive for hybrid solar panels to share solar collecting areas for both PV and solar water heating. Another beneficial point is that the heat recovery from the cells results in decreasing the temperature of the cells and, therefore, improves the efficiency of electricity generation. This technological development is currently ongoing.

### 2.2.2 Heat Pumps

Heat pumps (HPs) are widespread devices that are able to extract heat from a low-temperature source, making it available on a higher temperature level. The process is performed at the expense of

## 2 Micro-Generation Technologies and Systems

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mechanical or thermal energy. Different classifications are possible by taking into account different features:

- type of energy source (mechanical, electrical, thermal)
- low-temperature source (air, water, ground, waste heat)
- kind of service (heating, domestic hot water (DHW), combined)
- type of fluid (air, or water)

An electrically driven compression HP, the best known system, employs an inverse vapour compression cycle; this extracts thermal energy from the low temperature source by evaporating a fluid. Following this, the vapour is compressed and releases the absorbed heat in a condenser. Afterwards, the condensed liquid is expanded in a valve to restart the cycle.

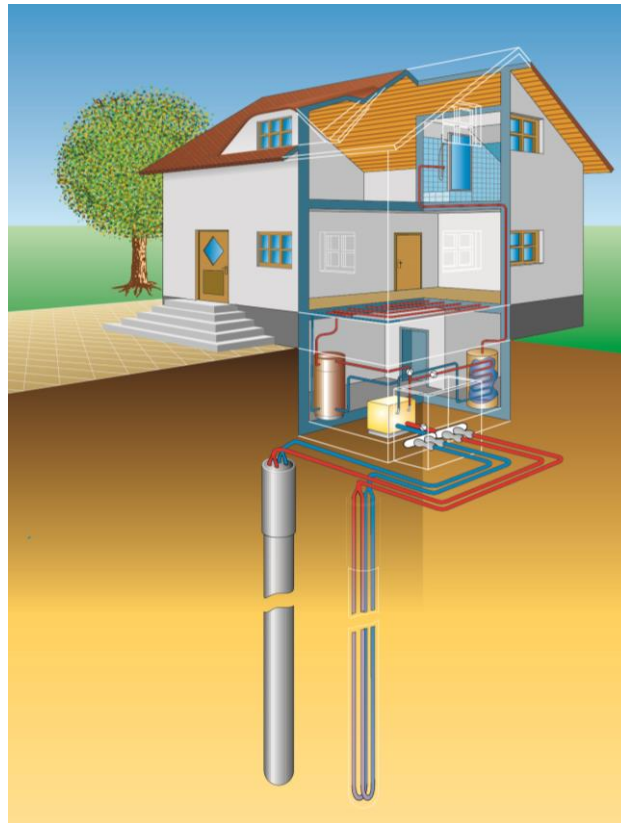
The efficiency of an electrically driven HP is given by the Coefficient of Performance (COP) and represents the ratio between the energy released to the high temperature source and the energy absorbed by the compressor. Depending on the temperature of the heat source and the heat supply, the COP is typically in the range of 3 to 5. As a HP consumes electricity, the effort required to generate the electricity has to be taken into account.

Absorption heat pumps (AHPs) use thermal energy to drive the process. The refrigerant is absorbed by an absorbing fluid; this forms a liquid solution. Heat provided to the generator separates the refrigerant, which evaporates and follows the same pattern of the vapour compression cycle, with condensation, expansion, and evaporation; however, instead of entering a condenser, the refrigerant is mixed with the absorbing fluid to start the process again. For HPs, the usual combination of refrigerant and absorbing fluid is ammonia and water, or water and lithium bromide.

Presently, AHPs are best suited to heating large buildings because heating capacity reaches a minimum of approximately 35 kW, which is usually higher than the capacity required for single dwelling. The COP for a gas driven AHPs is in the range of 1.5 to 2.0.

Common heat sources used are the external air and the ground:

- Air source heat pumps (ASHPs) extract thermal energy directly from external air and transfer it to internal ambient air (air-to-air HPs) or to a secondary fluid such as water (air-to-water HPs). The benefits of this arrangement are the low cost and easy installation, while the main drawback is the reduction of COP with low external temperatures, an additional problem occurs with frost formation occurring on the condenser.
- Ground source heat pumps (GSHPs) use the ground as a source, which is at a rather constant temperature. Therefore, the capacity of these systems is nearly constant and independent from the external air temperature. Additionally, the COP of a GSHP is constant and usually higher than that of the ASHP at low external temperatures. Heat can be extracted from the ground using horizontal or vertical tubes; Fig. 2-9 illustrates a possible solution for HP installation for heating and DHW production. The requirement of excavation or drilling for GSHPs represents the main drawback of the system, bringing a high initial cost.



**Figure 2-9: GSHP with vertical boreholes for heating and DHW**

HPs can be used for cooling purposes, too. The COP of GSHPs is higher than when using ASHPs. If the ground temperature is sufficiently low, the HP can be switched off, performing a free cooling of the conditioned spaces. Fig. 2-10 presents a GSHP with a free cooling unit



**Figure 2-10: A GSHP, centre, left connections with two boreholes with two tubes each, right the free cooling unit**

### 2.2.3 Batteries as Residential Electricity Storage

Battery energy storage (BES) is becoming relevant at the residential level when transient renewables are employed or with thermally led cogeneration systems that have a significant night time heat demand. A battery system for a single family home would typically include a battery pack with a capacity in the range of 4 to 8 kWh, capable of delivering up to 5 kW of power. In order to connect this battery to the household electrical system, as well as the external power grid, a DC to AC electrical inverter is required, along with a battery-management system in order to ensure safe and sustainable function of the battery pack. At present, there are a number of suitable battery types available, including the long-established and conventional lead-acid systems, batteries based on nickel-cadmium, nickel metal hydride, lithium ion, lithium polymer, sodium sulphur, vanadium redox, zinc bromine, or metal air compositions [2-12].

Depending on battery chemistry, the capital cost for equipment can range from \$65 to \$1560 per kWh, with roundtrip electrical efficiencies from 50 to approximately 95%, and service lifetimes ranging from only a few hundred cycles up to 10,000 cycles [2-12]. The characteristics of lithium ion batteries that make them highly suitable for electrical storage include very high energy density, good power output, good cycle life with a broad cycling range, high coulombic efficiencies, and comparatively low heat output [2-13]. For prolonged intensive use, such as a in a micro-cogeneration system, proper control and management of a lithium ion battery is crucial to ensure high capacity retention and safe operation. Lithium ion batteries at ratings of approximately 2 kW/6 kWh are of a size suitable for development for residential power supply and storage. It has been demonstrated that they can provide the consumer with economic benefit in a residential micro-generation context, as storing energy can reduce peak power demands. Benefits also apply to power utilities through offsetting costly infrastructure upgrades to the power grid [2-14]. Such a system, as illustrated in Fig. 2-11, was built with an integrated inverter and management electronics, at a prototype cost of approximately \$10,000.



Figure 2-11: Residential storage battery built by the Canadian manufacturer Electrovaya



High capital costs of residential batteries continue to be a concern. Studies have revealed that time shifting of grid power with batteries in time-of-use pricing environments is not a strategy that justifies the large capital expense [2-15]. Peak shaving can occur through widespread use of large residential batteries, but such a scenario would need to be led through the efforts of a coordinating utility, and has yet to be demonstrated. However, at present, some large-scale commercial BES systems have been built and installed [2-16]. At the current adoptive stage, progress towards economy of scale with batteries is occurring. The battery management electronics for smaller storage systems contribute to their current high cost, thus larger BES systems are more economically viable. Very recent initiatives, notably in Japan in response to the Fukushima crisis, are making residential batteries more of a commercial reality. Examples include the Honda Smart Home System [2-17], undergoing field trials in Saitama, which consists of CIGS thin-film solar panels, a home battery unit, a household gas-engine cogeneration unit, a hot water supply system, and control electronics. In November 2012, Toshiba [2-18] launched 6.6-kWh/3.0-kW “eneGoon” rapid-charge Li-ion residential batteries, claiming a 6000-cycle lifetime. US-based Power-One inverters and Japan’s Panasonic lithium ion batteries will be integrated into energy storage systems for the residential, commercial, and utility-scale, and grid-connected energy storage markets in 2013 [2-19]. Similarly, in summer 2013, Nichicon Corporation introduced an energy management system that combines a solar power generating system from partner Kyocera, with their long-lasting, high-capacity lithium-ion battery storage units [2-20]. Regulatory assistance in Germany to cover 30% of battery capital costs, in recognition of the value of combining residential battery storage to residential PV systems, was made available in late 2012 [2-21]. Related to this, it was reported that a 5.3-kW solar PV system could provide enough power for 24 hours of household demand, and a 10.6-kWh battery capacity would be suitable to discharge surplus power for use at night [2-22].

### 2.2.4 Thermal Storage

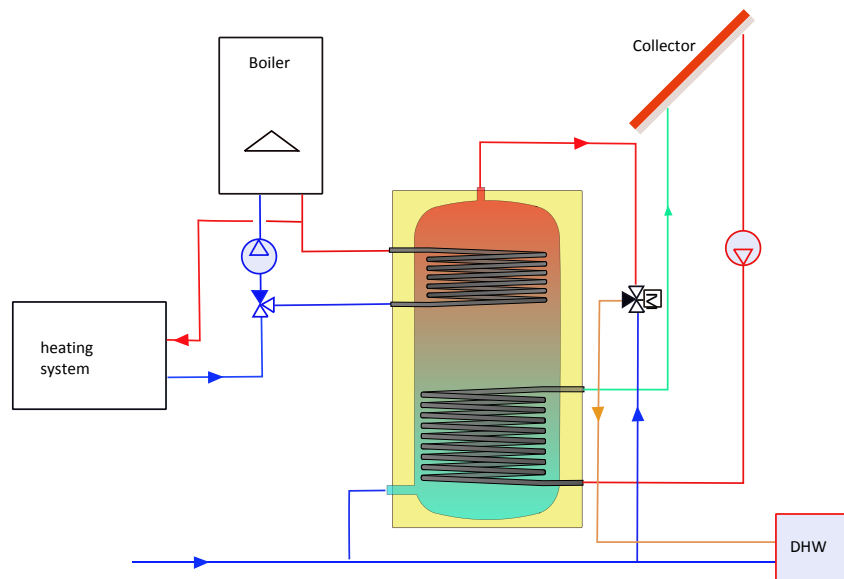
Thermal storage is a key component for thermal plants, which can be used in heating and cooling applications. The main purpose of thermal storage is to resolve the problem of the shift between energy demand and production, a typical problem encountered if renewable sources are used for energy production. Thermal energy storage can be of sensible or latent type, and various storage materials are employed. In heating plants, the dominant storage material used is water. The amount of energy that can be stored depends on the volume of the tank and the temperature difference between the outlet and return temperatures. Latent thermal storage using phase change materials (PCMs) can also be used to enhance the amount of stored energy. For cooling applications, ice storage is utilised, where ice slurry and ice-on-coil are the solutions employed.

#### Sensible storage systems

The typical storage medium in heating and cooling plants is water owing to its common availability, low cost, and the high specific heat content. A vertical cylinder tank is the most common solution adopted. Internal coils connected to thermal energy sources, such as boilers, cogenerator systems, or solar collectors can be used to heat the water in the tank. The number of heating coils usually varies between one and three. One may be used to charge the storage from a micro-CHP system, the

second coil can be used to integrate solar heat, while the third heat coil is used to heat domestic hot water.

Thermal storage in domestic plants is typically used for domestic hot water supplies. The stored water guarantees continuity of water service at a constant temperature. Thermal storage is also required in conjunction with solar collectors for collecting energy during sunny hours and to have hot water available when it is required. Fig. 2-12 represents a tank with two coils, the lower is usually connected to the solar collector, while the upper is connected to a boiler for backup heating. Multiple heat generators can be available so the tank can have additional coils; for example, the tank can be connected to a solar collector, and a wood boiler or a cogenerator.



**Figure 2-12: A tank with two heat exchangers for Solar Domestic Hot Water Systems**

Fig. 2-13 represents a tank-in-tank solution combining domestic hot water storage (inner tank) with a thermal storage for the heating system (outer tank). With this solution, a unique heat generator can provide energy to both the heating system and the domestic hot water system.

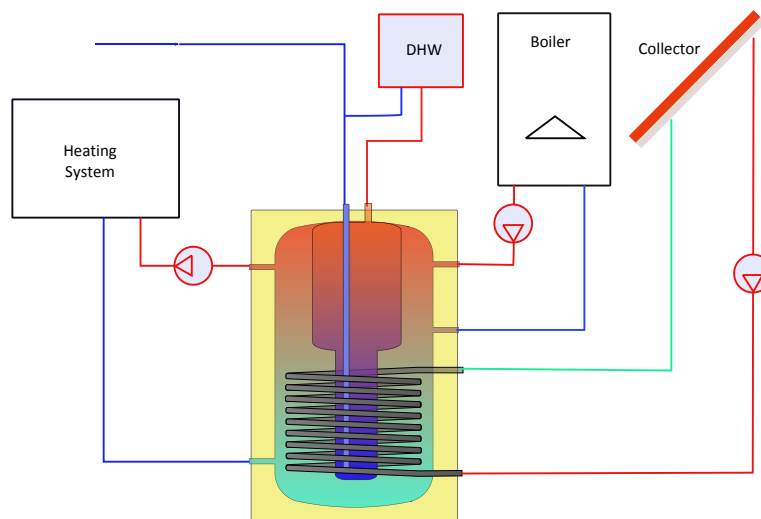


Figure 2-13: Tank in Tank plant for Solar Domestic Hot Water System

### Latent storage systems

Heat storage can be enhanced by means of substances undergoing a phase change during charge and discharge of the storage, usually from the solid to liquid phase. Consequently, the energy is stored as latent heat. The important parameters in such circumstances are the latent heat content of the material and the phase change temperature. Different materials based on paraffin or salt hydrates are available commercially, with phase change temperatures in the range 30 to 64°C [2-23]. Different approaches have been used to integrate PCMs into thermal storage. Typical methods are PCMs packed in cylinders or their inclusion in spherical containers.

### 2.2.5 Chiller

#### Absorption and adsorption chillers

Absorption chillers (Fig. 2-14) represent the most common thermally activated technology applied in existing Combined Cooling, Heating and Power (CCHP) systems (hotels, hospitals, commercial buildings, etc.) [2-24].

Typical absorption chiller installations, with a cooling capacity of 10 to 15 kW producing chilled water at a temperature level of 15 to 18°C, are operated using thermal power at a temperature level of 75 to 90°C, with an COP of approximately 0.65 to 0.78 [2-25,2-26]. Lithium bromide/water and water/ammonia are the working pairs that are typically used in these systems.

Adsorption cooling is a novel technology that incorporates low-grade heat sources [2-24]; however, this technology has the problems of low COP (0.3–0.5), low cooling power per volume, and significant weight. Few systems with a cooling power of 10 to 100 kW are available on the Chinese and American markets, and they have a high investment cost (600 €/kW of cooling power installed). In terms of small machines, two new companies are offering novel products: SorTech AG from Germany offers a 8-kW and 15-kW water-silica gel chiller (Fig. 2-13) and Invensor GmbH, also from Germany, offers a 7 kW and a 10 kW water-zeolite chiller.



(a)



(b)

Figure 2-14: a) absorption chillers; b) Sortech eCoo

### Desiccant wheel

A desiccant wheel (DW) (Fig. 2-15) is a rotor filled with a solid desiccant material, which rotates slowly between the process air, to be dehumidified, and the regeneration air. It can be regenerated by heat from a gas-fired boiler or an electric resistance. However, the energy saving and the reduction of the environmental impact that these systems can achieve are higher when the desiccant material is regenerated by means of “free” thermal energy, for example from cogenerators or solar collectors. In these cases, a desiccant material that can be effectively regenerated with low-temperature thermal energy is obviously needed, [2-27].

Desiccant materials that have been applied include silica gel, lithium chloride, or a molecular sieve. The process of regeneration occurs in the range 50:50 to 75:25.

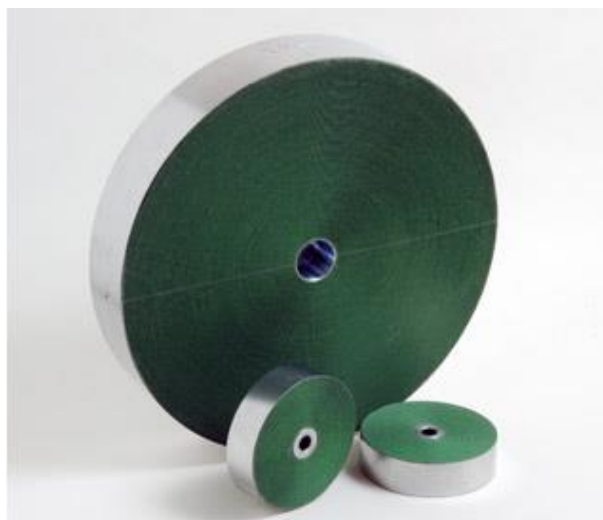


Figure 2-15: The desiccant wheel

Commercial applications of hybrid systems include schools, auditoriums, hospitals, office buildings, supermarkets, and restaurants, among others. However, thanks to its energy and environmental benefits, the use of desiccant technology is also spreading to tertiary and residential buildings.

### 3 System Modelling and Demand Profiles

Annex 54 activities on gathering load profile data, and modelling efforts on micro-generation equipment and systems are presented in this chapter. This work represents the main technical basis for the performance assessment work also performed in this Annex.

For all environment energy simulations constructed, it is understood that the basis and validity of any study hinges on the load profile data used as the energy demand input. Recently, micro-generation has witnessed a shift in focus towards system design, integration, and optimization, as the technology and the expertise linked to their implementation has matured. These changes have given rise to gaps in the suitability of existing load profile data as inputs for energy-use simulations. New understanding about system operations has demonstrated the stochastic nature of energy use, and consequently, higher resolution temporal load profile data that properly reflect this are required. These concerns were addressed in the Annex 54 activities on electric and hot water demand profiles that are reported in this chapter.

As Annex 54 has broadened the scope of the equipment and system configurations under consideration, so too have efforts in gathering load profile data broadened in recent years. A variety of building types, some with specialized activities have been studied. As part of the commitment of Annex 54 to contribute to the existing repository of load profile data, new member nations not present during Annex 42 were requested to provide load profile data. The present Annex includes these new load profile data from the new member nations, Japan and South Korea.

Modelling and simulation resides at the heart of the technical analysis performed in Annex 54. The set of established prime movers for micro-CHP systems has not significantly changed in the past few years. Consequently, the updated focus of the present Annex is directed more at auxiliary system components for cooling, humidity control and/or energy storage, and the focus is aimed at more optimal system efficiency, as well as performing investigations into system configurations and control schemes, with a view to overall energy-use savings.

This chapter presents an overview of the research on residential cogeneration systems conducted within Annex 54, reflecting an expanded scope that considered a diverse number of energy-use system configurations; these were conceived and optimized in view of regional climatic factors, local energy contexts, as well as associated impinging policy environments. Considerable attention has been given to energy storage; this is because optimizing efficiency with either a thermally led or electrically led system naturally leads to situations where the temporal load necessitates the generation of excess heat or electricity, which must be managed. As such, the interplay and compatibility of devices has become an important research topic. It has also become evident that the scale of the CHP system is critical in determining its economic viability; consequently, considering only single-residence applications may restrict the benefits of a broader implementation of micro-cogeneration. In addressing questions of scale, a number of systems are considered on the community or shared level, and the logistics and control of such systems have been examined in Annex 54.

In order to conduct performance assessment studies, the necessary inventory has to be developed. Numerical models of micro-generation equipment and whole systems have to be developed and implemented using suitable simulation tools, such as EPr, TRNSYS or Matlab/Simulink. Demand-profile data have to be investigated for later simulations. Laboratory experiments have to be performed for model calibration and validation purposes (Fig. 3-1).

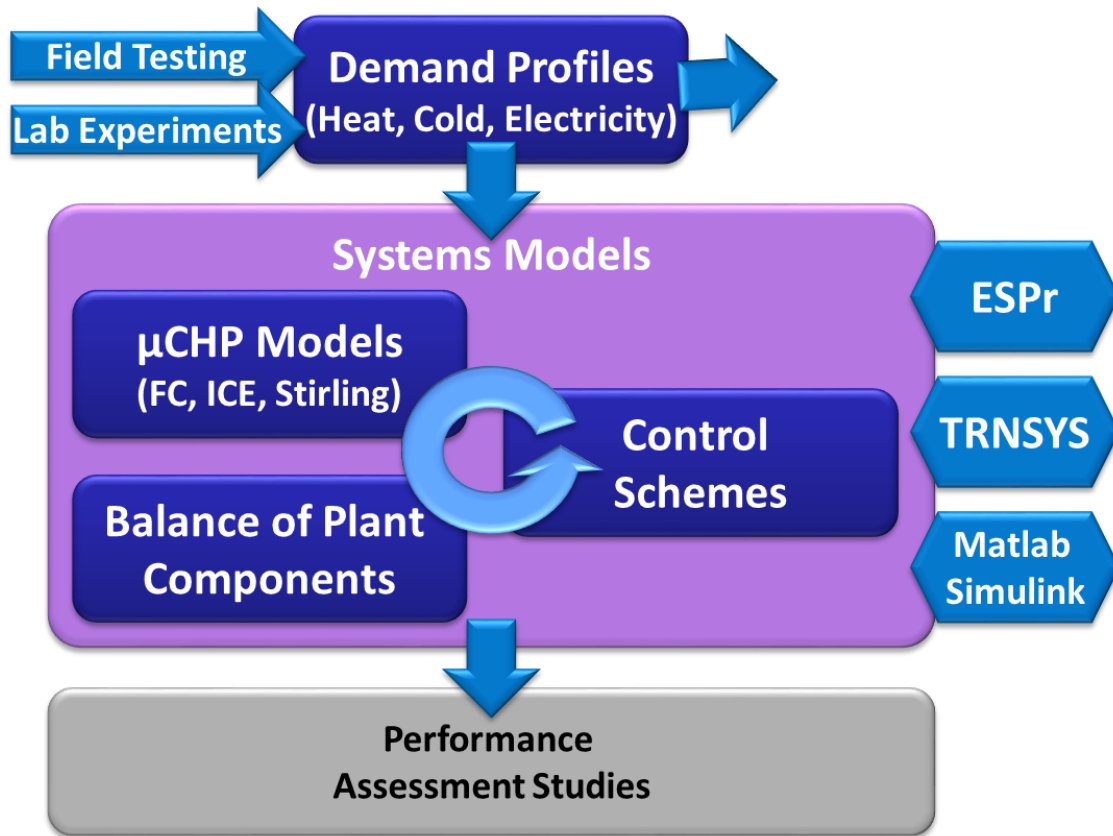


Figure 3-1: Context of data and models.

### 3.1 Demand Profiles

Typical reference energy-demand data for simulation purposes are needed for evaluating and comparing the performance of micro-generation equipment and systems.

As presented in Tab. 3-1, several load profiles for electrical, thermal, and cooling demands of different end-users and geographical areas have been provided by Annex participants. From field measurements, data with a sampling rate of up to one second could be collected. However, in most cases, data with time resolution of one or ten minutes are more common.

There were two approaches followed for defining energy-demand profiles:

- Experimental, using data measured from field tests and laboratory experiments
- Theoretical, using validated models of user behaviour and equipment data

Canadian, Japanese, South Korean, and German participants mainly followed an experimental approach.

**Table 3-1: Overview of load profiles provided by the Annex 54 participants**

Geographical area	Electrical	Heating	DHW	Cooling	Sector	Note
Ottawa, Canada	X				Residential	1-minute resolution; yearly demand; 12 buildings analysed [3-1]
Bavaria, Germany	X	X	X		Residential Service	1-second time resolution; i) four single families, ii) a health club, and iii) a hotel
Bavaria, Germany		X			Service	1-hour resolution; i) a public bath, ii) a hospital, iii) a hotel, and iv) a greenhouse
26 areas in Japan	X		X		Residential	Electrical load with 1-minute resolution, thermal loads with 10-minute resolution; yearly data measured between 2002 and 2004
Osaka, Japan		X	X		Residential	10-minute resolution; six family apartments, 200 day periods, taken from June 2007 through January 2009
Nagoya, Japan	X		X		Residential	1-second resolution; 50-unit block of bachelor flats
Kumagaya, Yokohama, Japan	X	X	X	X	Service	10-minute resolution; data comprise PV, micro-CHP, and solar thermal generation
UK	X				Residential	Two models for generating high-resolution electricity-demand profiles, based on experimental data
Daejeon, Korea		X		X	Residential	Two measurement campaigns: i) one residential building, ii) ten apartments
Incheon, Korea		X		X	Service	1,140-m <sup>2</sup> office building
Italy	X		X		Residential	Profiles derived by databases of Loughborough university and IEA-Annex 26 [3-2, 3-3]
Rome, Italy	X				Residential	Different types of dwelling (Economy, Luxury, Standard) and number of occupants (single/couple and family)
Rome, Italy	X				Service	4 years of measurement campaigns; office buildings

Carleton University gathered occupant electricity-consumption data from 12 houses in Ottawa, Canada. Analysing these data led to the following conclusions:

- Occupant tendencies are a strong determining factor for the annual non-HVAC consumption of a building,
- Occupant electricity-consumption profiles vary significantly between buildings.

Japanese Annex members collected several energy-demand profiles of residential and service buildings. Electricity-demand profiles were gathered for 26 different locations in Japan, thanks to measurement campaigns conducted between 2002–2004. More recent campaigns also encompass data of electricity and domestic hot water demand [3-4].

South Korea provided both heating- and cooling-demand data for residential and office buildings located in two different areas, which were also used to define the total demand required to characterize load-sharing applications.

German participants collected electricity- and heat-demand data of different residential and service buildings. It is worthy of note that a one-second acquisition frequency can capture the dynamic behaviour of the implemented energy systems.

The main difficulty in defining reference profiles lies in the high number of cases that need to be studied in order to make the profiles statistically consistent. Nevertheless, some general information could be derived from the experimental campaigns. Analyses of data from Italy show that buildings characterised by a similar specific electrical load (defined in  $\text{kW/m}^2$ ) demonstrate a very similar average seasonal load profile [3-5].

On the model-based generation of energy-demand data, two different approaches for generating high-resolution residential electricity-demand data, have been presented by UK participants. A first predictive energy-demand model for domestic electricity consumption was developed to define a one-minute resolution synthetic electricity demand [3-6], while a second model was developed for creating high-resolution electricity-demand data reflecting the effects of applying energy-efficiency improvements in future years [3-7].

Italian participants applied the model mentioned above, starting from the electrical demand of dwellings characterised by a different number of occupants (i.e. single/couple and family) and building typology, to generate single and aggregated electricity-demand profiles [3-8].

## 3.2 Models for CHP units

The IEA/ECBCS Annex 42 developed two simulation models for accurately determining the thermal and electric performance of residential cogeneration devices [3-9]; the first model was determined for fuel-cell-based cogeneration units (SOFC and PEMFC), while the second was derived for combustion-based systems (SE and ICE). Both models have been implemented within a variety of whole-building modelling platforms.

The Annex 42 models rely extensively on parametric equations describing the relationships between key input and output parameters; each of these parametric equations requires empirical constants that characterize aspects of the performance of specific cogeneration devices. The establishment of these empirical constants is known as model calibration and requires data from experimental investigations. Annex 42 developed and used an experimental protocol [3-10] to calibrate



cogeneration models. Several experiments with prototype or early-market residential cogeneration devices were conducted, attempting to adhere to the protocol as closely as possible. Three detailed calibration and validation exercises have been undertaken in Annex 42 [1-1]:

- the combustion cogeneration model was calibrated to the WhisperGen Stirling device [3-11]
- the combustion cogeneration model was calibrated to the SenerTec Dachs ICE device [3-12]
- the fuel cell cogeneration model was calibrated to the Fuel Cell Technologies SOFC device

Annex 54 continued the CHP model development and calibration with activities described in the following sections:

### 3.2.1 Calibration and Validation of AISIN SEIKI ICE micro-CHP unit

During Annex 54, the Annex 42 model was calibrated and validated to the AISIN SEIKI ICE device [3-13], [3-14]. The device was installed inside a fully instrumented test laboratory. Even if the facility was not optimally suited for model calibration owing to the difficulty in imposing steady-state conditions on the cogeneration device, a huge experimental database was collected, providing a rich description of the cogeneration unit's performance. Measurements characterizing the cogeneration device's operation were collected with a sampling time of one second and were applied to the most relevant parameters (fuel flow rate, cooling water flow rate, cooling water inlet and outlet temperatures, and net electrical output from the device). The experiments allowed the calibration of the majority of the inputs (99 out of 103) required by the Annex 42 model, showing that during steady-state operation, both electrical and thermal efficiencies depend on the electrical output with a negligible influence of both coolant temperature and flow rate. However, the experiments did not include sufficient measurements to directly calibrate all of the model inputs and, consequently, the calibration process required a methodology capable of deriving multiple model inputs from a limited set of measurements describing operation under dynamic conditions. The remaining uncalibrated model inputs were determined by adopting an iterative dynamic parameter identification approach with the assistance of the third-party optimization tool GenOpt [3-15].

An empirical validation was used to assess the validity of the calibrated model by comparing the simulation results with measurements collected under electric load-following operation. Fig. 3-2 plots the correlation between the model predictions and the experimental measurements in terms of both primary power  $q_{\text{gross}}$  and heat recovery  $q_{\text{HX}}$ . The calibrated model exhibited reasonable agreement when compared with the validation data set; the predicted fuel use, electric output, and heat recovery over the duration of the data set all differed from observed values by  $-6.1$ ,  $-0.2$ , and  $-1.0\%$ , respectively. Additionally, the performed comparison allowed some week points of the model to be highlighted, mainly related to both cool-down and warm-up periods, to be eventually improved in future model versions.

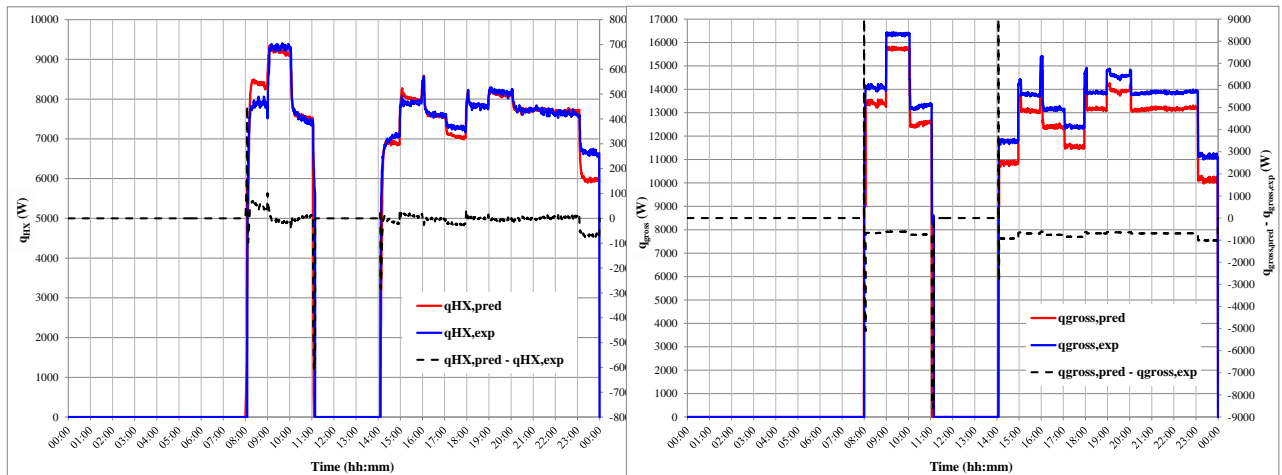


Figure 3-2: Comparison of simulation and measured data.

### 3.2.2 PEM Fuel Cell Model Calibration Using Multiple Regression Method

Both artificial neural network (ANN) and adaptive neuro fuzzy inference system (ANFIS) models can solve highly nonlinear, complex problems without requiring explicit mathematical representations. No clear relationship between the input and output variables needs to exist before the model is applied. These models are known for their robustness (adaptability) owing to the use of generalization techniques instead of memorization. The results revealed that the ANN and ANFIS models could predict the PEMFC performance with a high degree of accuracy. However, a special artificial intelligence (AI) toolbox is required in order to develop the ANN and ANFIS models. TRNSYS do not possess IA modelling capabilities and must be interfaced with Matlab in order to use a multiple regression method to predict the fuel cell performance.

The multiple linear regression (MLR) method was used to predict the PEMFC stack current, stack voltage, fuel cell DC power output, and cooling water temperature from the fuel cell. The inputs used in the MLR method are natural gas flow (sL/min), cooling water flow (L/min), and cooling water temperature ( $^{\circ}\text{C}$ ) entering the fuel cell. In these simple models, the output is a linear function of the three-input variables.

Three data sets: named as training, checking, and testing data, were randomly selected from the experimental data set with no repetition of any data points. A total of 3260 experimental data points were used. While the training and checking data sets each contains a quarter ( $1/4$ ) of the total data points, the testing data set contains half ( $1/2$ ) of the total data points. These sets were initially used in ANFIS models, developed for the PEMFC unit, for training, checking (for testing generalization capability, avoiding over fitting), and testing purposes. The same data sets were used in developing the MLR models. Half of the experiment data (training + checking) were used in the MLR method to calculate the regression coefficients. The testing data were used for model validation.

The measured experimental data and the results obtained from the MLR models are shown in Fig. 3-3 to 3-5. The results show that the simple three-input MLR model can predict the fuel cell stack

current, stack voltage, and DC power with reasonable accuracy. Larger errors occur during the fuel cell start-up and shut-down owing to the fewer data points collected are not enough for training.

The eight-input MLR was used to predict the cooling water outlet temperature with new nonlinear inputs as functions of the initial set of three variables (MNL model). The R-square of 0.86 indicates that the model accounts for a greater proportion of variance.

The RMSE and MRE results from the MLR models are compared with those from the ANN and ANFIS models, as shown in Tab. 3-2. The results indicate that the accuracy of the MRL models is lower in comparison with the AI models. More specifically, the MLR models have poorer performance during the fuel cell shut-down period in comparison with the ANN and ANFIS models. However, in general, the MLR models could predict the fuel cell performance with acceptable accuracy. Moreover, owing to their simplicity, the MLR models can be easily integrated into many simulation software platforms or even in spreadsheet models.

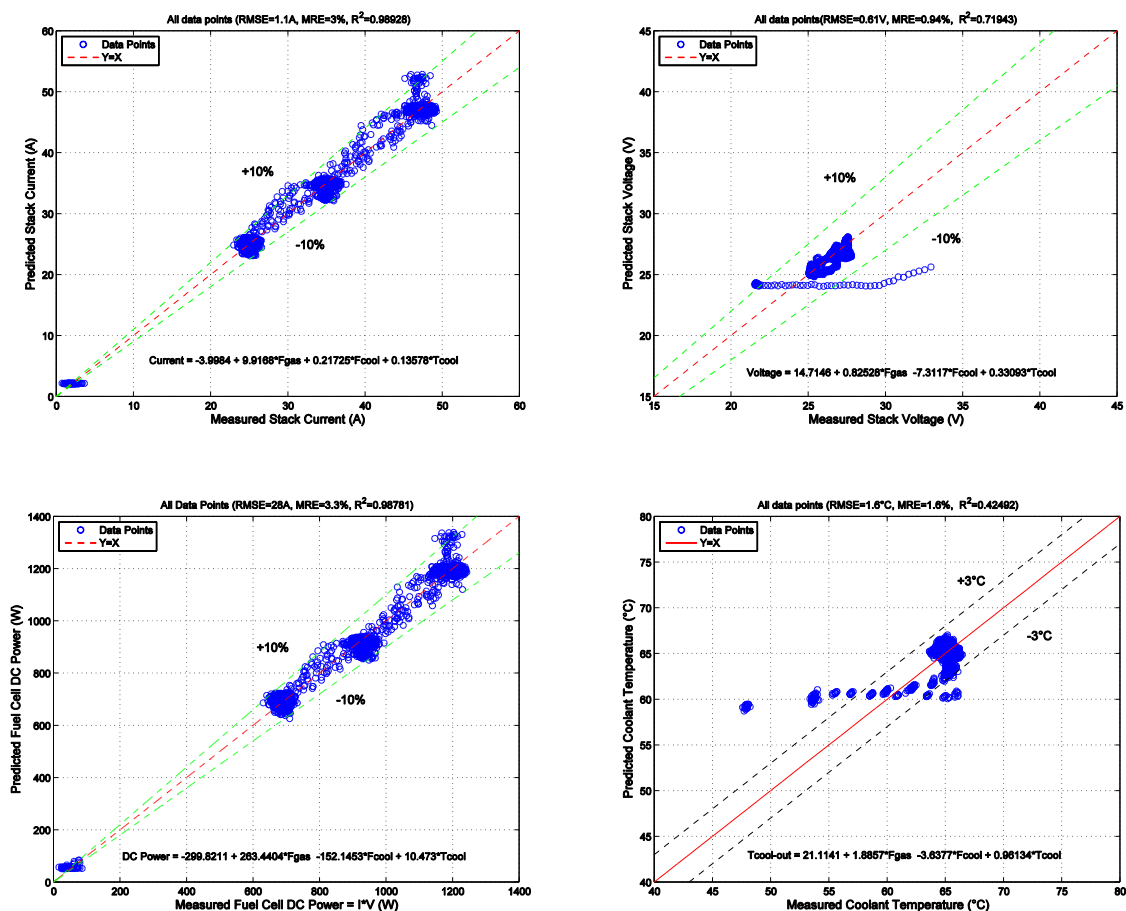


Figure 3-3: Predicted vs. Measured Fuel Cell Stack Current, Stack Voltage, Stack Power, and Cooling Water Outlet Temperature. MLR Models with 3-inputs.

### 3 System Modelling and Demand Profiles

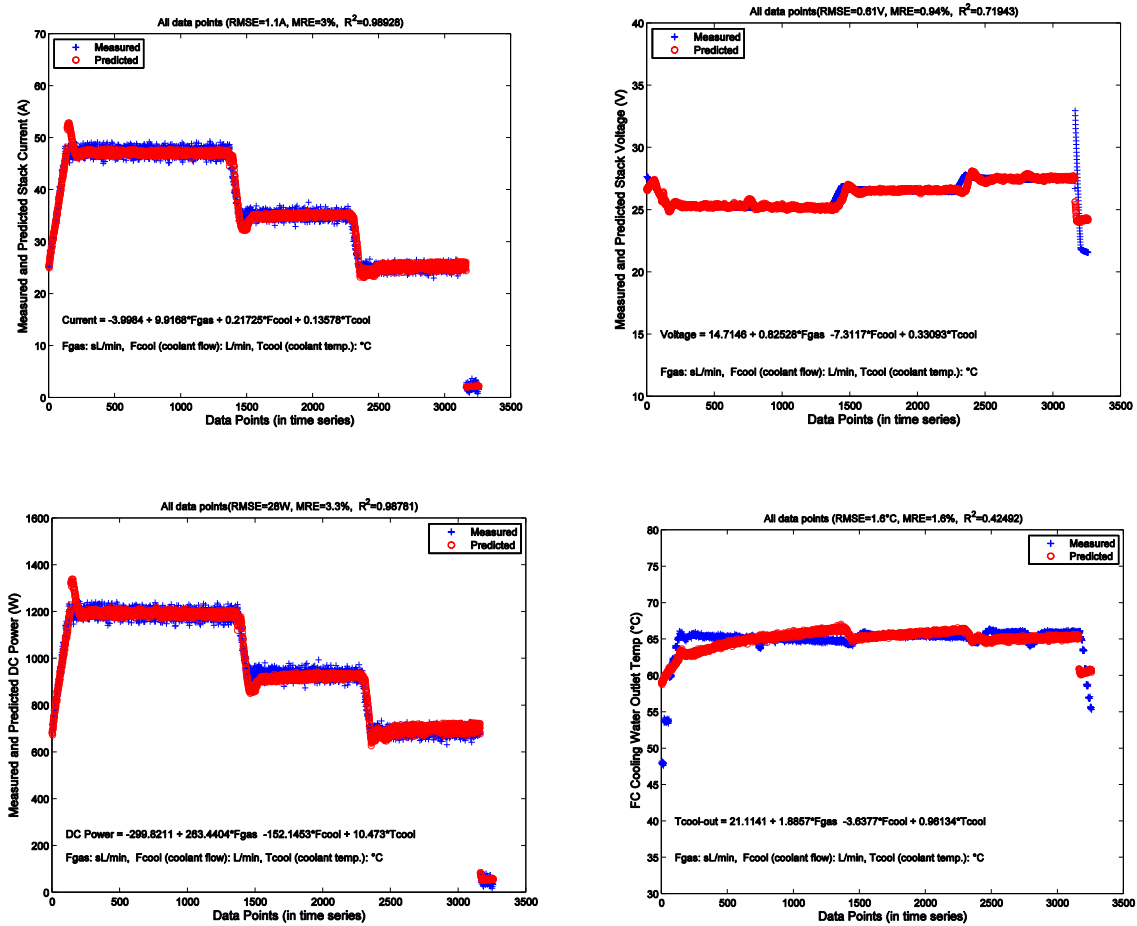


Figure 3-4: Predicted vs. Measured Fuel Cell Stack Current, Stack Voltage, Stack Power, and Cooling Water Outlet Temperature Plotted in Time-Series Format. MLR models with 3-inputs.

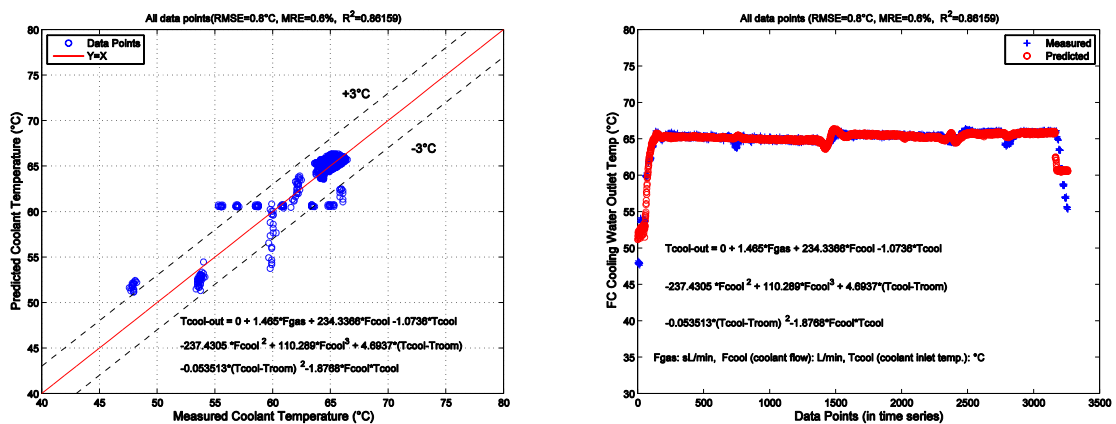


Figure 3-5: Predicted vs. Measured Fuel Cell Cooling Water Outlet Temperature Plotted in Time-Series Format. MNLR model with 8-inputs.

**Table 3-2: RMSE Values of ANN, ANFIS and MR Models for Predicting Fuel Cell Stack Current, Stack Voltage, and Cooling Water Outlet Temperature.**

	RMSE (all data)			MRE (all data)		
	MLR or MNLR	ANN (LM)	ANFIS (gbellmf)	MLR or MNLR	ANN (LM)	ANFIS (gbellmf)
Current (A)	1.10	0.74	0.74	3.00%	2.24%	2.25%
Voltage (V)	0.61	0.31	0.31	0.94%	0.47%	0.30%
Water Outlet Temp. (°C)	0.80	0.50	0.49	0.60%	0.42%	0.36%

### 3.3 Models of System Components

Besides CHP units, system components have also been modelled within Annex 54, or existing models have been used. Details have been included in [3-16]. These models comprise:

- Auxiliary boilers
- Thermal storage tanks as heating buffers or domestic hot water storage
- Battery storages
- Chillers also including DWs

### 3.4 Modelling of complete systems

An example of a building-integrated micro-generation system is illustrated in Fig. 3-6. It comprises a heating device to supply space heating and domestic hot water, as well as an electricity generator, e.g. a cogeneration unit or a PV system. Additionally, cooling devices can be taken into account, as well as thermal and electrical storage devices.

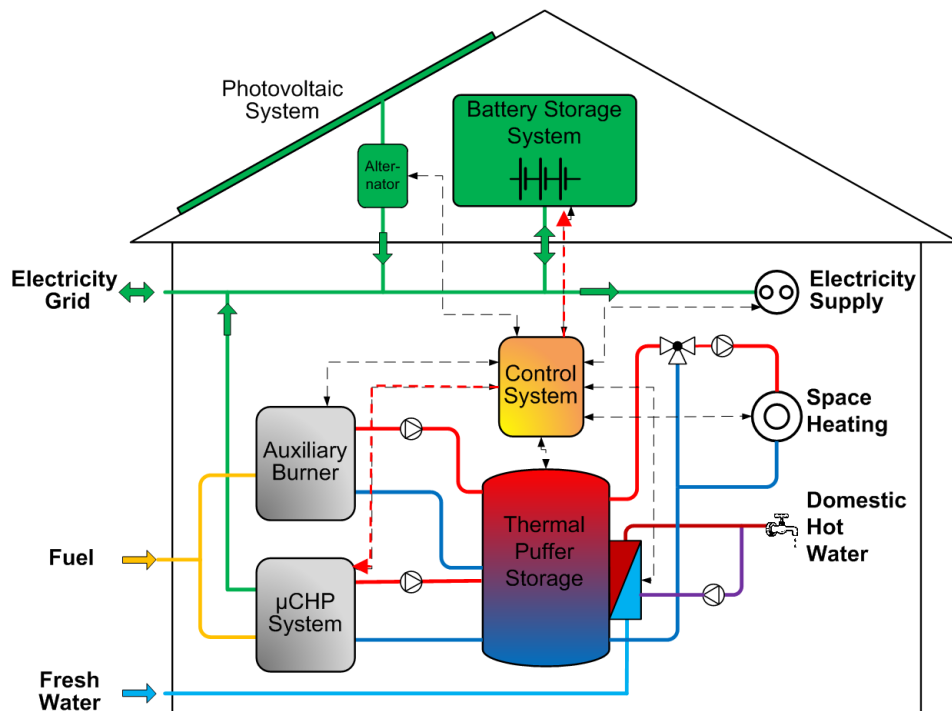


Figure 3-6: Scheme of an exemplary building-integrated micro-generation system

The following sections contain examples of system models developed and used for the performance assessment.

#### 3.4.1 System Model with Internal Combustion Engine implemented in TRNSYS

To analyse the performance of a desiccant-based air conditioning system, the University of Sannio designed and built an experimental plant whose main components are an air handling unit (AHU) equipped with a desiccant wheel (DW), a micro-cogenerator (MCHP) fuelled by natural gas, an electric air-cooled water chiller, a natural gas boiler, and a storage tank, Fig. 3-7.

Experimental data were used to calibrate and validate a model for the main components.

A simplified MCHP model was developed, calibrated, and validated by means of the available experimental data on the AISIN Toyota ICE-based MCHP, [3-17, 3-18, 3-19]. It has a gross electric power output of 6 kW, and a thermal power of 11.7 kW.

The TRNSYS reciprocating internal combustion (RIC) engine model has been used, by means of the “type 907 TESS” component. It uses a table of performance data to determine the outputs of the engine, given a set of input conditions. The model relies on an external data file that contains efficiency, air-flow rate, and heat-transfer data as a function of the intake temperature and the part-load ratio. The MCHP is modelled by three components, the RIC engine, a plate heat exchanger that is used to transfer the recovered thermal power to a secondary fluid (water), and a three-way valve that mixes the part of solution flow rate that passes through the plate heat exchanger and the part

that is bypassed towards the engine. A control system that manages the thermal-recovery circuit of the micro-cogenerator is also modelled.

The model used to simulate the described storage tank is "type 60". The thermal performance of a water-filled sensible energy storage tank, subject to thermal stratification, is modelled by assuming that the tank consists of N fully mixed equal volume segments; for each of them, a uniform temperature is considered. By means of experimental tests conducted in the test facility of University of Sannio, the model was experimentally calibrated and validated, [3-20]. The model has been designed to take into account the three internal heat exchangers, as well as two inlets and two outlets of the stored fluid. To model thermal stratification, 50 nodes were considered.

Experimental data acquired with different plant configurations were compared with the data produced during the corresponding simulation. The comparison was carried out between the temperatures measured by seven sensors installed in the tank, and the temperatures of the nodes of the model located at the same height of the sensors. The results demonstrated a good agreement between the model and the experimental data.

Existing theoretical models for the operation of the main subsystems of a desiccant air-conditioning system were calibrated experimentally before being validated using a wide number of measurements in a typical summer operating range for these systems, [3-21]. The operation of each subsystem is described by a specific efficiency factor. For each subsystem, the average value of the selected efficiency factor and standard deviations were calculated. The validity of the assumed models has been confirmed by the evaluation of the RMSE. The corresponding models were then implemented in TRNSYS, Fig. 3-8.

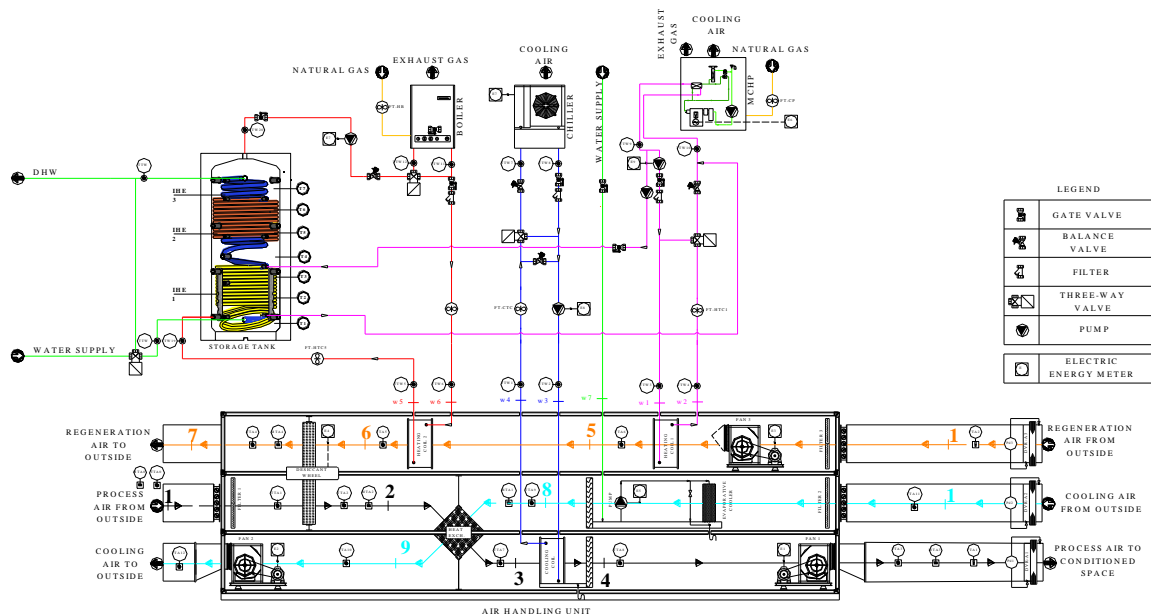


Figure 3-7: The layout of the test facility

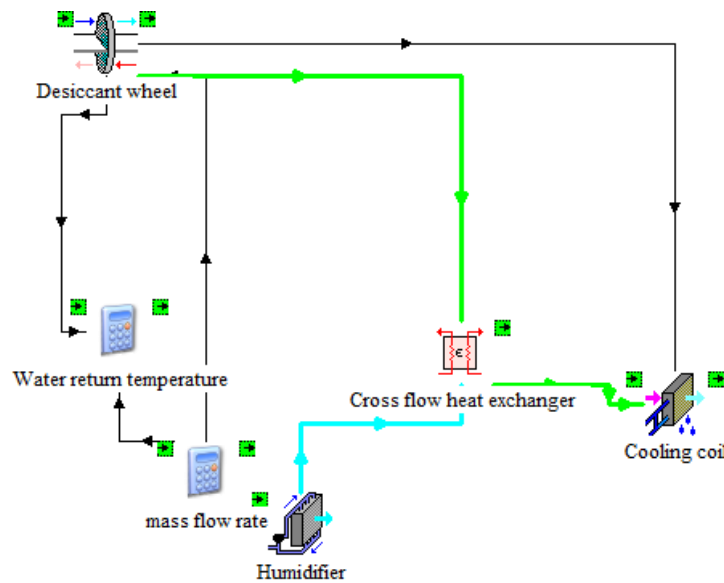


Figure 3-8: The AHU model in TRNSYS

For the DW, the simplified approach of Maclaine-Cross and Banks has been used, on which the “type 1716” of TRNSYS is based, as described in section 3.3. The models of the other AHU components, the types used, and the value of the main parameters are shown in Tab. 3-3.

The natural gas boiler was simulated with the "type 6" of TRNSYS. It represents an auxiliary heater that provides the necessary thermal power to the fluid (water) to reach the desired temperature within the limit of its rated power. The boiler type was characterized with a rated thermal power of 16.5 kW and a nominal thermal efficiency of 90.2%, the same characteristics of the unit installed at the test facility. This peak-load boiler can be used to integrate the thermal power available from the MCHP, for DW regeneration, or space heating/DHW requirements.

Table. 3-3: Main models used for the simulation and their main parameters.

Component	Type	Library	Main parameters	Value	Units
Cross flow heat exchanger	91	Standard	Effectiveness	0.446	-
Humidifier	506c	TESS	Saturation efficiency	0.551	-
Heating coil	670	TESS	Liquid specific heat	4.190	kJ/(kg·K)
			Effectiveness	0.864	-
Cooling coil	508	TESS	Liquid specific heat	4.190	kJ/(kg·K)
			Bypass fraction	0.177	-



The chiller was simulated by means of “*type 655*”, which is a performance map-based model that evaluates the performance of the device (both at full and partial load) in terms of cooling capacity and energy efficiency ratio (*EER*) as a function of chilled water and ambient air dry-bulb temperatures. Data provided by the manufacturer were used to simulate the chillers. In particular, a rated cooling capacity and a nominal *EER* of 8.50 kW and 2.98 were assumed, respectively. This corresponds to the values of the unit installed at the test facility.

### 3.4.2 System Model with Internal Combustion Engine implemented in Matlab/Simulink

The layout of the cogenerator is reported in Fig. 3-9; the ICE is coupled with an electric generator and is connected to the grid through a rectifier and an AC converter; this arrangement allows the engine to be operated at variable speed while delivering 50 Hz AC to the grid. The thermal power discharged by the engine is recovered through an engine-coolant/water heat exchanger and an exhaust/water heat exchanger. A fan-cooled heat exchanger is fitted into the engine-coolant circuit to provide additional cooling in case of low thermal demand. A by-pass valve fitted in the exhaust’s circuit permits the decoupling of electric and thermal power production. In order to satisfy the thermal demand when the CHP unit is switched off for technical–economic reasons, or for maintenance, a back-up boiler is added to the cogeneration unit, as shown in Fig. 3-9. The main technical features of the CHP unit are reported in Tab. 3-4. [3-22]

The system can be operated in two different heat-recovery modes:

- “thermal priority” mode: in this mode the requested thermal demand is followed and the electric power is adjusted automatically
- “electric priority” mode: in this mode the electric power demand is followed while the exhaust’s by-pass valve may be adjusted to try to maintain the requested water outlet temperature

The ICE has been simulated in a Matlab/Simulink environment by describing all of the subsystems that compose the ICE, such as the engine shaft, the engine, and the heat exchangers (Fig. 3-10). The key assumption made was that the thermo-fluid-dynamic processes of the engine are much faster than the change rate in thermodynamic boundary conditions. Consequently, the ICE has been modelled as a quasi-stationary machine and the ICE performances are simulated on the basis of two look-up tables defined according to the engine-performance maps provided by the manufacturer. Varying the number of cylinders, a 14-kW<sub>el</sub> (system 1) and 28-kW<sub>el</sub> (system 2) ICE have been modelled. The main technical parameters are shown in Tab. 3-4.

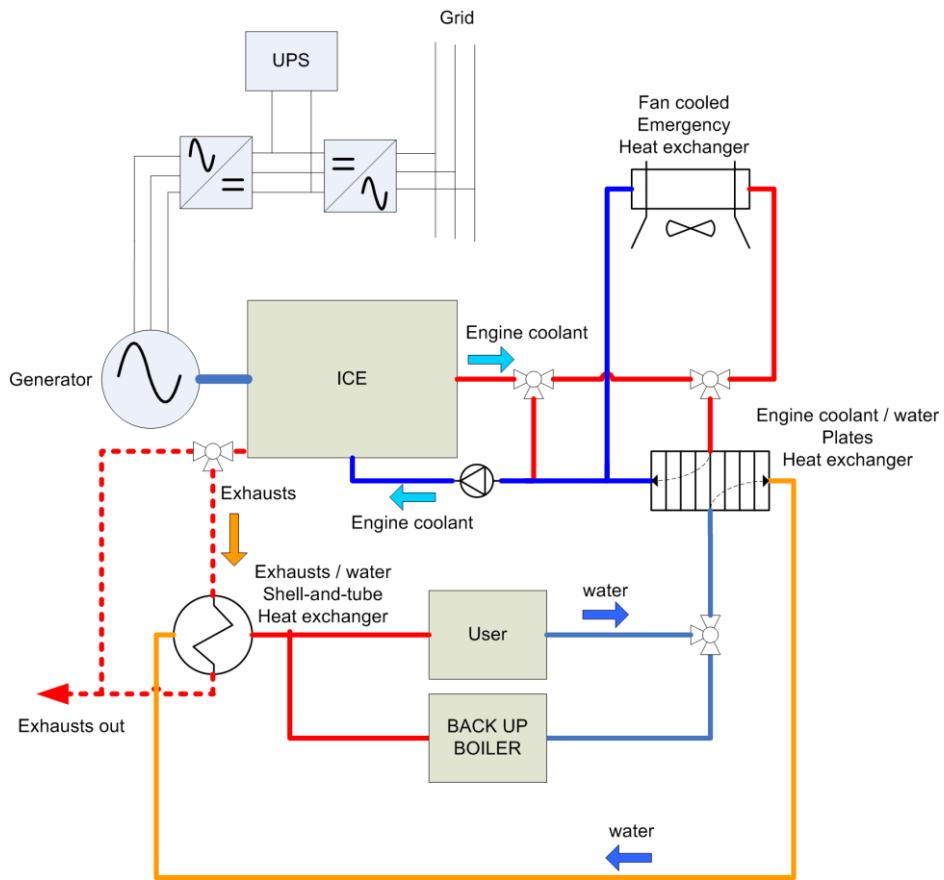


Figure 3-9: Functional scheme of the system

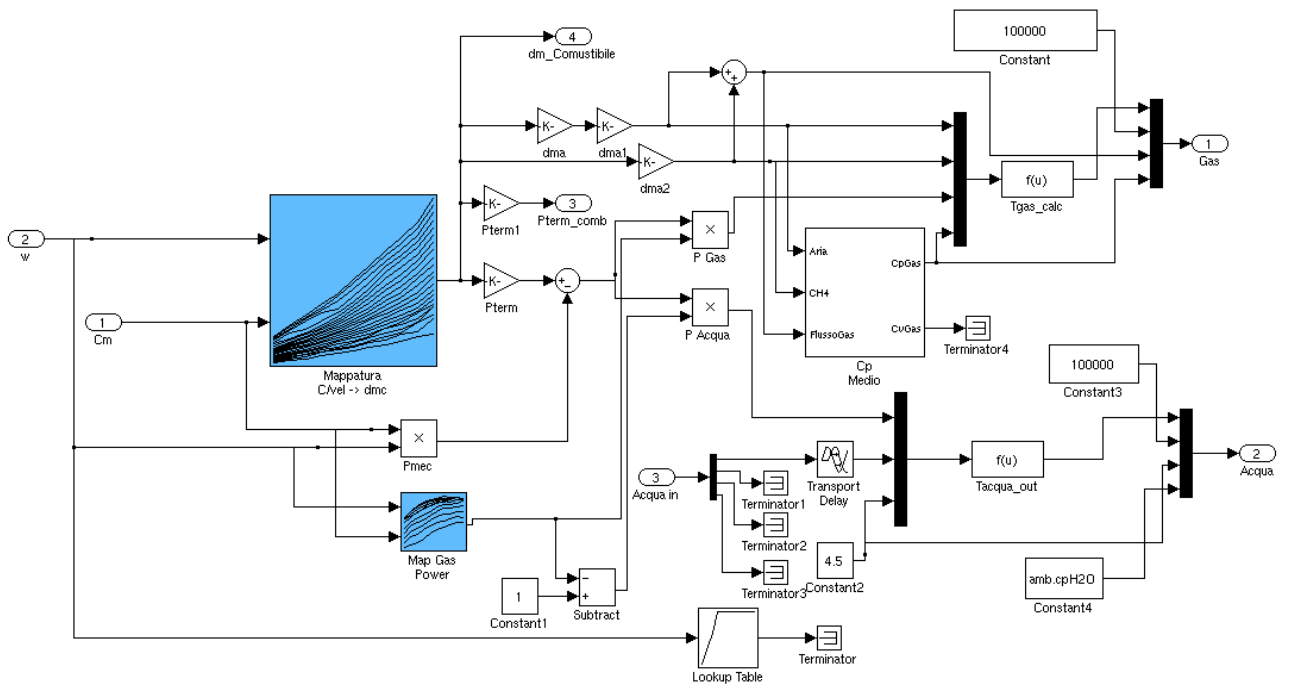


Figure 3-10: Engine sub-system

Table 3-4: Technical parameters of the ICE under analysis

Parameter	System 1	System 2
Maximum rated electric output	14 kW <sub>el</sub>	28 kW <sub>el</sub>
Maximum rated power output	29 kW <sub>th</sub>	58 kW <sub>th</sub>
Minimum electric power	3 kW <sub>el</sub>	6 kW <sub>el</sub>
Minimum thermal power	9 kW <sub>th</sub>	18 kW <sub>th</sub>
Electrical efficiency	28.5%	28.5%

A control model was developed for both the thermal and electrical priority modes. In electric priority mode, a speed regulator provides the desired electric power output from the system. The regulator is based on an optimization table that, for any given power, helps the system choose the speed that ensures the greatest electric efficiency. Electric efficiency gains can be obtained with the variable speed unit (in comparison with the constant speed machine at 3000 rpm); the lower the electric power setting, the greater the gain.

As typical applications, a ten-apartment building for the residential sector, and an office and a hotel for the service sector were chosen as test cases; the results were discussed in terms of energy performances and profitability. The technical–economic analysis revealed that good energy and economic performance could be achieved both in household and in hotel applications in comparison with a separate generation system, especially with variable speed operation. By contrast, any office application would be scarcely profitable because savings would only be achieved in the winter and would be too low to allow an economic return on the investment in a reasonable time period. The possibility of regulating the rotational speed of the engine enhances energy performance and, although it entails a higher initial investment, the variable speed concept shortens the payback period and increases profits.

### 3.5 Optimization Tool Using a Unit Commitment Approach

The optimal dispatch of cogeneration devices in a Virtual Power Plant (VPP) can be performed using a Mixed Integer Linear Programming (MILP) model. In order to undertake studies in the field of operating CHPs or other distributed energy devices, the first step is often to build up the model. The following description states the most common equation to build up a MILP model. Aside from this, [3-23] contains a comprehensive list of constraints used for modelling the dispatch of a VPP.

The objective of the optimization algorithm, to minimize the operational cost of the system, is expressed in equation (3-1) and is extended in equation (3-2). The operational cost is the sum of the fuel cost of the CHPs and boilers ( $C_{\text{CHP}}$ ,  $C_{\text{boiler}}$ ). Conversely, the savings include the revenues due to the sale of electricity to the grid ( $G_{\text{grid}}$ ) and the savings owing to the self-consumption of the electricity generated by the CHP ( $G_{\text{local}}$ ):

$$\min \text{objective function} = \sum_{t=1}^T \sum_{n=1}^N (Cost_{op}(t,n) - Savings(t,n)) \quad (3-1)$$

$$\min = \sum_{t=1}^T \sum_{n=1}^N (C_{CHP}(t,n) + C_{boiler}(t,n) - G_{local}(t,n) - G_{grid}(t,n)) \quad (3-2)$$

The relationship between the electric and the thermal output of the CHP is described in equation (3-3). In a similar manner, equation **Fehler! Verweisquelle konnte nicht gefunden werden.** details the electric output and the primary energy. The parameters  $a_{th}$ ,  $b_{th}$ ,  $a_p$ , and  $b_p$  are calculated from measured data of commercial CHPs provided by the IEA annex 54 and those reported in [3-24]. Figure 3-11 shows the linear relationship between electric and primary energy (dashed line) and the electric and thermal energy (full line). The markers correspond to the measured data. Conversely,  $\gamma$  is a binary variable that indicates the on/off status of the CHP.

$$\dot{Q}_{chp}(t,n) = a_{th}(n) \cdot \dot{E}_{chp}(t,n) + b_{th}(n) \cdot \gamma(t,n) \quad (3-3)$$

$$P_{chp}(t,n) = a_p(n) \cdot \dot{E}_{chp}(t,n) + b_p(n) \cdot \gamma(t,n) \quad (3-4)$$

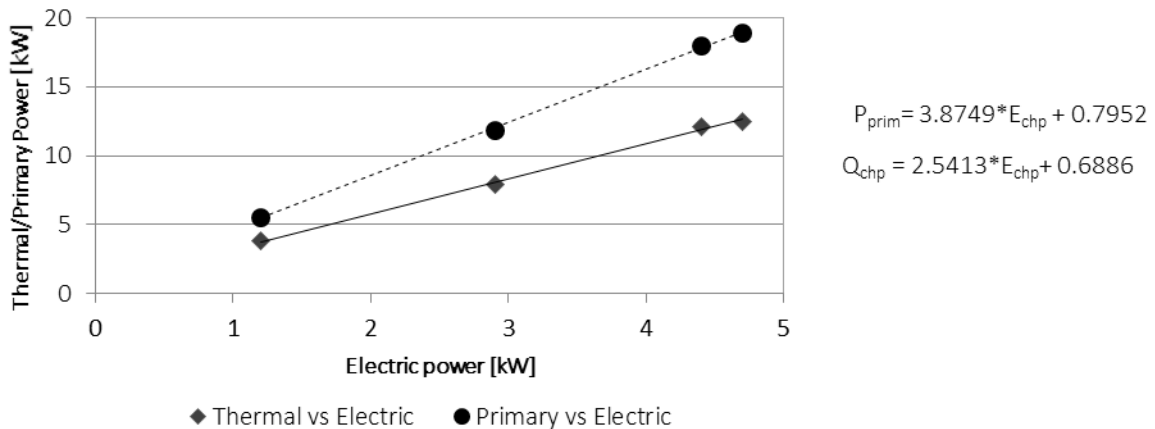


Figure 3-11: Technical characteristics of a Micro-CHP

### Constraints

The optimization is constrained by several operational and technical conditions. The operational constraints ensure that the heat demand ( $\dot{Q}_{demand}$ ) will always be met using the CHP ( $\dot{Q}_{chp}$ ), the boiler ( $\dot{Q}_{boiler}$ ), or that the heat that is discharged from the thermal storage buffer ( $\dot{Q}_c$ ), as described in equation (3-5):

$$\dot{Q}_{demand}(t, n) = \dot{Q}_{chp}(t, n) + \dot{Q}_{boiler}(t, n) + \dot{Q}_c(t, n) \quad (3-5)$$

The state of charge of the storage tank ( $Q_{st}$ ) is calculated using equation (3-6). The efficiency of the storage tank<sup>1</sup> ( $\eta_{st}$ ) is assumed to be constant. The time step ( $\Delta t$ ) of the analysis is 15 minutes:

$$Q_{st}(t, n) = \eta_{st} * Q_{st}(t - 1, n) - \dot{Q}_c(t, n) * \Delta t \quad (3-6)$$

It is assumed that the boiler has a constant efficiency and, therefore, the primary energy can be estimated as in equation (3-7).

$$\dot{P}_{boiler}(t, n) = \frac{\dot{Q}_{boiler}(t, n)}{\eta_{boiler}} \quad (3-7)$$

The cost of the CHP system (boiler and primary mover) can be calculated by multiplying the primary energy consumption by the gas price  $P_{ng}$ . This is illustrated in equation (3-8).

$$C_{chp}(t, n) + C_{boiler}(t, n) = (\dot{P}_{CHP}(t, n) + \dot{P}_{boiler}(t, n)) \cdot P_{ng} \quad (3-8)$$

Conversely, the electric demand is the aggregated electric demand of the houses. Therefore, the electricity generated by the linked CHPs ( $\dot{E}_{chp}$ ) is equal to the sum of the individual production of each CHP device:

$$\dot{E}_{CHP}(t) = \sum_{n=1}^N \dot{E}_{chp}(t, n) \quad (3-9)$$

The electricity generated by the CHP ( $\dot{E}_{chp}$ ) can be used inside the VPP ( $\dot{E}_{local}$ ) or sold on the electricity market ( $\dot{E}_{grid}$ ):

$$\dot{E}_{CHP}(t) = \dot{E}_{local}(t) + \dot{E}_{grid}(t) \quad (3-10)$$

Consequently, the revenues obtained from selling or using the produced electricity are estimated in equation (3-11), where  $P_{spot}$  represents the market price and  $P_{local}$  the price to buy electricity from the grid.

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<sup>1</sup> The efficiency of the storage tank represents the percentage of heat that is preserved from the storage after it has been stored during one time step.

$$G_{LOCAL}(t) + G_{GRID}(t) = P_{local} * \dot{E}_{local}(t) + P_{spot} * \dot{E}_{grid}(t) \quad (3-11)$$

Conversely, some technical restrictions prevent exceeding the operational limits of the machines when they are turned on. This is expressed in equations (3-12) to (3-15) for the thermal storage, the boiler, and the CHP, respectively:

$$0 \leq Q_{st}(t, n) \leq Q_{st_{max}}(n) \quad (3-12)$$

$$0 \leq \dot{Q}_{boiler}(t, n) \leq \dot{Q}_{boiler_{max}}(n) \quad (3-13)$$

$$\dot{Q}_{chp_{min}} \leq \dot{Q}_{chp}(t, n) \leq \dot{Q}_{chp_{max}}(n) \quad (3-14)$$

$$\dot{E}_{chp_{min}} \leq \dot{E}_{chp}(t, n) \leq \dot{E}_{chp_{max}}(n) \quad (3-15)$$

Other technical constraints control the minimum start up time of the CHP device. This is performed as explained in [3-25] and it is important to consider this in order to avoid wearing out the machinery.

## 4 Performance Assessment

One key goal of Annex 54 is to analyse the benefits micro-generation can yield regarding the energy supplies of buildings. Consequently, Subtask B was dedicated to performance assessment. Aside from investigating performance factors as efficiencies or energetic effort to deliver defined energy services, aspects including primary energy demand, connected greenhouse gas (GHG) emissions, and occurring costs have been taken into account.

The method to evaluate the energy, environmental and economic performance is termed 3-E analysis, as illustrated in Fig. 4-1.

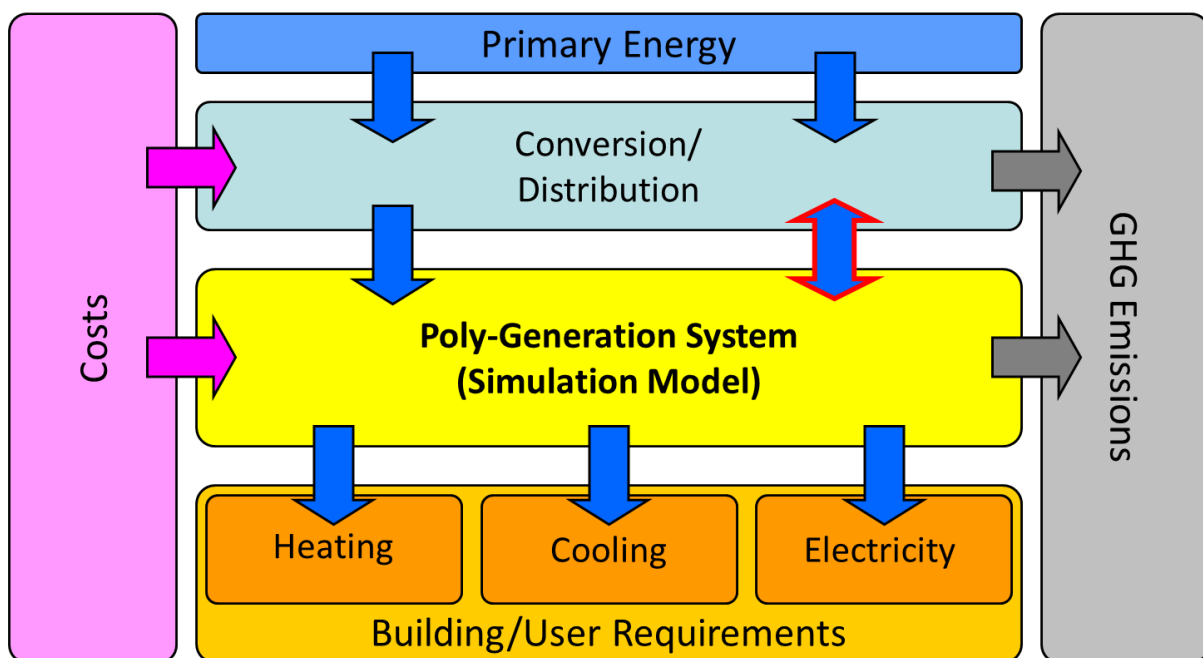


Figure 4-1: Scheme of 3E analysis

### 4.1 Methodology

The performance assessments of Annex 54 are based on Annex 42 methodology definitions. Additions have been made to implement cooling, energy storage, and to be able to assess complete micro-generation supply systems.

An approach in evaluating the energy, environmental, and economic performance of a micro-generation system (alternative system, AS) is to compare its primary energy demand ( $PE$ ), operating costs ( $OC$ ) and equivalent  $CO_2$  emission ( $m_{CO_2}$ ) with those of a reference system (or conventional system, CS), with respect to a specific time period. The time period used is typically an annual basis [4-1, 4-2, 4-3], Fig. 4-2.

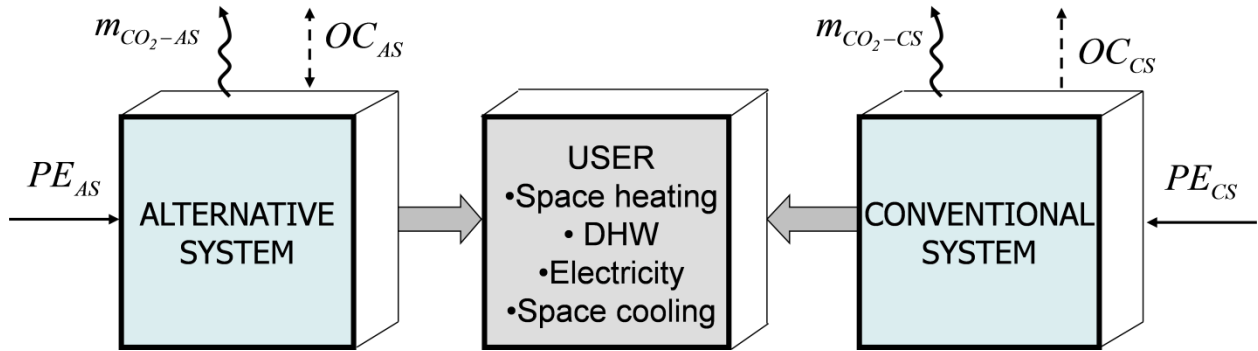


Figure 4-2: Energy flow of alternative and conventional systems

The following systems are suggested as conventional reference systems [4-1]:

- condensing gas boiler, providing heat for space heating and DHW
- electric compression chiller, providing cold for space cooling
- electricity supply from the power system through the electric grid

### Energy analysis

The primary energy saving achieved with a polygeneration system can be evaluated, with respect to the reference system, by means of the Fuel Energy Saving Ratio (*FESR*) [4-4]:

$$FESR = \frac{PE_{CS} - PE_{AS}}{PE_{CS}} = 1 - \frac{PE_{AS}}{PE_{CS}} \quad (4-1)$$

where  $PE_{CS}$  and  $PE_{AS}$  are primary energy inputs to CS and AS, respectively.

### Environmental analysis

From the different environmental parameters that could be analysed, such as GHG emissions, land use, and acidification potential, GHG emissions have been selected as one of the most relevant parameters for energy supply systems in buildings.

The main pollutant contributing to global warming is carbon dioxide ( $CO_2$ ), emitted by combustion-based processes. The reduction in  $CO_2$  emissions that an alternative system can guarantee with respect to the conventional one can be evaluated, typically on an annual basis, as:

$$\Delta CO_2 = \frac{m_{CO_2-CS} - m_{CO_2-AS}}{m_{CO_2-CS}} = 1 - \frac{m_{CO_2-AS}}{m_{CO_2-CS}} \quad (4-2)$$

where  $m_{CO_2-CS}$ ,  $m_{CO_2-AS}$ , are the  $CO_2$  emissions of the systems.

These emissions can be calculated from the applied energy carriers using specific emission factors  $\mu_{CO_2}$

Aside from  $CO_2$ , other greenhouse gases must be taken into account (4-3).



$$\Delta CO_{2,eq} = \frac{m_{CO_{2,eq-CS}} - m_{CO_{2,eq-AS}}}{m_{CO_{2,eq-CS}}} = 1 - \frac{m_{CO_{2,eq-AS}}}{m_{CO_{2,eq-CS}}} \quad (4-3)$$

where  $m_{CO_{2,eq-CS}}$  and  $m_{CO_{2,eq-AS}}$  are the  $CO_2$  equivalent emissions of the systems.

These can be also derived by taking the global warming potential (GWP) of a process into account.

$$\mu_{CO_{2,eq}} = GWP \cdot \mu \quad (4-4)$$

## Economic analysis

In order to evaluate, with a simplified approach, the economic performance of alternative and conventional systems, the commonly used parameters are the Simple Pay Back (SPB), the Net Present Value (NPV), the Profitability Index (PI), and the Internal Rate of Return (IRR).

By means of the SPB method, the number of years required in order to recover the higher investment cost of the alternative system with respect to the conventional system can be evaluated:

$$SPB = \frac{EC}{\sum_{k=1}^n F_k} \quad (4-5)$$

where  $EC$  is the initial extra cost of AS with respect to CS and  $F_k$  is the yearly cash flow for year  $k$ , i.e. the difference in operating costs between the conventional and alternative system.

The NPV compares the discounted cash flows in a given time period ( $n$  years) with the initial investment extra cost:

$$NPV = \sum_{k=1}^n \frac{F_k}{(1+a)^k} - EC \quad (4-6)$$

where  $a$  is the discount rate.

The PI evaluates the ratio between the discounted cash flows and the  $EC$ :

$$PI = \frac{\sum_{k=1}^n \frac{F_k}{(1+a)^k}}{EC} \quad (4-7)$$

Both in NPV and PI indices, the discount rate  $a$  is fixed *a priori*. Instead, the IRR method evaluates the value of  $a$  that annuls the NPV:

$$\sum_{k=1}^n \frac{F_k}{(1+a)^k} = EC \quad (4-8)$$

The IRR represents the value of the interest rate over which the project is no longer economically profitable in investments for which a banking loan is used.

### Frame conditions

One of the most important issues in the 3-E analysis is the characterization of the reference system, in terms of:

- $\eta_{El,ref}$ : energy performance factor of reference system for electricity supply (ratio of electric energy output to primary energy input, [kWh<sub>El</sub>/kWh<sub>PE</sub>])
- $\mu_{El,ref}$ : equivalent carbon dioxide specific emission factors of the reference system for the electricity supply (ratio of equivalent CO<sub>2</sub> emissions to electric energy output, [kg<sub>CO2,eq</sub>/kWh<sub>El</sub>])
- $\eta_{Th,ref}$ : energy performance factor of the reference system for the heat supply (ratio of thermal energy output to primary energy input, [kWh<sub>Th</sub>/kWh<sub>PE</sub> or kWh<sub>Th</sub>/kWh<sub>DE</sub>])
- $\mu_{NG}$ : equivalent carbon dioxide emission factor of natural gas (ratio of equivalent CO<sub>2</sub> emissions to primary energy input, [kg<sub>CO2,eq</sub>/kWh<sub>PE</sub>])
- $EER_{Cool,ref}$ : energy efficiency ratio of the reference system for the cold supply (ratio of cooling energy output to electric energy input, [kWh<sub>Cool</sub>/kWh<sub>El</sub>])

On estimating the energy and environmental performance of the reference system based on separate “production”, three different approaches can be used. The first is to use energy performance and CO<sub>2</sub> factors on the basis of a national/regional technological mix. The second is to use the best available and economically justifiable technology (BAT), e.g. a combined cycle natural-gas fired power plant for electricity supply. The third is to use the values provided by some national or international directive, such as European Directive 2004/8/EC [4-5].

Two different approaches can be used when selecting the specific emission factors:

- **‘Standard’ emission factors**, in line with the Intergovernmental Panel on Climate Change (IPCC) principles, which cover all the CO<sub>2</sub> emissions that occur owing to energy consumption, either directly due to fuel combustion or indirectly via fuel combustion associated with electricity and heat/cold usage. The standard emission factors are based solely on the carbon content of each fuel. In this approach, CO<sub>2</sub> is the most important GHG. However, other greenhouse gases can also be included in the analysis.
- **Life Cycle Assessment emission factors**, which take into consideration the overall life cycle of the energy carrier. This approach includes not only the emissions of the final combustion but also all the emissions from the supply chain. It includes emissions from exploitation, transportation, and processing (e.g. refinery) steps, in addition to the final combustion. In this approach, the GHG emissions from the use of biomass/biofuels, as well as emissions of certified green electricity, are higher than zero. If this approach is used, greenhouse gases other than CO<sub>2</sub> may play an important role.

Furthermore, the CO<sub>2</sub> emissions from the sustainable use of biomass/biofuels, as well as emissions of certified green electricity, are considered to be zero.

The following parameters should be defined to perform the economic feasibility analysis:

- $UP_{El}^{Grid}$  : unitary price of electricity from the grid, (ratio of electric energy cost to delivered electric energy, [€/kWh<sub>DE</sub> or \$/kWh<sub>DE</sub>])
- $UP_{NG}$ : unitary price of natural gas (ratio of natural gas cost to its standard volume, [€/Sm<sup>3</sup>, €/Nm<sup>3</sup>, \$/Sm<sup>3</sup> or \$/Nm<sup>3</sup>]). In order to convert energy quantities to volumetric quantities, a suitable Lower Heating Value of natural gas ( $LHV_{NG}$ , [kWh/kg], [kWh/Sm<sup>3</sup>] or [kWh/Nm<sup>3</sup>]) must be used

In Tab. 4-1, the parameters for reference system characterization used by some Annex 54 participating groups are shown.

**Table 4-1a: Parameters for reference system characterization produced by some Annex 54 participating groups**

		<b>Germany</b> (TUM,FfE)	<b>USA</b> (NIST)	<b>Italy</b> (Uni Sannio, SUN)	<b>Japan</b>	<b>UK</b>
Heating	Type of device	SB – CB	Natural gas furnace (NC) A/A Heat Pump (SC) <sup>1</sup>	SB CB		
	$\eta_{Th,ref}$ [-]	SB = 80% CB = 95%	AFUE = 94% (NC) HSPF = 8.5 (SC)	SB = 85–90% CB = 95–102%	73.5% <sup>4</sup>	
Storage water heater	Type of device		Natural gas (NC) Electric (SC)			
	$\eta_{Th,wh,ref}$ [-]		EF = 0.7 (NC) EF = 0.92 (SC)			
Cooling	Type of device		Air conditioner	Air cooled electric chiller		
	$EER_{Cool,ref}$ [-]		SEER = 13	EER = 3.0 (average) – 3.5 (BAT)		

## 4 Performance Assessment

**Table 4-1b: Parameters for reference system characterization produced by some Annex 54 participating groups**

		Germany (TUM,FfE)	USA (NIST)	Italy (Uni Sannio, SUN)	Japan	UK
Electricity	$\eta_{El,ref}$ [-]	38.5%	Vary by region	42.0% <sup>3</sup> (Italian mix) 54.3% <sup>3</sup> (BAT)	36.1% <sup>4</sup> (daytime) 38.8% <sup>4</sup> (night time)	
	$\mu_{El,ref}$ [g <sub>CO2</sub> /kWh <sub>El</sub> ]	540	Vary by region (both marginal and overall)	573 (Italian mix) 400 (BAT)	559	
	T&D losses		7% (US average)	6.23% (average)		
	$UP_{El}^{Grid}$ [€/kWh <sub>El</sub> ]			0.243 peak hours 0.225 off-peak hours	0.1 (industrial) 0.2 (domestic)	0.17
Natural gas	$PEF_{NG}$ [kWh <sub>PE</sub> /kWh <sub>DE</sub> ]	1.1		-		
	$UP_{NG}$ [€/Sm <sup>3</sup> ]			0.941 <sup>2</sup> 0.771 for MCHP use	0.5 (industrial) 1.2 (domestic)	0.424 <sup>5</sup>
	$\mu_{NG}$ [g <sub>CO2</sub> /kWh <sub>DE</sub> ]	205		207	205	
	$LHV_{NG}$ [kWh/Nm <sup>3</sup> ]			9.52		

<sup>1</sup>NC = Northern Climate; SC = Southern Climate;

<sup>2</sup>a lower value is assumed for MCHP use, depending on its electric efficiency; <sup>3</sup>including T&D losses;

<sup>4</sup>based on HHV;

<sup>5</sup>considering a LHV of 9.99 kWh/Sm<sup>3</sup>;

SB = Standard Boiler; CB = Condensing Boiler; AFUE = Annual Fuel Utilization Efficiency; HSPF = Heating Seasonal Performance Factor; SEER = Seasonal Energy Efficiency Ratio

## 4.2 Test Procedures

Several standard testing procedures were prepared, or are in a developing phase, in many countries in order to provide test methods for determining the performance of CHP and MCHP devices. In fact, it could be useful to define a procedure for testing, *ex-ante*, the energy performance of a device that is representative of a unit type. This procedure is an alternative to the conventional *ex-post* assessment of energy savings achieved by each installed unit, which is not economically justified, especially in the case of a very large number of small sized units. For example, manufacturers or energy service companies that expect to install a large number of identical units in similar applications can use the *ex-ante* method, allowing them to classify the energy performance of the MCHP with tests conducted in a certified test facility by an independent third party.

These standard procedures usually specify the equipment and instrumentation required, the test methods, and the calculation procedures. In particular, they characterize the cogeneration unit both at nominal operating conditions and according to appropriate test cycles, which typically vary with geographical characteristics and meteorological conditions of the installation location.

Examples of such standard procedures for cogeneration devices are as follows:

- UNITED KINGDOM: Publicly Available Specification 67 (PAS 67), [4-6]
- ITALY: prUNI E0204A073 (in stand-by), [4-7]; UNI/TS 11300-4, [4-8]
- EUROPE: prEN 50465, [4-9]
- GERMANY: DIN 4709, [4-10]
- JAPAN: industrial standards for performance and safety testing of CHP

For example, Fig. 4-3 illustrates the thermal load profile for heating purposes, as defined by DIN 4709. Since the return and supply temperatures have to be controlled at constant levels of 30 and 50°C, respectively, the heat rejection can be adjusted by the volume flow rate only in the heating circuit. This thermal profile load does not match the profile of a day in winter for a properly designed CHP plant because the mean ratio of heat demand to nominal thermal power of the CHP unit should be much higher. For similar reasons, the profile is not comparable to a day in summer, where this ratio would be much smaller owing to low heat demands. The profile refers to a day in spring or in autumn or, in other words, to a transition time during the year. In fact, because it is not feasible to test cogeneration units for a period of one full year, any short-cut method should represent the variable heat demands during the year as appropriately as possible. Obviously, neither winter days nor summer days can serve as a meaningful profile to this aim, [4-11].

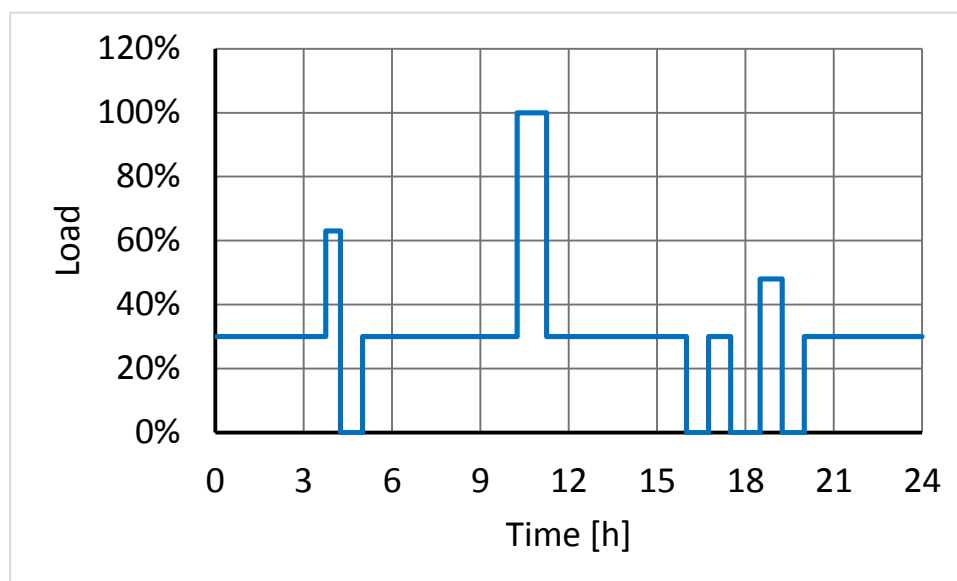


Figure 4-3: Thermal load profile defined by DIN 4709

From a comparison of the analysed standards [4-12], it was derived that they have many common general elements, for example:

- the MCHP has to be heat-led
- they refer to a control volume that includes the whole heating system, not just the MCHP
- they require only a limited number of tests, both at nominal operating conditions and according to appropriate test cycles
- they specify the equipment and instrumentation required, such as sensors' accuracy
- they define the reference testing conditions (supply and return water temperatures, etc.)

Nevertheless, some major differences can be detected; for example, they differ in terms of:

- the limiting value of power (electric, thermal or primary) in terms of applicability
- the thermal load profiles:
  - the Italian standard defines four day types
  - the German standard defines a single profile
  - in the UK standard, the heat-load profile is represented by the number of days per heating season with 13 part-load bands
- the type of energy performance parameter, that can be either energy based or environmental based

However, in conclusion, the analysed national standard methodologies seem to be based on the same fundamental elements. These elements can be also applied for the performance evaluation of micro-cogeneration systems, either for experimentally based assessment studies, or for experimental calibration and validation of models to be used in simulative analyses.

## 4.3 Review on National Studies

In the framework of Subtask B of Annex 54, contributing groups developed (mainly by simulation) a library of, among other variables, country-specific simulations, experimental and field test studies covering several technology types and combinations, climatic conditions, and end-users. These studies evaluated the performance of different micro-generation configurations (hybrid, poly-generation, etc.) within different operational contexts, and produced country-specific performance-related data.

The aim of this section is to highlight the main results of the performance assessment carried out in the country-specific studies, as well as in other analyses developed by Annex 54-participating countries.

### 4.3.1 Country-Specific Simulations, Experimental and Field Test Studies based on CHP systems

#### Japan

A performance assessment study was conducted for a number of micro-combined heat and power generation systems in residential buildings in Japan, [4-13]. The authors developed a residential energy end-use simulation model, in which the entire household stock was classified into several categories according to a number of criteria that directly affect energy consumption. This model can estimate all the demand profiles at five-minute intervals. Furthermore, household types are divided into detailed categories in order to account for the variation among households.

The performance in terms of primary energy consumption, CO<sub>2</sub> emissions, and cost was analysed for different cogeneration technologies, namely natural gas-fuelled ICEs (MGE), polymer electrolyte membrane fuel cells (PEFC) and solid oxide fuel cells (SOFC). Conventional systems and a condensing water heater (LHB) were also evaluated as controls.

These systems were examined for 19 household categories (that differ for the number of household members, family composition, and the number of employed household occupants), 12 building types (six categories for detached houses and six categories for apartment houses, according to floor area), and four different thermal insulation levels.

Simulation models for conventional and cogeneration systems were developed. In these models, the efficiency of each system was defined based on the manufacturers' design value.

The rated power generation capacity ranged between 0.5 and 1.5 kW for each household category.

In this study, only domestic hot water preparation was considered to be covered by micro-cogeneration systems and water heaters. All electricity from micro-cogeneration was assumed to be consumed in the residence. The capacity of MCHP units was optimized for the electricity and heat demands of each house.

Electricity and gas tariffs, weather data, and annual primary energy consumption of the residential sector of Osaka City (population: 2.6 million, households: 1.2 million) were used.

Fig. 4-4 shows the total annual primary energy consumption for a four-member family.

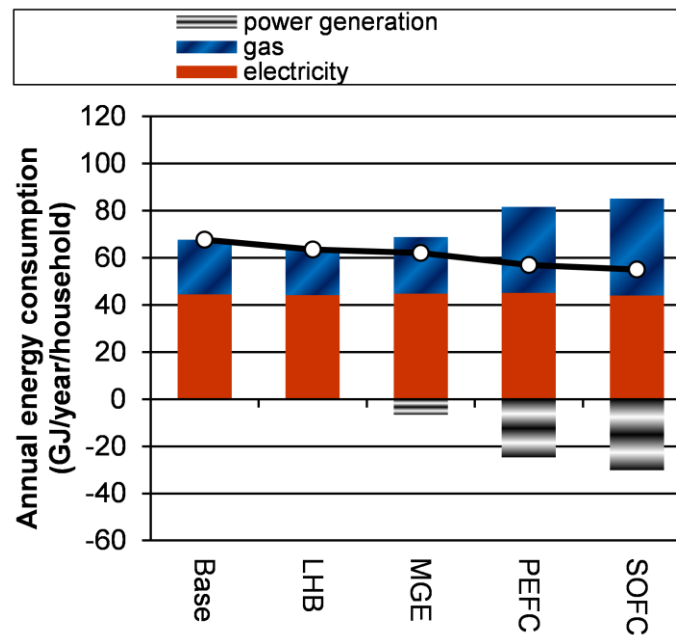


Figure 4-4: Total annual primary energy consumption for a four-member family

Negative values mean power generation by micro-generation. Total energy consumption is shown as a bold line. Since SOFC was operated in response to the electricity demand due to a lower heat-to-power ratio, it generated approximately two-thirds of the total electricity consumption. SOFC also demonstrated the highest energy reduction rate from the baseline, 15–20%.

A further result of the study is that the performance of cogeneration systems strongly depends on the household type (number of household members).

### Italy

The performance of a residential building-integrated micro-cogeneration system during the heating season has been investigated using building-simulation software (TRNSYS), [4-14].

The micro-generation system was based on a natural gas-fuelled RIC engine-based cogeneration unit with nominal electric and thermal output rated at 6.0 and 11.7 kW, respectively. Auxiliary thermal energy was supplied by a natural gas-fired boiler; the heat was provided by both the MCHP device and the boiler, and was accumulated within a storage tank. The cogeneration system supplying thermal and electric energy to a multi-family house was compliant with the transmittance values suggested by Italian Law. In order to evaluate the influence of the climatic conditions, the analyses were performed by considering a multi-family house located in four different Italian cities (Palermo, Napoli, Roma, and Milano), representing the different Italian climatic conditions. System operation was also evaluated by considering two different electric-demand profiles; in the first, the operation of lighting systems and other domestic appliances was considered, while in the second, the electric consumption associated to the overnight charging of an electric vehicle was added.



The energy, environmental, and economic sensitivity analyses were performed with both electric and thermal load-following control strategies of the MCHP. For each scenario, the simulated performance of the MCHP was compared with the performance of a conventional system consisting of a natural gas-fired boiler and an electricity supply from the national grid.

The cogeneration unit was simulated by using the detailed dynamic model developed within Annex 42. It was calibrated and validated on the basis of laboratory tests performed by the Second University of Naples.

The combined tank for both heating purposes and domestic hot water production was modelled by means of the “Type 60f”. The optimal value of the tank volume was determined by carrying out a sensitivity analysis; three different commercially available hot water storage tanks, characterized by different sizes, were considered: TANK1 = 0.855 m<sup>3</sup>; TANK2 = 0.738 m<sup>3</sup>; TANK3 = 0.503 m<sup>3</sup>.

The layout of the building is a multiplication of a single-family house-type building geometry. All three floors have the same useable floor area (96.0 m<sup>2</sup>) while the net height of each floor is 3.0 m. Fan-coils are installed into the building in order to balance the space-heating sensible load.

The quantity of heat originating from occupants, personal computers, and lighting systems was assumed to contribute to the internal gains of the building. The “Type 56a” was used for modelling the building envelope, indoor air set-point temperature, infiltration, and internal gains.

The domestic hot water demand profile, with an average basic load of 200 L/day, was used for estimating the demands of each flat, according to the profiles defined within IEA/SHC Task 26.

The electric consumptions of appliances were derived from a domestic electricity demand model, developed at Loughborough University (UK). The electric consumption associated to the overnight charging of an electric vehicle was derived from data provided by a manufacturer. The electricity consumption of auxiliary appliances (fans and pumps) was also taken into account.

The FESR as a function of the city, the MCHP control logic, and the electric demand profile, are shown in Fig. 4-5. It is worth noting that:

- the values of the FESR are always negative in the case of electric load-following logic and positive in the case of thermal load-following logic
- the overnight electric vehicle charging facilitates a significant increase in FESR only in the case of electric load-following operation
- for thermal load-following operation without the electric vehicle charging, the maximum value of the FESR is obtained when the building is located in Napoli or Milano

The CO<sub>2</sub> equivalent emissions of the alternative system during the complete heating season, as a function of the tank volume (TANK1, TANK2, TANK3), the city, and the MCHP control logic, have been analysed. The electric-demand profile without the overnight charging of the electric vehicle was considered. The tank with the largest volume (TANK1) facilitates minimizing the CO<sub>2</sub> equivalent emissions of the alternative system, while the tank with the intermediate volume (TANK2) provides the maximum pollutant emissions. In the case of electric load following-operation, the operation with TANK1 facilitates reduction of CO<sub>2</sub> emissions ranging from 3.6 (Palermo) to 4.7% (Milano) in comparison with TANK2. In the case of thermal load following-operation, the reduction in emissions with TANK1 was in the range of 9.1 (Napoli) to 15.7% (Milano) in comparison with TANK2. The

## 4 Performance Assessment

thermal load-following logic produces lower values of carbon dioxide-equivalent emissions in comparison with the electric load-following control strategy.

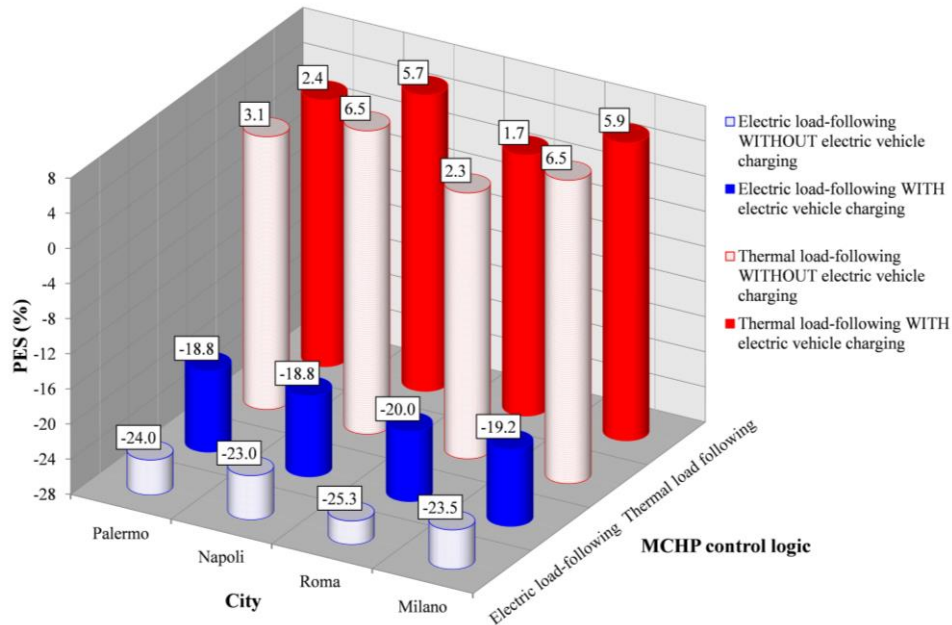


Figure 4-5: Values of FESR as a function of city, MCHP control logic, and electric-demand profile.

## Canada

A study has been performed to analyse the hybridization of a SE-based residential cogeneration system with solar thermal systems to meet the space and water heating loads of a typical Canadian family household. Simulation results from four hybrid system configurations applied in various locations in Canada are presented and compared to base case systems without solar input. [4-15]

The hybrid systems were simulated in TRNSYS for various locations in Canada representing different climatic conditions. Performance of the hybrid systems was compared with that of a reference system that did not receive renewable energy input.

A SE-based micro-cogeneration system is the heart of the Base Case system. The SE provides heat to a 284-litre DHW storage tank through an immersed heat exchanger. A second heat exchanger in the tank allows heat to be extracted for space heating through a hot water-fed air handler. The storage tank is equipped with a back-up boiler to provide additional heat in case the SE is not able to keep the DHW water at the desired temperature level.

Solar heat is used in four variants of a hybrid renewable–micro-generation energy system to replace fossil fuel energy for space heating and DHW production. In cases 1 and 2, solar heat is only used to heat DHW; in cases 3 and 4 the output of the solar collectors is used for both DHW and space heating. Cases 2 and 4 differ from cases 1 and 3 in that they have a preheat tank interacting with the solar circuit, aimed at enhancing the solar yield (Tab. 4-2).

**Table 4-2: Overview of the different system layouts considered**

	Case 1	Case 2	Case 3	Case 4
Solar DHW preparation	X	X	X	X
Solar support to space heating			X	X
Preheat tank integrated		X		X

The micro-cogenerator model was based on the Annex 42 combustion cogeneration model using a model calibration resulting from experimental testing of a modern SE. The SE was operated in an on/off mode and produced approximately 7 kW of heat.

TRNSYS “Type 539” was used to model the thermal performance of flat-plate solar collectors. The solar collector model was calibrated on the basis of manufacturer specifications. The solar collectors were assumed to be installed at the optimum angle for the investigated locations.

Heat storage tanks were modelled as vertical storage tanks with immersed coiled-tube heat exchangers, and with flow streams passing in and out of the tanks (TRNSYS “Type 534”). Each storage tank was divided into ten isothermal temperature nodes to model stratification within the tank.

The house model was based upon the twin research houses of the Canadian Centre for Housing Technology in Ottawa. A daily schedule was applied incorporating six DHW draws, totalling 200 litres of hot water each day. The main results for the simulated cases are presented in Fig. 4-6.

The Base Case system was simulated for four cities in Canada: Vancouver, Calgary, Ottawa, and Halifax. These cities represent different geographical areas and climates. The operational characteristics of the Base Case system were very similar for all locations. Cases 1 and 2 use solar heat for DHW production. The reductions in natural gas consumption and GHG emissions were 9.9% for case 1 and 12.2% for case 2 in comparison with the Base Case.

Solar heat was used in cases 3 and 4 for both space heating and DHW. The reduction in natural gas consumption and GHG emissions was 11.2% for case 3 and 10.4% for case 4, when the location was Ottawa. For both cases 2 and 3, the operation and performance of the hybrid systems were very similar over the range of heating conditions for the analysed cities.

Parameter variation cases were performed in order to investigate the effect of doubling the solar collector area, doubling the volume of the heat storage tanks, and removing the low-flow pump between the two heat storages. Furthermore, a number of simulations were performed for case 3 (Ottawa) with a variation in solar panel angle. A slightly higher angle (50°) than the 37° used in the first round of simulations was found to be favourable towards optimum overall efficiency.

With the solar panel at the optimum angle of 50°, two routes for further optimization were investigated. The first route was focused on maximizing the use and performance of the SE, while also trying to capture the greatest quantity of solar heat. Owing to its similarities to case 1, this case was called ‘Case 1–Optimized’. With a 13.7% reduction in natural gas use and associated emissions; this configuration demonstrated a better performance than both the original case 1 and case 3 with a solar panel angle of 50°.

## 4 Performance Assessment

The second route for optimization was the application of the hybrid system with a low-temperature heating (LTH) system, i.e. a floor heating system. Using a similar configuration to case 3, the results for case 3–LTH clearly demonstrate the positive effect of lower heat storage temperatures on the performance of the SE and the solar panels. The thermal efficiency of the SE increased to 73.6% in comparison with 70.5% for case 3 with solar panels at an angle of 50°. The heat production by the solar panels increased by 6%. Case 3–LTH exhibited the highest reduction in natural gas use and associated GHG emissions of all the evaluated cases: 15.0%.

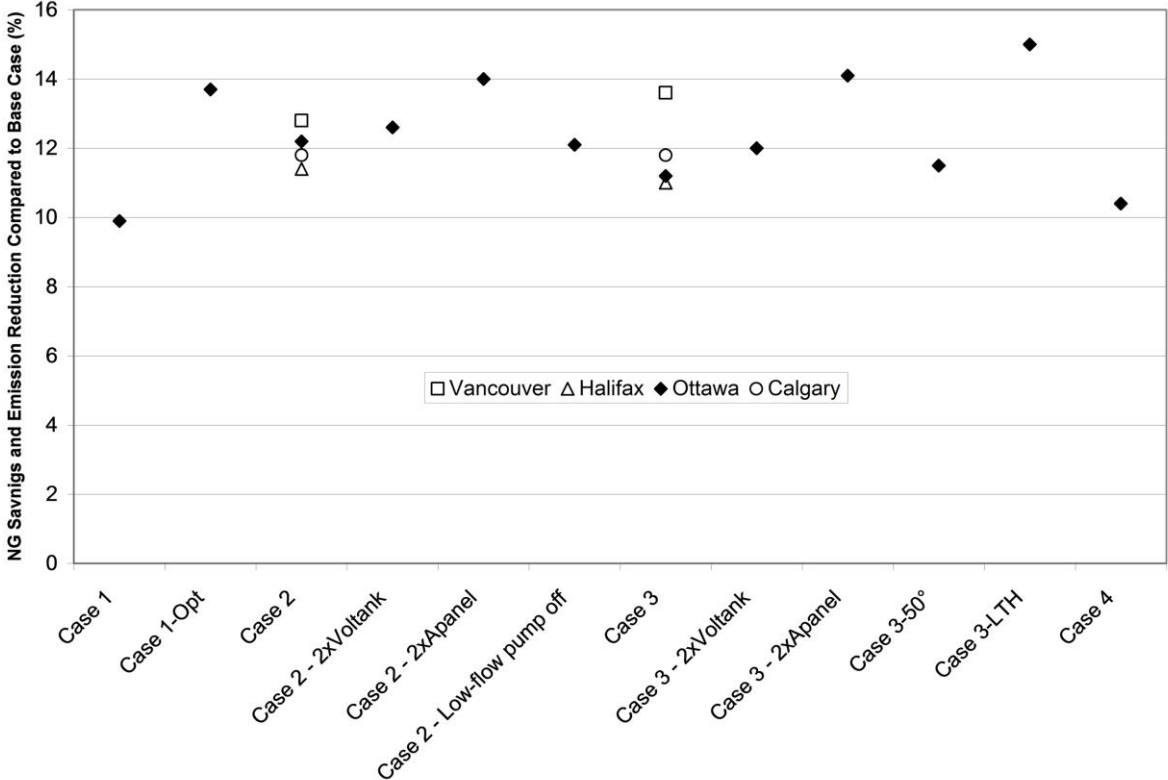


Figure 4-6: NG savings and GHG emission reduction for simulated cases in comparison with the Base Case for the same location

From this study, it was concluded that:

- adding solar collectors to a residential cogeneration system resulted in a reduction in annual natural gas consumption of 10–15%, which corresponds to a reduction of approximately 700–1200 kg GHG per house per year
- providing low heat-exchange temperatures for both the SE and the solar thermal system, as well as sufficient storage capacity for the collected solar heat is crucial for high system efficiency
- system performance increased with solar collector area
- the angle of solar panels has a limited impact on the overall system performance
- the hybrid systems demonstrated similar operation and performance when applied in four cities across Canada with a broad range of heat demands

## Germany

In order to calculate the potential of small-scale cogeneration in Germany, technical data from MCHP systems, and performance data from field tests and laboratory experiments were taken into consideration in [4-16]. The business areas were selected according to a significant heat demand, for example, a butcher shop, a small hotel, and a fitness centre. To derive the economic potential, cost data of the systems, tariffs for electricity and natural gas, and the current regulatory framework have been included.

Fig. 4-7 illustrates a sensitivity analysis of such a system. In addition, the base values for the different parameters are included in the legend. A MCHP system with a maximum electrical output of 50 kW and a thermal output of 120 kW, achieving 5000 full-load operating hours annually, is considered in the analysis.

The profit is very sensible in terms of the utilization time, the electricity purchase costs, and the investment costs. The crucial parameter is the utilization time; a decrease of only 5% would lead to an economic deficit from the CHP system.

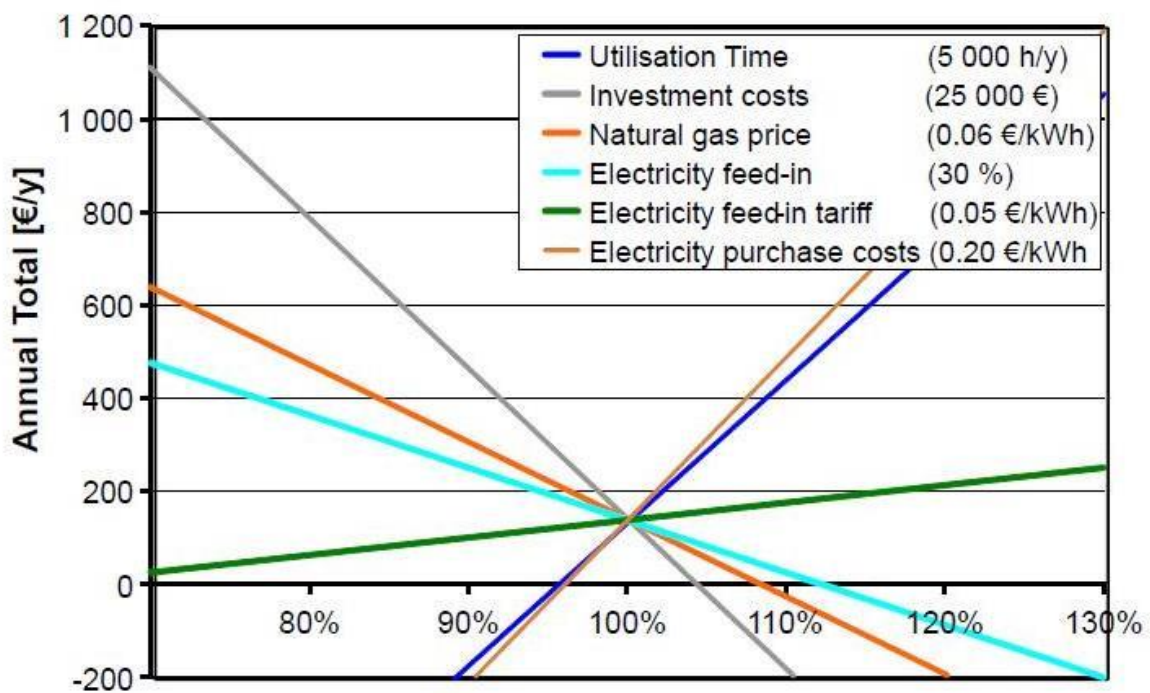


Figure 4-7: Influencing factors on annual total profit of MCHP

### 4.3.2 Country Specific Simulations, Experimental and Field Test Studies based on CCHP systems

#### Korea/Canada

The CanmetENERGY Research Centre and Korea Institute for Energy Research (KIER) analysed seven systems, incorporating conventional, micro-generation, and renewable energy technologies, for applications in residential and commercial buildings, [4-17]:

- Case 1: conventional set up – a boiler and chiller to meet the heating and cooling demands of a single detached house
- Case 2: the same conventional set up as case 1 – a boiler and chiller to meet the heating and cooling demands of an office building that has the same layout as the house in case 1
- Case 3: a simple summation of case 1 and case 2 systems and loads
- Case 4: a load-sharing setup featuring a common boiler and chiller being used to meet the combined loads of both the house and the office
- Case 5: a load-sharing case with a GSHP to meet the combined loads
- Case 6: a load-sharing case where a hybrid PEMFC and GSHP system is used to meet the combined loads
- Case 7: a load-sharing case where a photovoltaic-thermal (PVT) and GSHP system is used to meet the combined loads

As an example, the more complex system (case 7) is illustrated in Fig. 4–8.

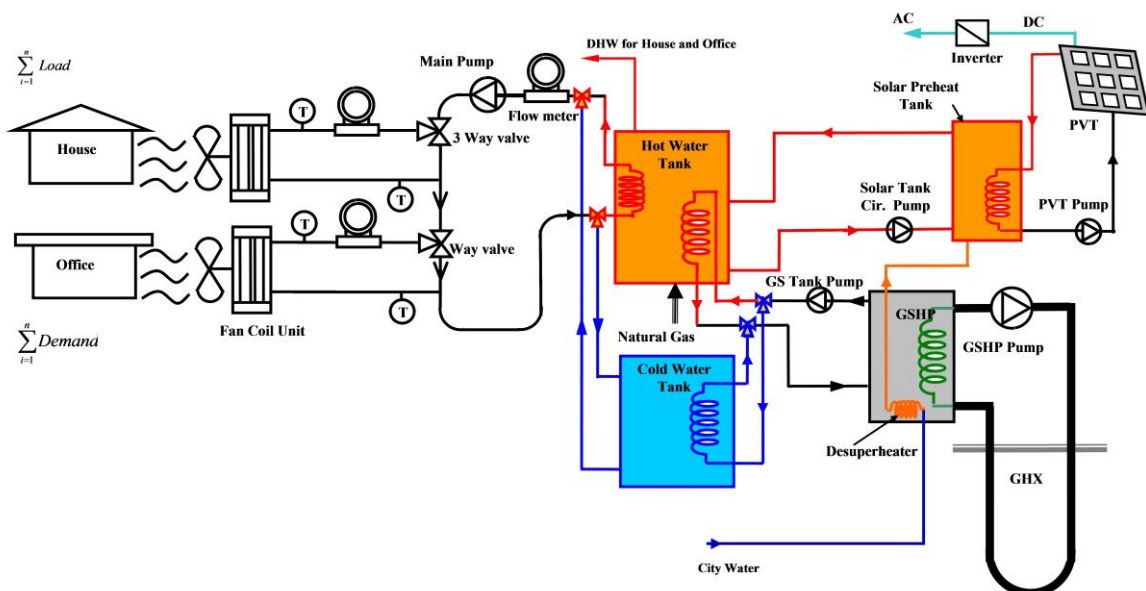


Figure 4-8: Layout of case 7.

Detailed simulation models were developed using the TRNSYS-17 software platform and were enhanced with latest manufacturers' systems performance data. The models incorporated Ottawa (Canada) weather and the data over the course of a year were analysed.

Both the thermal and non-HVAC electric loads of the two buildings (house and office) were analysed using appropriate time-series methodology. The house and office were assumed to be separate from each other, with no thermal interaction occurring between them. Both buildings were considered to have identical geometries with floor areas of 200 m<sup>2</sup>, and were assumed to have a single interior zone for the purposes of the simulations. Detailed building models were developed using typical Canadian house/office heating and cooling loads.

While significant thermal loads occur in the evening through the early morning in residential houses, the thermal loads in offices take place during the daytime. The two thermal loads have opposite profiles. In general, the separated systems are operated at very low part-load conditions during the day for houses and during the evening for offices. By combining the two opposite loads, the peak thermal demand could be reduced and, consequently, the initial capital cost could be reduced considerably. Moreover, the load-sharing system could be operated at higher part-load ratios.

The energy consumption analyses results from the seven case studies are summarized in Tab. 4-3.

**Table 4-3: Annual energy consumption, production, and savings in kWh for cases 1–7**

Energy Use (kWh/m <sup>2</sup> y)		Case 1	Case 2	Case 3 (Reference)	Case 4	Case 5	Case 6	Case 7
Space Heating + DHW Heating	Natural Gas	133	97	115	111	5	1	56
	Electricity	-	-	-	-	31	30	28
Space Cooling	Electricity	7	10	8	7	6	6	6
Non HVAC (lighting, equip., etc.)		40	52	46	46	46	46	46
Fans		6	7	7	7	7	7	7
Pumps		3	2	3	2	11	10	6
Electricity Production		0	0	0	0	0	-22	19
Total (Net) End Use		189	168	178	173	106	132	77
Energy Saving					5	72	46	101
Energy Saving (%)					3.0	40.6	25.8	56.6

The following is the summary drawn from the energy analyses and from the comparisons between the three load-sharing, hybrid renewable energy systems and the reference system:

- the consumption of a load-sharing system with separate “production” (case 4) was 3% less than that consumed by reference case 3
- case 5 exhibited an overall energy saving of 40.6% owing to the introduction of a significant renewable component
- case 6 demonstrated an overall energy saving of 25.8%

## 4 Performance Assessment

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- case 7 resulted in an overall energy saving of 56.6% in comparison with the conventional system (case 3) owing to the contribution of both geothermal and solar renewable energy
- In comparison with the reference case (case 3), the load-sharing case 4 reduced the boiler and chiller capacities by 18 and 25%, respectively. Consequently, the initial capital cost could be reduced significantly owing to both equipment quantity and capacity reduction.

### Italy I

The work of the Università e-Campus and Università Politecnica delle Marche was concerned with a performance assessment of a hybrid micro-combined cooling heat and power (MCCHP) system, consisting of a variable speed ICE cogenerator and a high concentrator photovoltaic (HCPV) system [4-18]. The hybrid system was applied to representative public buildings of a small urban area in central Italy, Corinaldo.

Three building types have been considered in the analysis: office buildings, school buildings, and sports facilities. Numerical simulations were performed in a dynamic state with “EnergyPlus” [4-19]. A virtual model was developed for each building under analysis in order to determine heating and cooling loads. A typical load profile on an hourly basis was determined for each month by simulating one full representative day in terms of climatic conditions and the building operation schedule. Input data included climatic data records of the location on an hourly basis, the geometry of the building, the characteristics of the building envelope and HVAC systems, and the operation schedules. Output hourly profiles of net heating and cooling demands were compared with measured monthly consumption data for each building in order to check the reliability of the simulation tool.

To assess the hybrid system, both HCPV and ICE have been modelled using “Matlab/Simulink”.

The complete hybrid system is made up of a MCHP based on an ICE, a HCPV unit, a thermal energy storage system, an additional heating boiler, an absorption chiller, and a vapour compression chiller. Both micro-CHP and HCPV systems are connected in parallel to the grid and to the end-user. The cooling demand can be satisfied either by the vapour compression chiller or by the absorption chiller.

Since energy, economic, and environmental performance of hybrid systems depend on several parameters including fuel tariffs, purchasing and selling price of electricity, ambient conditions, and energy loads, an optimization approach is required to assess the potential of the introduction of hybrid systems correctly.

The algorithm developed follows a multi-objective approach, aiming at minimizing operating costs, primary energy usage, and carbon dioxide emissions. For the calculation, all the three objectives have been expressed on a cost basis, and weighting factors have been defined *a priori*. Finally, a sensitivity analysis has been conducted to understand the influence of the defined weighting factors.

The objective function is given by the yearly weighted sum of operating costs, primary energy consumption cost, and CO<sub>2</sub> emission costs.

In order to assess the system performance and advantages derived from hybrid applications, two other configurations, including the single cogeneration unit and the solar power unit, have been analysed. Fig. 4-9 summarises the studied configurations, considering both the alternative (A, B, C) and conventional (D) systems.



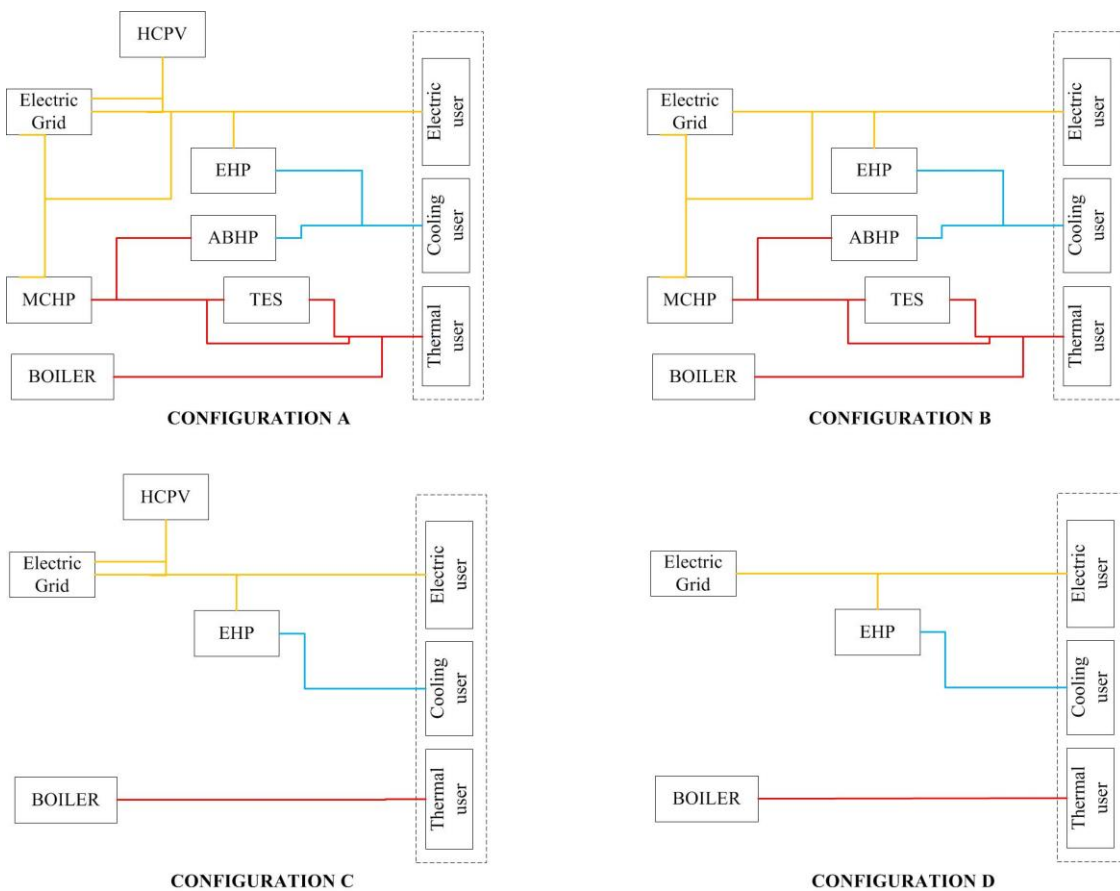


Fig. 4-9: Configurations analysed

The main results of this analysis are:

- hybrid system configurations provide energy and environmental benefits of approximately 40% in comparison with conventional systems
- the energy performance of hybrid systems is better than the single use of either MCHP or HCPV; the advantage increases when the number of MCHP operating hours increases
- assuming the same weight to all criteria, the ICE works in thermal priority in order to maximize the primary energy savings, thereby reducing CO<sub>2</sub> emissions
- the economic performance of the system depends heavily on the specific ratio between thermal and electric load, rather than on energy prices. A limited thermal load reduces the number of operating hours of the ICE, which penalizes the return on investment
- with regards to the HCPV, the high investment cost could be better recovered in regions that can be characterized by a higher value of the direct component of solar radiation
- the introduction of the hybrid system strongly cuts the operating cost by a minimum of 35% to a maximum of 60%
- the high capital investment cost can only be recovered in some cases
- in none of the cases studied, the optimal algorithm chooses the absorption chiller,
- the adoption of hybrid MCCHP by public administration provides a reduction in public expenditure and acts as an exemplary action in promoting the reduction of carbon dioxide emissions

- specific financing mechanisms should be promoted in order to overcome the problems related to high investment costs

### Italy II

In this work, performed at Università degli Studi del Sannio, a system consisting of a small scale tri-generation system, in which a heat-led micro-cogenerator interacts with a desiccant-based AHU, equipped with a silica-gel DW, is analysed [4-20].

The small-scale tri-generation system, based on the desiccant-based cooling system, provides the air-conditioning service to a lecture room (63.5-m<sup>2</sup> floor area, activation schedule from Monday to Saturday from 09:00 to 19:00) during summer and winter periods.

During the summer season, the AHU operates as a desiccant cooling system; the DW balances the latent load of the process air, while an electric chiller manages the sensible load. The MCHP provides thermal energy to regenerate the DW by means of a thermal storage tank; a peak load boiler, fuelled with natural gas, provides thermal energy integration. Electricity from the cogenerator is used to drive the electric chiller, the auxiliaries of the AHU, and the MCHP itself (fans and pumps), as well as further eventual electric appliances in the lecture room (lights, computers, etc.); this is illustrated in Fig. 4-10.

During the winter season, the MCHP and the boiler provide thermal energy for space heating purposes. Electricity is supplied to auxiliaries and electric appliances. During the intermediate season, the AHU is inactive and cogenerated electricity is supplied to electric appliances of the lecture room. Furthermore, throughout the year, the system provides thermal energy for DHW preparation, to a nearby user (a gym).

This tri-generation system was compared with a reference system (conventional system, CS) that was equipped with a conventional AHU based on cooling dehumidification for summer operation. Electricity to power an electric chiller, the auxiliaries of the AHU, as well as electric appliances, was drawn from the grid. Thermal energy for winter space heating, air post-heating during summer, and DHW purposes was provided by a natural gas boiler.

Experimental data acquired in a test facility of Università degli Studi del Sannio, in Benevento (Southern Italy), as well as data provided by the manufacturer, were used to calibrate and validate models of the main components and energy conversion devices. These models were used to simulate the current MCCHP system by means of TRNSYS software, in order to evaluate operational data and performance parameters.

A simplified MCHP model has been developed, calibrated, and validated by means of the available experimental data on an AISIN Toyota MCHP. The "TRNSYS" RIC engine model was utilised by using the "Type 907". It uses a table of performance data to determine the outputs of the engine, given a set of input conditions.

The model used to simulate the described storage tank is "Type 60", which represents the most detailed model available in TRNSYS, to simulate stratified thermal storage. By means of experimental tests conducted in the test facility of University of Sannio, the model was calibrated and validated experimentally.

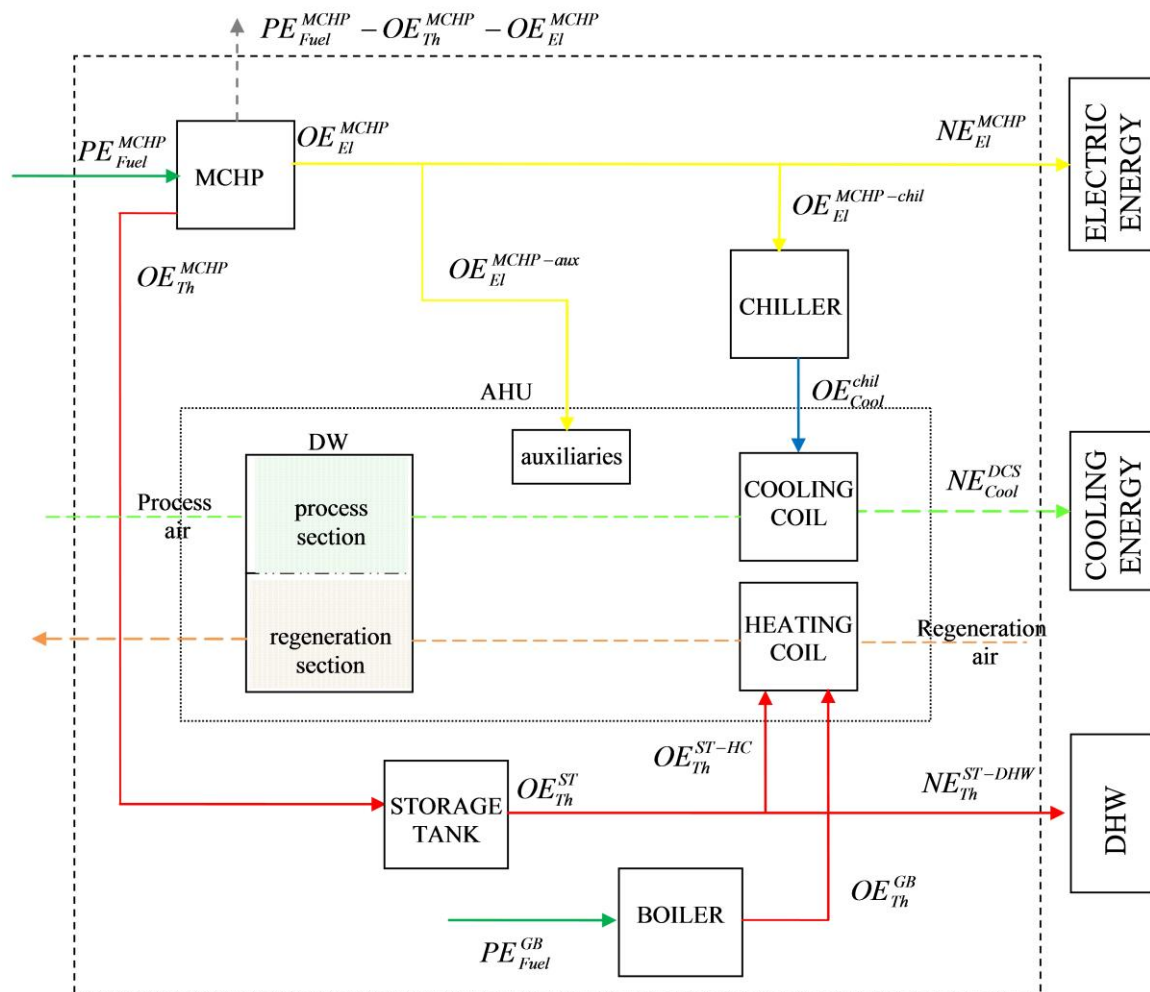


Figure 4-10: Main energy flows of the tri-generation system during summer operation

Concerning the DW, the simplified approach of Maclaine-Cross and Banks has been used to model the DW. This approach models the dehumidification process, a combined heat and mass transfer process, in a similar manner to a simple heat-transfer process. Equations for coupled heat and mass transfer were reduced to two uncoupled differential equations of two independent variables (characteristic potentials). The actual outlet conditions were then estimated using two effectiveness indices of the wheel, calculated in a similar manner to the efficiency of a heat exchanger.

The performance of the AS and CS depend heavily on several operating conditions. First, the electric demand profile, which influences the proportion of the generated electricity used on site. The best case is achieved when the maximum value of the proportion of the generated electricity used on site is assumed; for the analysed case, the maximum value of this ratio means that no electricity is drawn from the grid for electric appliances and auxiliaries, and approximately 10% of the cogenerated electricity is exported to the grid.

The analysed system performs favourably in comparison with the conventional system in terms of energy and environmental performance, achieving a primary energy saving of approximately 7% and a CO<sub>2</sub> emissions saving of approximately 15%. To ensure the economic feasibility of the system (a

quite acceptable simple payback period of approximately 9 years), it is necessary that it is possible to access support mechanisms introduced by Italian legislation for small-scale gas-fuelled tri-generation systems. This legislation includes a lower taxation on gas price, the white certificates, an investment subsidy (up to 40% of the investment cost), and the net metering scheme.

### United Kingdom

In the UK, HPs are often promoted as a means to provide low-carbon space heating and hot water for future dwellings if the electricity supply decarbonises or if they are activated by micro-cogeneration systems. However, a major issue with the diffusion of HPs powered by the grid is the additional load that this could place on the electrical network. A means to alleviate potential demand problems is to stagger the operating times of HPs by integrating them with thermal buffering. Thermal storage featuring PCM offers the potential of more volumetrically efficient heat buffering, which may be more suitable for integration into domestic heating systems.

In [4-21], the potential to shift the operating time of HPs integrated with PCM-enhanced thermal storage was assessed and compared with conventional hot water storage. In particular, an integrated “ESP-r” model of a conventional UK detached dwelling (usable floor area of 136 m<sup>2</sup> spread over an upper and ground floor), featuring an 11-kW nominal thermal output ASHP heating system, was used to investigate the potential for PCM thermal storage.

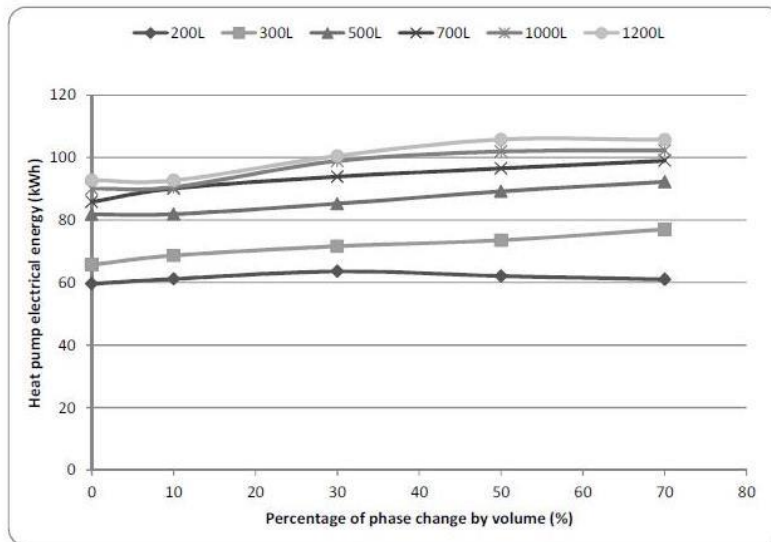
The operating times of the HP were set to off-peak periods (when the house was unoccupied or when the occupants were asleep) whilst the volume of the thermal buffer was varied from 200–1200 L and the percentage of PCM (by volume) was varied from 0 to 70%. The performance of both the buffered systems (with and without PCM) was compared with the system with no load shifting, where the HP was connected directly to the heating circuit and the DHW tank (reference case). In the unbuffered system, the hours of heating operation were set to the periods of active occupancy within the dwelling.

The simulations were performed for winter, spring, and summer weeks for warm (southern England) and cool (north east Scotland) climates. In total, 186 simulations were performed. The results indicated that, in all cases, the size of the PCM-enhanced buffer tank could be reduced by between two–three times in comparison with the system incorporating hot water buffering. However, thermal buffering with load shifting can increase HP energy demand and (at present), in the UK, results in increased emissions and cost penalties for the end user. These results may change in the future as the energy mix of the UK electricity system changes and if tariff structures are revised to encourage load shifting.

Fig. 4-11 illustrates that, in the case of the warm-climate winter week, increasing the buffer size and the addition of PCM to the buffer tank increased the electrical energy consumption of the HP. In the worst case, the PCM-enhanced buffer resulted in a 38% energy penalty in comparison with the reference case.

The increased HP electrical energy use is attributable to two main causes. First, the addition of the buffering tank introduces extra standing system losses. Second, the COP of the HP is reduced by up to 15% owing to the addition of a heat exchanger in the buffer (it is necessary to supply water to the

buffer at a higher temperature) and because the HP operates at off-peak times when ambient temperatures are lower.



**Figure 4-11: Electrical energy consumption of a HP with operation shifted to off-peak against % of PCM in a buffer tank for different buffer-tank volumes; plotted data are from the warm UK climate, winter-week.**

## Conclusions and “rules of thumb”

From the analysed national performance assessment studies, it can be concluded that fossil fuel-based micro-generation systems can achieve primary energy and emissions savings in the range 5–20%, depending on the type of system and applications. These savings increase up to 40% when renewable energy technologies are involved in hybrid micro-generation systems. A maximum value of 60% was found, in terms of primary energy and emissions savings, when more than one renewable energy source was exploited (e.g. geothermal and solar energy).

In terms of economic performance, significant capital cost savings (approximately 20–30%) can be obtained; however, very often, the initial installation cost is still considerably high, especially for very complex small-scale tri-generation systems, determining quite long periods to recoup the initial financial outlay, even assuming that all the support mechanisms introduced by national legislation are achieved effectively. Consequently, specific financing mechanism should be promoted in order to overcome the problems related to high investment costs. Moreover, a reduction in the installation costs charged by manufacturers and distributors of high-efficiency energy conversion devices would also be highly desirable.

In conclusion, it should be highlighted that the aforementioned energy, environmental, and cost benefits can be achieved if the following main “rules of thumb” are observed:

- the energy-saving effects differ with household-type; therefore, an optimal solution exists for each household category

- the best energy, environmental, and economic performance are obtained with thermal load-following logic of the MCHP, rather than electric-load following logic
- the benefits increase when the utilization time of the micro-generation system increases
- the performance of the system depends heavily on the ratio between thermal and electric load
- the correct sizing of the storage tank is a crucial issue because it allows the optimization of the performance of the micro-generation system
- the thermal recovery circuit should be properly designed, to maximize the performance of combustion based devices and solar thermal systems
- the performance of micro-generation systems strongly increases with the proportion of the generated electricity used on site
- the inclusion of the overnight charging of an electric vehicle in the demand profile provides better results of the MCHP, if the MCHP unit is operated with electric load-following logic
- higher operational energy savings can be achieved with the load-sharing approach, with optimal system sizing and appropriate control strategies implemented
- presently, an electrically driven cooling device is preferable to a thermally activated device (absorption chiller or desiccant cooling system) in small -scale tri-generation systems; this is because the former allows higher overall efficiency to be achieved
- the economic feasibility of micro-generation systems is very practical in terms of the electricity purchase costs and the investment costs
- with progressing market penetration of micro-generation technologies, lower investment costs and better profitability can be expected

## 5 Drivers of Commercialization and Support Mechanisms

A number of countries and regions aspire to improve energy efficiency, strengthen energy system security and resilience, and achieve significant reductions in GHG emissions in the coming decades. Tackling these multiple aims will require a far-reaching overhaul of energy systems in a number of cases. Change is necessitated in all aspects of the energy system, from core infrastructure, through transformation, to changes in technology choice and behaviour in the end-use sectors.

Whilst some measures to improve energy-system performance bring “no regrets” in the sense that they are cost effective, it is clear that interventions will be required that are more expensive than the status-quo if long-term goals are to be achieved. This poses a problem for governments in that it implies that regulations and incentives are required to ensure an appropriate optimum is reached, rather than each individual or company behaving in a self-interested or uninformed fashion, and simply adopting the least expensive and/or most convenient energy solution.

Micro-generation and associated technologies are a good example of a possible solution to the energy challenge. They are often low-carbon technologies, and generally offer a less-attractive economic proposition than current energy provision options. However, they can provide a level of decarbonisation, a reduction in primary energy consumption, and they may even result in improvements in the resilience and security of energy systems in some cases. Technologies such as these are important candidates for government interventions, enabling them to gain a market share commensurate with their system-wide and broader social value.

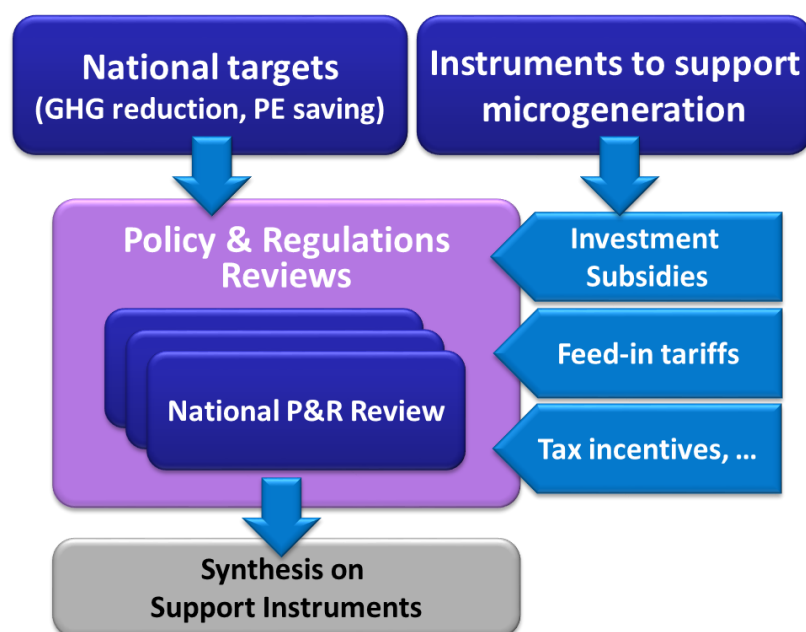


Figure 5-1: Structure of policy and regulation analysis

Subtask C of Annex 54 has provided an evidence base for decision makers considering support mechanisms for micro-generation (Fig. 5-1). No specific technology or approach is advocated but an independent view of the approaches that have been implemented in various jurisdictions is presented. The potential of support mechanisms or regulations to influence technical performance was also investigated, highlighting that some mechanisms can lead to unintended consequences.

### 5.1 Landscape of Support Mechanisms

This section presents and discusses a selection of the range of support mechanisms available to incentivize the adoption of micro-generation systems. An important caveat to this material is that the support mechanisms can change quickly. *As such, this report provides a snapshot of approaches over the lifetime of the Annex, which spanned the years 2009 through 2013. The reader should refer to primary sources to obtain information on the current arrangements.*

Feed-in tariffs (FiTs), grants, building regulations, and the role of micro-generation and associated technologies in smarter energy systems are discussed below. Details of further instruments are presented in the Annex 54 Subtask C report, “A Comparative Review Of Microgeneration Policy Instruments In OECD Countries” [5-1].

#### 5.1.1 Feed-In Tariffs for Microgeneration

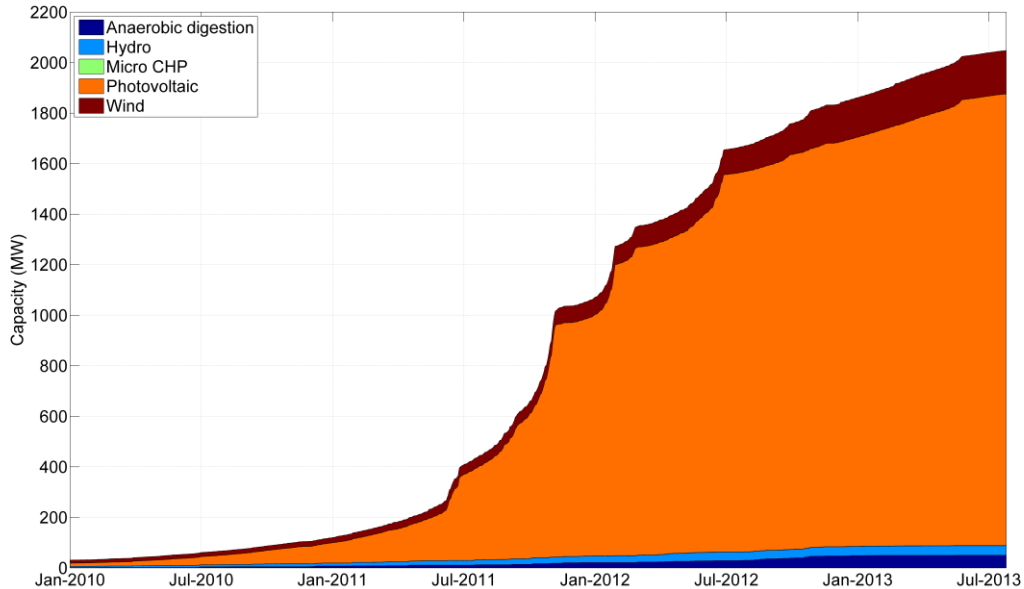
FiTs have been the support instrument of choice in supporting micro-generation uptake over the past 5–10 years, with prominent examples found in Germany, Spain, Italy, and the UK. However, there is great diversity of arrangements that fall under the FiT category [5-2], with differing set-ups for the significance of rewards (e.g. export tariff versus generation tariff). These include cost containment methods, stated reasoning behind rate decisions, and the presence of underpinning laws to create confidence for the supply chain and relevant beneficiaries that the level of support will not be withdrawn suddenly.

The key benefit of FiT instruments is that most implementations provide for a positive rate of return on the investment in micro-generation systems, meaning that the technologies are almost guaranteed to be economically attractive. Additionally, particularly in the case of PV technology, FiTs have proven to be a popular instrument, driving significant uptake in many jurisdictions. A review of the characteristics of each FiT mechanism reviewed is shown in Tab. 5-1, and the observed uptake under the UK FiT program is illustrated in Fig. 5-2.

The key criticism of FiT instruments is that they do not provide direct assistance with capital costs. Even where a consumer has capital available, they may be unwilling to make an investment in an arrangement with a long-term return on the investment (i.e. empirically, the consumer appears to have a high opportunity cost of capital). Proponents of FiTs argue that consumers do have access to financing mechanisms to offset this drawback, and some jurisdictions even provide this access, such



as the Green Deal in the UK<sup>2</sup>, which goes as far as to attach the financing to the property rather than the investor, thereby also circumventing the “split incentives”<sup>3</sup> barrier.



**Figure 5-2: UK micro-generation installations under a FiT mechanism [5-3]**

Overall, the application of FiT instruments up until the time of writing can best be characterized as a “learning experience”, with many examples of support leading to unintended consequences, particularly relating to cost containment of the mechanism. In response to these issues, there has been an increasing tendency towards the tuning of FiT mechanisms to encourage or restrain demand for micro-generation installations (by increasing or decreasing tariff rates). Such approaches may better enable cost containment alongside achieving uptake targets.

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<sup>2</sup> The Green Deal incorporates a “Golden Rule” whereby loan guarantee support is only available if the technology can pay for itself over its lifetime. For many micro-generation technologies this is a challenging rule to satisfy.

<sup>3</sup> Split incentives refers to the principal-agent problem, where the investor in a measure cannot benefit from the savings it provides. This occurs in situations such as a landlord investing in a measure (where tenants receive the energy savings benefit) or householders investing in a measure and then moving house (where the new owner/tenant benefits).

## 5 Drivers of Commercialization and Support Mechanisms

Table 5-1: FiT mechanisms for micro-generation in a selection of OECD countries [5-2]

Country	Fixed or Premium FiT	Generation or Export Tariff	Timespan	Technology Coverage	Return on Investment	Tariff change mechanism
<b>Italy</b>	Premium	Generation	15 years	RES	6–12% [4]	Degression Cap on yearly cost of € 6.7 billions
PV under separate law Conto Energia, 20 years' support. 16 GWel installed as of October 2012, only 0.4 GWel of this at residential scale 1–3 kWel. Net metering for high efficiency CHP up to 200 kW.						
<b>Japan</b>	Fixed	Export	10 years	PV	No data	Review
The Japanese government was considering a “generation” tariff for all RES at the time of writing.						
<b>Germany</b>	Both	Both	20 years	RES, $\mu$ -CHP	5–7%	Degression Cap on installed capacity of 52 GW
Formal price review every 4 years. Priority T&D access. Separate tariffs for grid export and own-use. Cogeneration is also exempt from energy tax for fossil fuels – for natural gas this is 0.00511€/kWh. Hydropower receives 15 years' support. Biomass systems 15-year timespan, 10 years or 30,000 hours for $\mu$ -CHP						
<b>UK</b>	Fixed	Both	20–25 years	RES, $\mu$ -CHP	5–8%	Degression
Micro-CHP pilot only for the first 30,000 installations, only <2kWel. Systems receive technology-differentiated reward per kWh generation, plus additional reward for electricity exported (identical across techs).						
<b>Canada (Ontario)</b>	Fixed	Generation	20 years	RES	11%	Price review every 2 years. Inflation adjustment.
Introduced by Green Energy Act, 2009. Priority T&D access, with Economic Connection Test. Re-distributed via utility bills. Hydropower systems receive 40-year support.						
<b>USA (Oregon)</b>	Premium	Generation	15 years	PV	No data	Review by Oregon Public Utility Commission
Capped at “net metering” level (i.e. no aggregate production). Retail electricity rate is subtracted from the FiT payment.						
<b>Spain</b>	Both	Generation	15–25 years	RES	No data	Capacity-related degression. Inflation adjustment
Dynamic between fixed and premium FiT models, where investors can choose between mechanisms. Re-distribution mechanism ineffective as price to final consumers in Spain is regulated.						
<b>Korea</b>	Fixed	Generation	15 years	RES	No data	Review
498 MWel of PV power plant installed by 2011. For PV, in 2012 the system has been replaced by a market mechanism (Renewable Standard Portfolio)						

### 5.1.2 Grants

Before the introduction of FiTs, grant mechanisms were the most widespread means of incentivising the adoption of micro-generation systems. Indeed, they continue to be an important mechanism, with a range of examples in place throughout the OECD. Even grants that are relatively small with respect to the overall cost of the equipment can be effective in certain circumstances.

The main advantage is that grant mechanisms provide support to cover high-investment and installation costs, or to create the conditions to kick-start a market of low-carbon technologies. Two generic approaches to grant mechanisms can be identified via a review of instruments in place in OECD countries:

- (1) those intended to support commercialisation of a new technology; these are characterised by relatively large grants that decrease over time as the cost of the technology (ideally) decreases
- (2) those intended to support conventional micro-generation systems because they are more efficient, lower carbon, etc.

An example of the first case is that of ENE-FARM in Japan, where grants supported the uptake of fuel cell micro-CHP technologies when their capital cost was very high. This has resulted in a continuous increase in the sales volume concurrent with continuous reductions in capital cost [5-4, 5-5]. Data from the ENE-FARM support programme are presented in Figure 5-3. By the end of 2012, approximately 40,000 fuel cell micro-CHP installations had been completed in Japan. Furthermore, the government proposed support for 36,000 more installations in 2013.

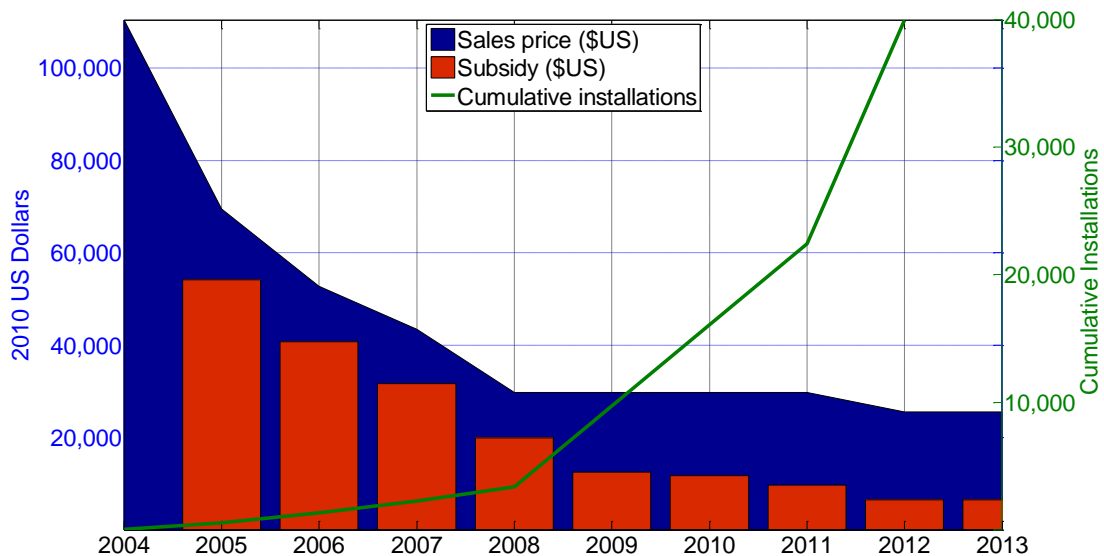


Figure 5-3: Historical selling price, government subsidy, and cumulative number of installations for ENE.FARM micro-cogeneration systems in Japan based on data from Staffell and Green [5-4, 5-5]

### 5.1.3 Building Regulations

The relationship between building regulations and micro-generation is often overlooked. Increasingly, the remit of building regulations is extending beyond aspects of a building's shell including such areas as insulation, glazing, and air tightness; regulations are beginning include the technologies within the building as well. This is particularly true of heating and cooling micro-generation systems owing to their inherent relationship with thermal performance and their importance in achieving energy or carbon standards in the built environment.

An area of specific note with respect to micro-generation is net-zero-energy or net-zero-carbon building performance standards. Such standards for new buildings are being proposed for implementation in many OECD countries during the next decade. This development is particularly apparent in Europe, where the recast of the European Performance in Buildings Directive [5-6] (EPBD) asks member states to implement an optimal-cost level of minimum energy performance standards, with all new buildings being net 'zero energy' from 2020 onwards. Net-zero-energy and net-zero-carbon standards are potentially very important for micro-generation because onsite electricity-generating capacity can be installed, and the related electricity export can be used to offset onsite energy use or carbon emissions; this makes it possible to achieve the "net zero" standard. Even where standards do not strive for the "net zero" outcome, micro-generation can be an important part of mitigating building net energy consumption and emissions. The implementation of future building regulations is clearly very important for the future of micro-generation systems. Nevertheless, the fundamental intention of regulations is and will remain related to building shell energy efficiency; however, alongside this, decision makers should consider the impact of proposals on micro-generation technology and allow it to make an appropriate contribution.

### 5.1.4 Regulation for Smarter Energy Systems

A further potential role of micro-generation systems and associated technologies is in achieving a more integrated and coordinated energy system, also known as a "smart" energy system. Micro-generation systems and associated technologies, such as electricity and heat storage, could be important in this context because they provide a potential demand-side bridge between electricity, gas, heat, and possibly more energy vectors. This would enable support of the broader energy system via arbitrage between these resources. The potential benefits of more integrated and coordinated energy systems are:

- Enabling the generation of a higher portion of large-scale intermittent and/or base-loaded carbon at a lower system cost. This could be achieved by allowing micro-generation and distributed storage to aid the balance of large-scale supply and demand.
- Enabling switching between low-carbon energy vectors according to their availability, cost, and infrastructure constraints. For example, use of bivalent micro-generation heating systems to switch between gas and electricity for final energy consumption.
- Designing integrated packages of decentralised energy resources to defer or avoid infrastructure investment and to support hour-to-hour system operation. For example, installing a micro-CHP in dwellings alongside HPs in nearby dwellings in order to achieve a balance in the aggregate network load.

- Improved energy system resilience where demand and supply are more controllable and responsive. For example, situations where sets of micro-generation systems can function together, acting as a “virtual power plant”.

Furthermore, a smart energy system could integrate micro-generation with other decentralized energy resources such as manipulation of demand and energy storage. This could be useful in balancing intermittent renewable sources, deferring network and generation asset investment, and could help to achieve tighter integration between energy vectors at the point of end-use.

### 5.1.5 Summary of Support Mechanisms

A wide range of different support mechanisms have been used to encourage the adoption of micro-generation technologies. For the countries reviewed, and within the timeframe of ECB Annex 54, the types of measures employed and the technological coverage are summarised in Tab. 5-2.

Table 5-2: Support mechanisms for micro-generation systems in a selection of OECD countries

Country	Fixed or Premium FIT	Grant and subsidies	Trading mechanism	Tax reduction
UK	RES-E, RES-H	RES-H	μ-CHP, RES-E <sup>#</sup>	RES
Germany	RES-E, μ-CHP	μ-CHP		RES, μ-CHP
Italy	RES-E; RES-H (solar collector, biomass); HP		μ-CHP, RES-E	
Japan	RES-E <sup>##</sup>	μ-CHP (fuel cell) RES-E (PV)	RES-E	RES; μ-CHP
Netherlands	RES-E	RES-H (solar collector); HP; μCHP		
Canada	RES-E*	RES-H (solar collector); μ-CHP**		RES
Flanders (Belgium)		RES, μ-CHP***	μ-CHP, RES-E	RES (biogas, biomass, solar, geothermal), μ-CHP
Korea	RES-E	RES		RES

\* Available only in some provinces; \*\*concluded in 2012; \*\*\*defined for ecological investment including μ-CHP; <sup>#</sup>CERT and ECO scheme include microgeneration, although rarely used; <sup>##</sup>from 2012;

The confluence of net-zero-energy/-emissions building regulations, financial support via FiTs or grants to support the market while it matures, and the longer-term prospect of a more integrated

and coordinated energy system all point to a promising future for micro-generation systems and associated technologies. Key challenges remain in overcoming practical barriers, supporting R&D appropriately to drive down costs, and in increasing the acceptance of these alternative technologies in consumer markets.

### 5.2 Micro-generation Economics with Support Mechanisms

#### 5.2.1 Economic Performance Assessment with Support Mechanisms

The economic aspects of performance assessment in Annex 54 largely followed the Annex 42 performance assessment methodology. The revised performance assessment approach is presented in section 4.1 of this report. Further economic assessment was also performed in order to assess the impact of support mechanisms in contributing countries. To support this analysis, a simple assessment tool was developed to enable the calculation of parameters such as net present value, payback period, CO<sub>2</sub> savings, and primary energy savings. The flowchart for this tool is presented in Fig. 5-4.

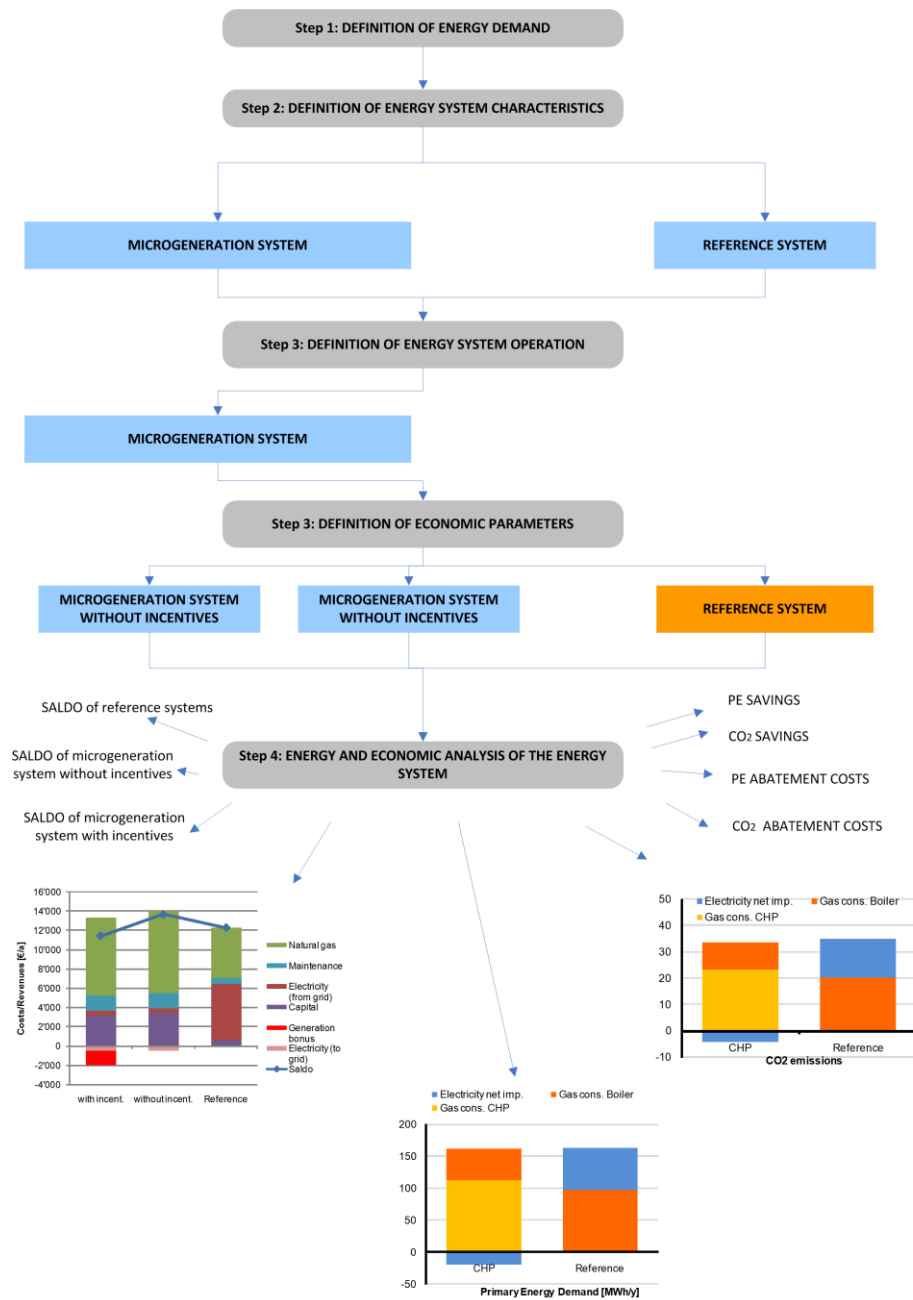
#### 5.2.2 Economic Performance with Support Mechanisms

Through the application of the tool presented in Fig. 5-4, the effects of changes in the economic situation on the costs of a range of micro-generation systems were investigated. While direct comparison between technologies, sites, and countries is not usually appropriate, it is possible to draw some crosscutting conclusions.

One important observation is that the level of support offered differs very substantially between countries. For example, support for micro-CHP systems in Germany, Italy, and the UK led to a positive economic situation for the consumer. Support in Belgium and the Netherlands was more modest. However, over the life of the Annex 54, substantial changes in the structure and level of support were observed. A prime example of this was South Korea, where small incentives were replaced by large 50% grants on capital costs. This highlights the rapidly changing nature of recent government interventions. These interventions can be considered positive when support is generally improving, as has been the case in the years up to the time of writing, but can also be cause for concern for supply chain investors; this may result in a perceived risk that support will be withdrawn suddenly.

Three examples of the economic case, from the consumer's perspective, for micro-CHP systems operating in Germany, the UK, and Japan are illustrated in Fig. 5-5, 5-6, and 5-7. While the level of incentives differs in each country, and the aggregate effect differs, the net result in each case is that micro-CHP becomes economically attractive to the consumer after the incentives are taken into consideration. The reader should refer to Annex 54 Subtask C report, "Impact of Support Mechanisms on Microgeneration Performance in OECD Countries" [5-7] for details of each jurisdiction assessed, details of the technical system and economic characteristics, and details of the support mechanism considered.

## 5 Drivers of Commercialization and Support Mechanisms



**Figure 5-4: Flow chart of a simple tool to calculate the economic performance of micro-generation systems with and without support mechanisms**

## 5 Drivers of Commercialization and Support Mechanisms

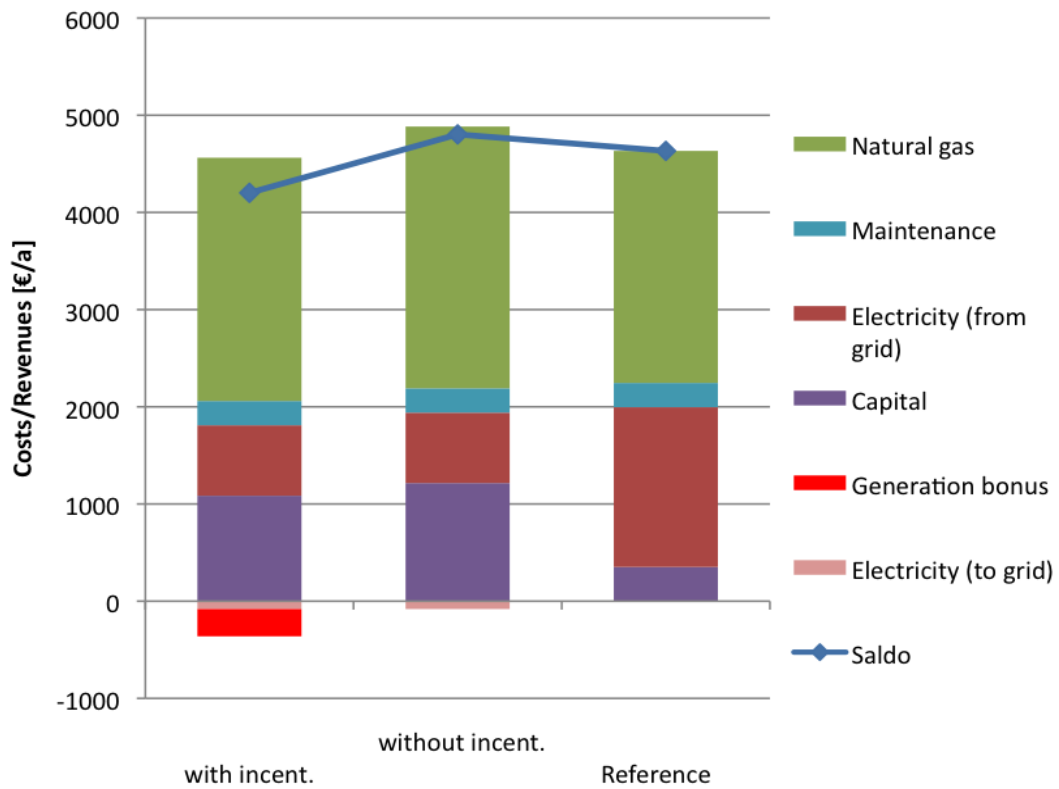


Figure 5-5: Comparison between the micro-CHP case, with and without incentives, and the reference case, in Germany

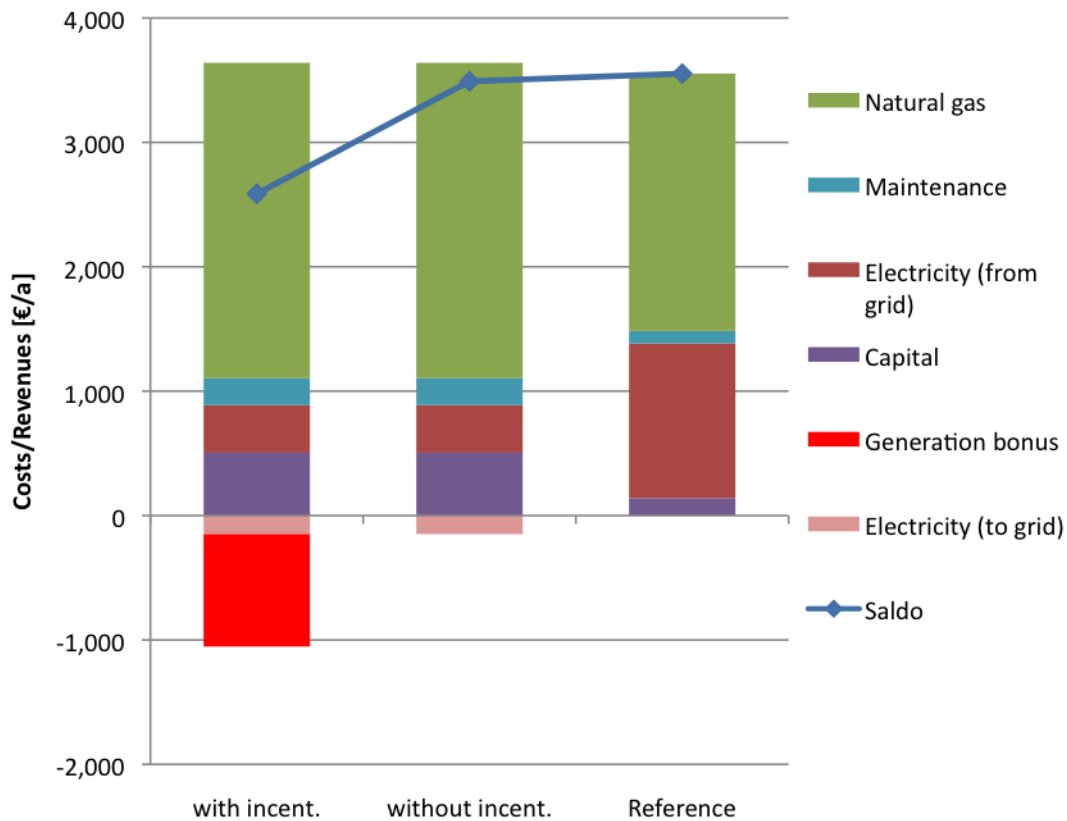


Figure 5-6: Comparison between the micro-CHP case, with and without incentives, and the reference case, in the UK.



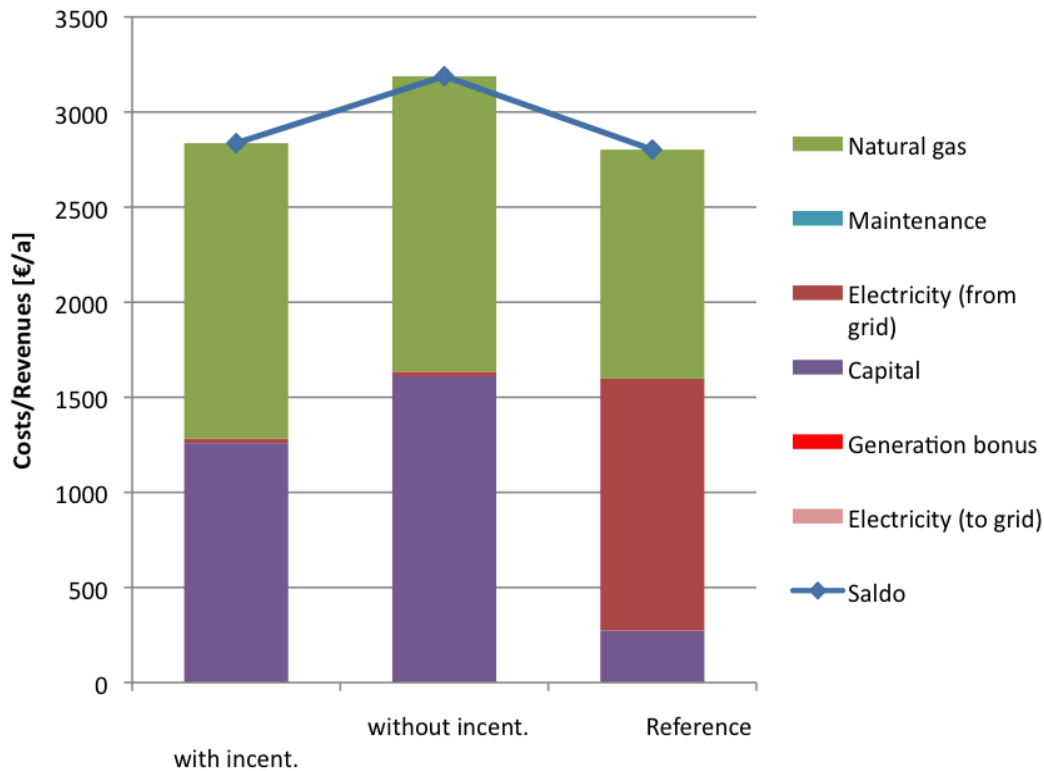


Figure 5-7: Comparison between the PEMFC case, with and without incentives, and the reference case, in Japan.

### 5.2.3 Advanced Performance Assessment with Support Mechanisms

In addition to the simple assessment tool applied above, more advanced methods for performance assessment were developed in the Annex. Specifically, optimisation models were applied in the Flanders and Italian case studies. The use of optimisation models facilitates the assessment of the best strategy for the management of the systems, where the incentives created by a support mechanism are considered endogenously. Both investment and operating strategies are optimised to maximise both energy and economic savings for the consumer.

The Flanders study assessed the possibility of integrating a group of micro-CHP technologies in the Belgian balancing market. In order to assess the economic benefits derived from entering the market, a mixed integer linear programming model was applied. It was demonstrated that the real-time profits could be improved for the CHP systems if they *do not* benefit from specific supporting mechanisms (for the Flanders case, the specific mechanism was CHP certificates). This can be explained by the fact that without certificates, the motivation to maximise CHP output is reduced, and, consequently, greater up-regulation is possible. Therefore, the balancing market itself could be an effective support mechanism for CHP, even more so than conventional certificate-based systems.

In the Italian case, a multi-objective optimisation procedure was developed with the aim of studying a hybrid micro-generation system under variable electricity prices. The system consisted of a variable-speed ICE co-generator and a HCPV system. Three main criteria were considered, the minimisation of; i) operating costs, ii) primary energy usage, and iii) carbon dioxide emissions. An interesting result of this study was that no difference in operating schedule was observed between

## 5 Drivers of Commercialization and Support Mechanisms

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cases with and without incentives (when the same weight is given to the three criteria). The primary effect of the support mechanisms was a strong reduction in the payback period, sufficient to enable a good economic case for the hybrid renewable micro-generation system. However, when only the cost is minimised, the optimal operation schedule of the system changes in comparison with the case where incentives are offered. Specifically, the micro-CHP unit is only used when the electricity price is high. The net result is that the total site energy bill decreases, but this is accompanied by a slight increase in both carbon dioxide emissions and primary energy consumption.

## 6 Summary, Conclusion and Outlook

### 6.1 Summary

Annex 54 of the IEA/EBC programme was established in 2009 to examine the building integration of micro-generation technologies. The focus was expanded from single cogeneration units towards micro-generation systems that supply buildings with electricity, heating energy, and cooling energy.

Based on the work performed within Annex 42 on the modelling of micro-cogeneration systems, these models should be further developed and expanded. Other energy supply technologies such as PV, HPs, and chillers should be included. Thermal and electrical storage systems should be investigated. State-of-the-art building simulation tools should be used to facilitate an in-line simulation of building thermal behaviour and the technical supply system's operation.

As advanced micro-generation systems have to compete against conventional established technologies, proof is required that micro-generation on the level of a whole building is beneficial in terms of saving primary energy resources, reducing GHG emissions, and is economic reasonable. Consequently, performance assessment of micro-generation systems must be performed. The methodology defined during Annex 42 should be expanded to take into account cooling systems and energy derived from renewable resources. Harmonized frame parameters, such as primary energy and emission factors, have to be defined and applied.

In many countries, support schemes have been initiated to foster the development and deployment of micro-generation technologies. Consequently, one task within Annex 54 was to collect information on support schemes, to deliver an overview, and to analyse their impact.

To manage the targets described above, the work of Annex 54 was divided into three subtasks:

- Subtask A: Technical development
- Subtask B: Performance assessment
- Subtask C: Technically robust mechanisms for diffusion

Annex 54 successfully developed models of micro-generation units and system components, and implemented them into state-of-the-art building performance-simulation tools such as TRNSYS, ESPr, or Matlab/Simulink. Predefined and reproducible laboratory conditions are favourable to determining the necessary model parameters. The objects of these measurements were several commercial available micro-CHP units; prototypes of different technologies including ICEs, SEs, or fuel cells were also included. Huge quantities of data have been collected from field testing performed by Annex 54 participants. These data have been used to determine demand-side profiles and, additionally, to gain knowledge on micro-generation system performance under real operating conditions. The developed models and data collected by Annex 54 are available to the scientific community for further study in this field.

Validated system models were then used to execute performance-assessment analyses of micro-generation systems. Several participants in Annex 54 have performed performance-assessment studies. To obtain comparable results, a common methodology was used to define the frame parameters and reference system of the comparisons. A synthesis of the country-based performance assessment studies then was performed to provide an overview.

As micro-generation on the building level is still an emerging technology, many countries offer support for related technologies; this support is offered according to different mechanisms. Annex 54 participants brought together information on the support schemes of their home country. Following this, the impact of national support mechanisms on the economic impacts of micro-generation systems was analysed.

During the lifetime of Annex 54, the participants contributed to the scientific community with journal publications, three seminars, and presentations at two international conferences.

### 6.2 Conclusions

The major conclusions of this four-year, multinational project are structured in the categories technology aspects, system performance, and economics.

#### Technology aspects

The heating or cooling energy demand of a building correlates highly to the outside weather conditions, especially the temperature. DHW demand is driven by the individual occupants; however, charging of the hot-water storage can be influenced to a certain degree. Models to predict the thermal loads of a building demonstrated sufficient accuracy. The measured electricity-demand data of residential consumers demonstrated a highly stochastic behaviour, with peaks that were characterized by high amplitudes and short durations. Consequently, the accuracy of electrical-demand forecasting is very limited.

Since the beginning of Annex 54 in 2009, clear progress in micro-generation systems has been noticeable. Many manufacturers started market deployment of their products. However, some systems have already disappeared owing to funding problems, which can sometimes be caused by delayed market entry or technical problems. During Annex 42, many small technologically driven companies were involved with their micro-cogeneration systems. Now, more established manufacturers of heating appliances have become involved and are bringing micro-generation products to market.

- ICE-driven micro-CHP systems are actually available from many manufacturers in a wide range of sizes.
- SE micro-CHP systems recently entered the market in many European countries. Most of these are based on the Microgen Engine Corporation technology that is implemented by several heating appliance companies into their products.
- Fuel cells have experienced irregular sales levels in the 2000s; however, in the years after 2010, fuel cells have begun selling at markedly increased rates and, as of 2012, became the

leading technology in terms of volume of units sold among the range of micro-generation prime movers. This was achieved through high numbers of newly installed systems in Japan.

- Regarding tiny micro-CHP systems with approximately 1–2-kW electrical capacity, a trend is visible in integrating the cogenerator into a full-scale heating appliance, with auxiliary burner, pumps, and control systems.

The development of cooling units, namely absorption and adsorption chillers and their integration into micro-CHP systems, offers new possibilities to apply this technology in places that have subdominant heating requirements but significant cooling needs.

### System Performance

Annex 54 participants were involved in several field test activities with micro-CHP systems. Energy flows of mainly micro-CHP installations in residential, as well as small commercial, buildings were measured and analysed. The measurements were performed over longer periods, typically one year; consequently, the following can be concluded:

- Electrical conversion efficiencies (based on lower heating value) were in the range of 8–15% for Stirling-driven systems, 20–25% for ICE systems, and up to 55% for systems using fuel cells. Overall (electrical plus thermal) energy conversion efficiencies range from 75% to as high as 95% (based on lower heating value). These efficiencies also consider the auxiliary power needs of the CHP system.
- The layout of the system was revealed to be suboptimal in some cases; in particular, in terms of the sizing of the cogeneration system and/or its integration into the supply system. In many cases, parameters were not properly adjusted to the needs of the consumers and the requirements of the supplied building. This led to lower efficiency of the systems.

Several country-specific studies have been performed during Annex 54. In each case, national characteristics in terms of the provision of fuel and electricity were taken into account, as well as the typical conventional reference systems. Consequently, the following can be concluded:

- Fossil fuel-based micro-generation systems can achieve primary energy and emissions savings in the range of 5–20%, depending on the type of system and application. These savings increase up to 40% when renewable energy technologies are involved in hybrid micro-generation systems. A maximum value of 60% was obtained, in terms of primary energy and emissions savings, when more than one renewable energy source is exploited (e.g. geothermal and solar energy).
- If excess electricity can be delivered into the electricity supply grid, the best energy, environmental, and economic performance is obtained with thermal load-following logic of the micro-CHP, in comparison with electric-load following logic.

Energy storage was revealed to be a very important component on the thermal side but also interesting on the electrical side:

- Thermal storage prevents the micro-generation system from frequent on/off operations, which is profitable over the lifetime and results in the efficient performance of the system.

- A thermal storage that was charged during periods with lower heat demand can reduce the operation of an auxiliary heater during high-load periods. The results in an increase in CHP operation and its profitability.
- For the integration of fluctuating solar thermal resources, a thermal storage is necessary because the period of available energy from the sun does not usually match the occupants' heat requirements.
- Furthermore, electricity from a micro-CHP is preferably generated during periods when it can be used on site. Active management of the thermal storage allows the heat demand to be decoupled from the electricity demand for certain periods.

### Economics

In terms of economic performance, significant capital cost savings (approximately 20–30%) can be obtained; however, the initial installation cost is often still considerably high, especially for very complex small-scale tri-generation systems. This can determine quite long pay-back periods, even assuming that all the support mechanisms introduced by national legislation are achieved effectively. Therefore, specific financing mechanisms should be promoted in order to overcome the problems related to high investment costs, such as, third-party financing, and a favoured access to national and international government funding. Moreover, there is the need to further improve the economic performance of micro-generation systems to increase the cost savings in comparison with conventional systems. A reduction of the installation costs performed by manufacturers and distributors of high-efficiency energy-conversion devices would be also highly desirable. From analysing the economic situation and support mechanisms, the following conclusions can be made.

- The benefits increase when the utilization time of the micro-generation system increases; it represents the most crucial parameter.
- The economic performance of micro-generation systems increases significantly with the proportion of the generated electricity that is used on site.
- The economic feasibility of micro-generation systems is very practical in terms of the electricity purchase costs and the investment costs.
- With progressing market entry of micro-generation technologies, lower investment costs and better profitability can be expected.
- Expected increases in prices for fossil energy carriers, together with decreasing system costs for micro-generation systems, will lead to increasing profitability for these new technologies

### 6.3 Outlook to Possible Future Work

Based on experiences from Annex 42 and Annex 54, clear progress in micro-generation technologies is visible. However, significant research still has to be performed to improve the performance of the systems, to optimize their integration into the building energy supply systems, and to increase the

benefits offered by the flexible operation of these systems. Recommendations emanating from the work performed and the experience gained within Annex 54 include the following:

- CHP systems produce electricity and heat concurrently. As one target is to decrease the thermal energy demand of buildings, cogeneration systems with high power-to-heat ratios would be beneficial in the future. Further work should investigate the potential of cogeneration technologies in terms of these requirements.
- While current installations often only involve one micro-generation technology, such as micro-CHP or PV, a combination of different technologies could become more usual in the future. Research should be performed to optimize the layout and operation of these systems, as well as to develop advanced control schemes.
- The ability to store energy in the thermal, as well as on the electrical form, has been identified as one of the core parameters in optimizing a system's operation, and in enabling the integration of renewable energy resources. Storage technologies and their implementation into building energy supplies should be investigated further, taking into consideration charging of electric vehicles or using second-life batteries within buildings.
- The behaviour of individual users or households demonstrates highly stochastic profiles, making it difficult to optimize micro-generation systems. Widening the scope to include multiple homes within a neighbourhood makes the energy demand more predictable. Cross-linking technologies as load sharing, virtual, or swarm power plants should be included in future work, as well as concepts such as smart energy networks and micro-grids.
- Future work should investigate the impact of a significant number of micro-generation installations on the power supply system. Future work should investigate this because, currently, PV installations influence the power supply grid and the operation of conventional power plants in some regions. Integrated into a smart-grid, micro-generation technologies could support the security of supply by offering system services as demand response.
- Analysing business cases of micro-generation technologies demonstrates high variety and, sometimes, great complexity of parameters influencing the profitability of these systems. Further research should be performed on how commercialization can be increased.





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## Abbreviations

AHP	Absorption Heat Pump
ANFIS	Adaptive Neuro Fuzzy Inference System
AHU	Air Handling Unit
ASHP	Air Source Heat Pump
ANN	Artificial Neural Network
BES	Battery Energy Storage
BEMS	Building Energy Management System
COP	Coefficient of Performance
CCHP	Combined-Cooling-Heating-and-Power
CHP	Combined-Heat-and-Power
CPV	Concentrating Photovoltaic
DR	Demand Response
DW	Desiccant Wheel
DHW	Domestic Hot Water
EV	Electrical Vehicle
EER	Energy Efficiency Ratio
EBC	Energy in Buildings and Communities
ECBCS	Energy in Buildings and Community Systems
EPBD	European Performance in Building Directive
FiT	Feed-in tariffs
FC	Fuel Cell
FESR	Fuel Energy Saving Ratio
GWP	Global Warming Potential
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
HP	Heat Pump
HVAC	Heat, Ventilation, and air conditioning
HCPV	High Concentrator Photovoltaic
HEMS	Home Energy Management System
IPCC	Intergovernmental Panel on Climate Change
IC	Internal Combustion
ICE	Internal Combustion Engine
IRR	Internal Rate of Return
IEA	International Energy Agency
KIER	Korea Institute for Energy Research
LTH	Low-Temperature Heating
MRE	Mean Relative Estimation Error
MCCHP	Micro Combined Cooling Heat and
MCHP	Micro-Combined-Heat-and-Power

## Abbreviations

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MILP	Mixed Integer Linear Programming
MLR	Multiple Linear Regression
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
PCM	Phase Change Material
PV	Photovoltaic
PVT	Photovoltaic-Thermal
PHEV	Plug-in Hybrid Electric Vehicles
PE	Primary Energy
PI	Profitability Index
PEMFC	Proton Exchange Membrane Fuel Cells
RES	Renewable Energy System
RIC	Reciprocating Internal Combustion
R&D	Research and Development
RMSE	Root Mean Square Error
SPB	Simple Pay Back
SOFC	Solid Oxide Fuel Cells
SE	Stirling Engine
TES	Thermal Energy Storage
VPP	Virtual Power Plant
μCHP	Micro Combined Heat and Power

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## Image Sources

- Figure 2-1, 2-2 University of Sannio, Benevento, Italy
- Figure 2-3, 2-4 SenerTec Kraft-Wärme-Energiesysteme GmbH, Schweinfurt, Germany ([www.senertec.de](http://www.senertec.de))
- Figure 2-5 Remeha GmbH, Emsdetten, Germany ([www.remeha.de](http://www.remeha.de))
- Figure 2-6 Tokyo Gas, Japan
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- Figure 2-8 University of Tokyo, Japan
- Figure 2-9 Bundesverband Wärmepumpe (BWP) e.V, Berlin, Germany ([www.waermepumpe.de](http://www.waermepumpe.de))
- Figure 2-10 National Research Council Canada, Ottawa, Canada
- Figure 2-11, 2-12 University of Trieste, Italy
- Figure 2-13a, 2-14 University of Sannio, Benevento, Italy
- Figure 2-13b SorTech AG, Halle, Germany ([www.sortech.de](http://www.sortech.de))



## 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 (\*)

## 0 Background Information

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- 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