Energy in Buildings and Communities Programme

Methodologies for the Performance Assessment of Micro Hybrid Polygeneration Systems

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October 2014

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

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1 Introduction

1.1 Motivation and Aim

Reducing the primary energy consumption and greenhouse gas emissions in the building sector to sustainable levels will require significant effort to increase both energy efficiency and the proportion of energy used that comes from renewable energy sources. In addition, owing to the increase in the demand for air conditioning in recent years, this must be accomplished in both the commercial (shops, warehouses, offices, schools, etc.) and residential sectors.

The primary function of Annex 54 is the analysis of micro-generation performance in buildings. Within the context of Annex 54, the term 'micro-generation' relates to a broad range of low-carbon technologies that can provide power, heating, and/or cooling to buildings, as well as district heating and cooling networks. These technologies include combustion engines, fuel cell-based cogeneration and polygeneration systems, heat pumps, photovoltaic, micro-wind power, and biomass. Micro-generation technologies can be deployed individually or in combination (so-called hybrid systems). In particular, the term hybrid usually refers to the simultaneous presence of both fossil fuel-based energy conversion devices and renewable energy technologies.

Micro-generation systems in residential applications may help to improve the situation in terms of the supply side by reducing the non-renewable energy demand for residential buildings, as well as reducing grid losses due to the transmission and distribution of energy over long distances. Moreover, these systems could help to mitigate problems related to high peak electric loads and black-outs affecting the electric grid.

Although there is no standard size that is used to define micro-generation [1], this report will be focused on systems delivering electric power output lower than 50 kW, which represents a valid and interesting application that is especially suitable for the residential and tertiary sectors, as set by the EU Directive on the promotion of cogeneration, [2].

In recent years, significant attention, in both research and application fields, has been focused on the transition from centralized to decentralized or distributed generation. Furthermore, an industrial trend towards the miniaturization of energy conversion equipment has resulted in the availability of a wide variety of small-scale power, refrigeration, and heat pump systems on the commercial market. Very soon, small and micro mechanical and thermal devices will be used in everyday applications. In many sectors, mainly tertiary and light industrial, small-scale energy conversion plants (combined cooling heat and power [CCHP] systems) can meet different energy requirements (electricity, cooling, and heating) and there is considerable potential for primary energy saving and the reduction of greenhouse gas emissions. Moreover, owing to these benefits, these technologies have also spread into residential and office buildings in recent years.

Consequently, Subtask B of IEA Annex 54 aimed to define the methodology for the performance assessment of micro-generation systems in terms of energy, emissions, and economic criteria. It adopted the approach, nomenclature and symbols used in the Annex 42 "The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM)" Subtask C report "Methodologies for the Performance Assessment of Residential Cogeneration Systems" [3]; this ensures continuity with the work of Annex 42. In addition, the nomenclature used in the present report was also derived from [3], and it is described in section 3 and 4. This nomenclature partially applies to section 2, where micro-generation national testing procedures are described. In section 2, it was decided not to replace the original symbols and terminology to better describe and highlight the contents and main principles of the analysed testing procedures.

In particular, the following new elements are addressed in this upgraded performance assessment methodology report with respect to [3]:

- A section dedicated to micro-cogeneration national testing procedures;
- The use of a performance assessment methodology based on a minimal number of simple parameters, which is close to the real methodologies used by the Annex 54 research groups;
- Greater attention is placed on the definition of the energy/environmental and economic performance index of the reference system based on separate "production" (best available technology [BAT], national energy mix, annual/hour based data, etc.);
- New performance indices, which focus on cooling devices (electric heat pumps, absorption heat pumps (AHPs), adsorption heat pumps, desiccant wheels (DWs), etc.), hybrid systems, and on-site "production".

The purpose of this report is to provide guidance, as well as a framework and methodologies, for the individual performance assessment studies within Subtask B of Annex 54. In particular, the specified definitions, nomenclature, performance indices, boundary conditions, reference cases, and methods were designed to be commonly applied in all the individual performance assessment studies. However, while this report provides one possible methodology, different alternate valid approaches and criteria may be chosen as well. Consequently, the use of different approaches and criteria in individual studies is also acceptable, provided they are clearly defined.

Furthermore, this Subtask uses simulations in the form of models, algorithms, and optimization approaches developed in Subtask A, to develop an extensive library of country-specific performance studies. These studies cover different micro-generation technologies, combinations, and performance in different countries and applications (individual residences, multi-residences, and small commercial buildings). Finally, a synthesis analysis was undertaken to identifying generic performance trends and "rules of thumb" regarding the appropriate deployment of micro-generation technologies.

1.2 Deliverables of Subtask B

The deliverables of Subtask B with respect to the Annex 54 proposal are (Fig. 1):

- A review of current micro-generation performance assessments studies and experimental activities, RECCHP54;
- This methodology report, Methodologies for the Performance Assessment of Micro Hybrid Polygeneration Systems, PACCHP54;
- The individual study reports, containing country specific simulations, and experimental and field test studies based on a template, CSCCHP54;
- A synthesis analysis of the performance studies, SCCHP54;

- A report that analyses the impact of single- and multiple-technology devices on the low-voltage electricity grid, ILVG54;
- The respective summary and conclusions, presented in the Annex 54 summary report.

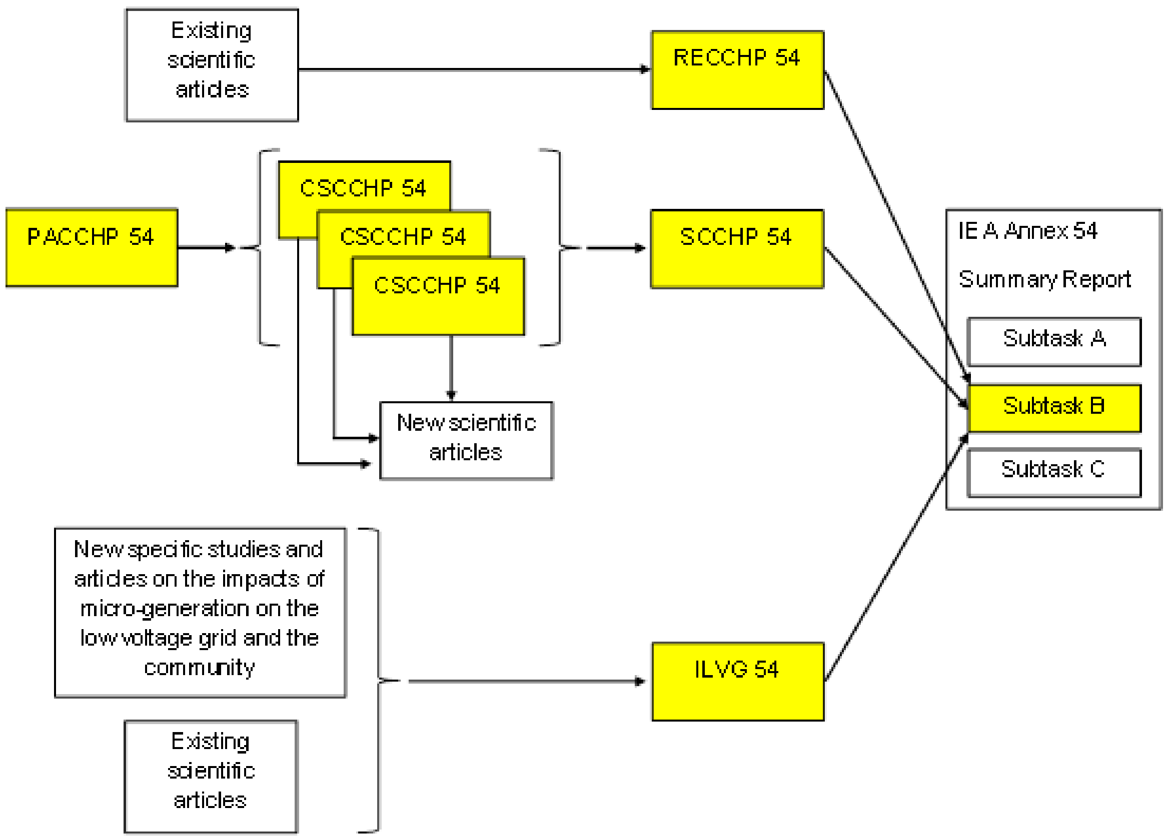

Fig. 1: Subtask B deliverables

1.3 Content of this report

The following topics are covered in this report:

Section 2: overview of the micro-cogeneration national testing procedures available worldwide

Section 3: overview of the performance indices to be used for hybrid micro-cogeneration and micro-polygeneration systems

Section 4: overview of the evaluation methods for cogeneration systems, with a special focus on 3-E (Energy, Environmental and Economic) analysis, which is the proposed approach for performance assessment

Section 5: nomenclature, symbols, and acronyms to be used in the performance assessment studies

2 Micro-cogeneration National Testing Procedures

Several standard testing procedures have been prepared or are still in the development phase in many countries in order to provide test methods for determining the performance of combined heat and power system (CHP), and micro combined heat and power system (MCHP) devices.

These efforts are mainly to the result of the quick diffusion of micro-cogenerators worldwide. For example, Honda and Osaka gas have developed the Ecowill model (1 kW_{El} and 2.80 kW_{Th}), designed for single-family applications and in the period 2003–2009 approximately 86,000 of these units were sold in Japan. In Europe, more than 20,000 units of internal combustion engine-based MCHPs have been sold, with two notable models be the Vaillant Ecopower (4.7 kW_{El}) and the Baxi Senertec (5 kW_{El}). Moreover, in Europe, approximately 3,000 units of Stirling engine-based MCHPs (WhisperGen – 1 kW_{El} and Disenco – 3 kW_{El}) have been installed.

This increasing diffusion in micro-generation systems is mainly due to existing national financial tools (white certificates, feed-in tariffs, etc.) that support MCHP penetration in the energy-efficient devices market.

These financial tools require that specified energy performance is achieved by the micro-cogenerator, such as primary energy saving, allowing access to economic benefits.

Moreover, in some countries, micro-cogeneration devices may be required to meet certain minimum standards to be marketable.

For small-scale cogenerators, it is 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 the energy savings achieved from each installed unit, which could not be economically justified, especially in the case of a very large number of small-size units. For example, manufacturers or ESCo (Energy Service Companies) that expect to install a wide number of identical units for similar applications can use the *ex-ante* method. This is because it allows the classification of the energy performance of the MCHP using experimental tests conducted in a test facility; this can possibly be certified by an independent third party.

The diffusion of such standard procedures can also support the introduction of energy labelling schemes for MCHPs, such as those already in place for various electric appliances; these could help potential users to understand the energy, environmental, and economic savings that are achievable.

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.

There is a wide variety of micro-generation standards across different nations and they differ, for example, by type (testing, rating, labelling), devices (MCHP, heat pumps, etc.), and scope.

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

- USA: ASHRAE SPC 204 – Method of Test for Rating Micro Combined Heat and Power Devices (in progress);
- UNITED KINGDOM: Publicly Available Specification 67 (PAS 67);

- ITALY: prUNI E0204A073 - Draft of a proposed UNI standard: micro-cogeneration devices fuelled by gaseous or liquid fuels – *Ex-ante* measurement of energy performance (in stand-by);
- EUROPE: prEN 50465: Gas appliances – Combined heat and power appliance of nominal heat input inferior or equal to 70 kW;
- GERMANY: DIN 4709 (2011-11): Determination Of The Standard Efficiency Factor For Micro-CHP-appliances Of Nominal Heat Input Not Exceeding 70 kW;
- JAPAN: industrial standards for performance and safety testing of CHP.

One of the activities of Subtask B was to gather information from countries in which the national standard testing procedures have been developed or are still in the development phase, in order for the performance assessment methodology to conform to the general rules of these procedures.

For example, ASHRAE SPC 204 (in progress) will be focused on devices with net electrical output less than 50 kW. This standard will be technology independent and will have the purpose of developing a standard test method for determining the performance of MCHPs, which would be in terms of net electrical generating performance and heat recovery performance, while specifying the equipment, the instrumentation, the test methods, and the calculation procedures.

In the following sections, the main principles of the available national testing procedures are summarized.

2.1 Italian activity on standardized procedure for the test of small scale cogeneration systems fuelled by gaseous or liquid fuels – *Ex-ante* measurement of energy performance (ITALY)

In Italy, there are currently several ongoing activities aimed at defining a standard procedure for the testing of small-scale cogeneration systems. In the following paragraphs, the main topics of a draft standard, currently in a stand-by phase, are described, [4]–[6].

Aim and scope

This standard focuses on the evaluation of the energy performance of small- and micro-cogeneration systems. It defines a methodology for an *ex-ante* evaluation of the performance of a unit type, representative of a product type. The aim is to define a procedure for micro-cogeneration (electric power less than 50 kW) performance assessment that allows for the characterization of the device's energy performance through a series of experimental tests.

A necessary condition for the application of this procedure is the operation of the cogenerator in heat-following mode.

The experimental tests aim to assess the performance of a system composed of a cogenerator, a heat storage, if any, and an integration boiler, if needed, following the variation of the heat load.

Definition of the cogeneration unit

The cogeneration unit is generally composed of a prime mover for electric or mechanical energy supply, supported by a heat recovery system for thermal energy supply, possibly integrated with a boiler, with peak and/or back-up functions, and a thermal storage.

In the case of a tri-generation system, a part of the system provides cooling by means of an absorption or vapour compression heat pump.

Boundary limits, measuring points and parameters

In this section, the boundary limits of the cogeneration unit are defined in terms of, among other properties, the inlet flange of primary fuel, air intake section, and the output terminals of the electricity system in AC. Also defined in this section are the quantities to be measured, which include, among others, the net electric, thermal cooling, the primary power and energy, and the temperature of the heat transfer fluid at the inlet and outlet of any thermal recovery circuit.

Measuring instruments and required accuracy

In this section, the requirements of the measuring instruments, particularly in terms of accuracy, is specified with reference to European or national technical standards.

Tests for the determination of energy performance

This section specifies the type of tests that should be performed at nominal conditions and according to test cycles.

Characterization of the unit at nominal conditions

The unit must be analysed in stationary conditions, which means that the system has reached the nominal electric or mechanical power, with a deviation of ±3%, and that the operating conditions are stationary, with a deviation of ±1%, for at least 10 minutes. Once these stationary conditions are achieved, the test has a length of 60 minutes.

In this section, the following test conditions are defined:

- Nominal operating conditions, which are, among others, 100% electric power, nominal temperatures, and the flow rate of water in all thermal recovery circuits.
- Outdoor conditions: the results should refer to outdoor reference conditions of 15°C temperature, 101325 Pa pressure, and 60% relative humidity, by means of correction curves provided by the manufacturer.

Moreover, the following nominal performance indices are defined and evaluated:

The electric and thermal efficiencies, respectively, are defined as:

$$\eta_{El,nom} = E_{El,nom} / E_{Fuel,nom} \quad (1)$$

$$\eta_{Th,nom} = E_{Th,nom} / E_{Fuel,nom} \qquad (2)$$

Heat Rate:

$$HR_{nom} = E_{Fuel,nom} / E_{El,nom} \qquad (3)$$

Where $E_{El,nom}$ is the supplied electric energy, $E_{Th,nom}$ is the supplied thermal energy, and $E_{Fuel,nom}$ is the input primary energy, all at nominal conditions.

Characterization of the unit according to test cycles

In this section, the load profiles for the different day types to be used for the test cycles are defined. A deviation of ±10% on the hourly required energy is acceptable.

Three day types, namely winter, intermediate, and summer, 24 hours in length, characterized by high, medium, and low thermal loads, respectively, are defined. However, for tri-generation systems an additional summer-day type, characterized by low thermal load and a cooling load, is defined.

Thermal load is determined as a percentage of the maximum thermal load. It is defined, for example, in systems without thermal storage, as the sum of thermal powers of the cogenerator and any vapour compression heat pumps or peak load boiler that is included in the system.

As an example, the thermal-load profile for the three day types is plotted in Fig. 2, while in Fig. 3 the thermal and cooling loads for the additional summer day are presented.

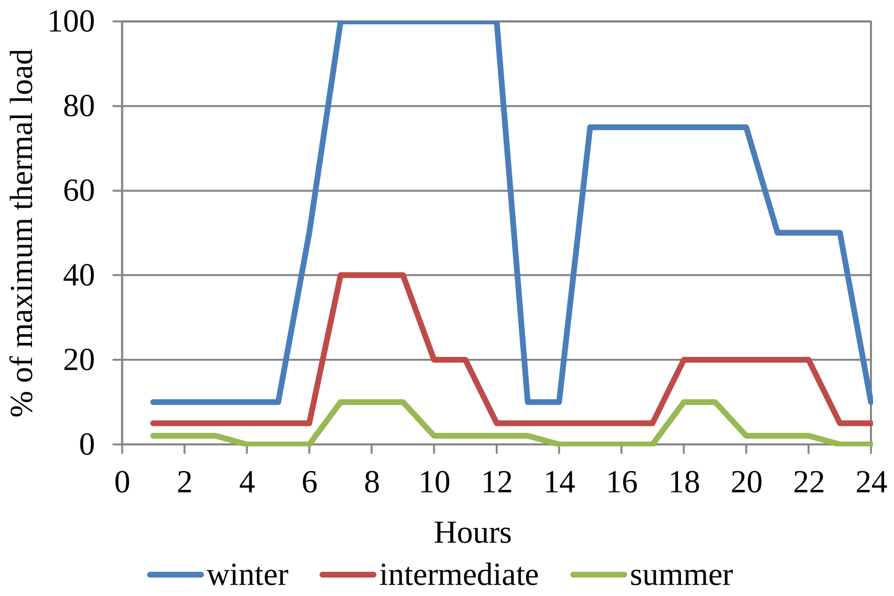

Fig. 2: Thermal-load profile for the three day types

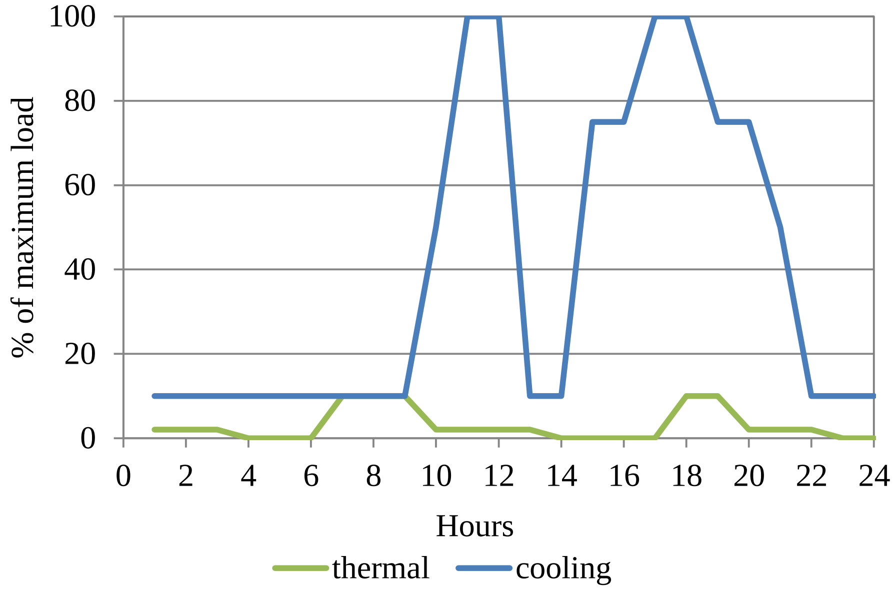

Fig. 3: Summer thermal and cooling load profiles for tri-generation systems

Evaluation of the annual energy performance

In this section, the methodology to evaluate the annual energy performance of the system based on the experimental tests is defined.

In particular, the evaluation of annual energy performance with reference to the test cycles is performed by multiplying the results obtained for each day type by the number of occurrences of that day type.

In Tab. 1, the number of days of each day type is present for cogeneration systems, with respect to the Italian climatic zone for installation. Tab. 2 applies for tri-generation systems.

Tab. 1: Number of days/year for each day type for cogeneration systems

Day type	Number of days / year					
	A	B	C	D	E	F
Winter	21	30	43	64	91	140
Intermediate	84	91	93	102	91	110
Summer	260	244	229	199	184	115

Tab. 2: Number of days/year for each day type for tri-generation systems

Day type	Number of days / year					
	A	B	C	D	E	F
Winter	21	30	43	64	91	140
Intermediate	84	91	93	102	91	110
Summer thermal load	130	124	119	99	94	75
Summer cooling load	130	120	110	100	90	40

On the basis of energy performance, both in nominal operating conditions and according to test cycles, the overall annual energy performance is evaluated; this also takes into account a coefficient, *K,* that varies linearly from 0 to 1. The zero value is relative to the case of cogeneration units applied in the absence of other heat generators, while the value 1 is relative to the case of cogeneration units applied in the presence of other widely prevalent heat generators.

Finally, the electric efficiency, the thermal efficiency, and the heat rate as defined for nominal operating conditions, as well as the primary energy saving, which is as defined by Legislative Decree 8 Feb. 2007, n. 20, are evaluated on an annual basis.

In particular:

$$PES_{year} = 1 - \frac{E_{Fuel,year}}{\frac{E_{El,year}}{\eta_{El,ref}} + \frac{E_{Th,year}}{\eta_{Th,ref}}} \quad (4)$$

Mechanical energy is calculated as the equivalent electric energy, assuming an electric efficiency of the generator equal to 0.92, for systems with electric power lower than 50 kW.

Appendix

In this section, the reference hydraulic scheme, as well as the supply and return temperatures of thermal recovery circuits to be used for the experimental tests, are defined, both for nominal operating conditions and for test cycles.

In particular, specified values of temperatures should be used in the case of “high temperature” tests where the supply temperature is equal to 75°C and the return temperature is equal to 60°C. An example of this is when the micro-cogenerator has to interact with radiators for space heating purposes. “Low temperature” tests apply when the supply temperature is equal to 50°C and the return temperature is equal to 30°C, an instance of this being when it has to interact with a radiant floor heating system or when a condensing unit is tested.

Finally, for systems with cooling energy supply, the supply and return temperatures of the cooling circuits to be used for the tests are defined as 7 and 12°C, respectively.

2.2 Micro-cogenerator system performance prediction using simple virtual operating cycle (ITALY)

This procedure presents a general methodology to estimate in advance the performance of MCHP systems in 1 year of operation, by means of limited information on the CHP prime mover and on the operating cycle [7].

The virtual cycle is obtained on the basis of the annual thermal demand, for example of a civil application in Northern Italy, assuming thermal-load following of the CHP system.

The proposed methodology to obtain a simplified virtual operating cycle of a MCHP is based on the actual monotonic load curve of the thermal demand, *R(t)*, presented in Fig. 4 by a continuous red line, referring to a specific residential user requiring 20 MWh/year of thermal energy.

In Fig. 4 a simplified empirical monotonic curve *S(t)* (dotted black line), which approximates the real monotonic curve, is also presented.

The curve *S(t)* is based on a simple analytical modelling expression that interpolates two characteristic points (C1 and C2 in Fig. 4) whose coordinates are:

C1: (h_1; $P_{Th,1}$) C2: (h_2; $P_{Th,2}$);

where

$P_{Th,1} = f_1 * P_{Th,peak}$ $P_{Th,2} = f_2 * P_{Th,peak}$

f_1 and f_2 being two dimensionless multipliers of the peak thermal power ($P_{Th,peak}$). For the considered case, the following data can be assumed:

$h_1 = 0$, $f_1 = 1.2$

and h_2 is equal to the maximum number of hours of thermal demand, which is 6000 hours in the assumed case illustrated in Fig. 4. The last term, f_2, can be calculated by equating the annual energy, which corresponds to the actual demand curve with the annual energy given by the model:

$$\int_{0}^{8760} R(t) \cdot dt = \int_{0}^{8760} S(t) \cdot dt \quad (5)$$

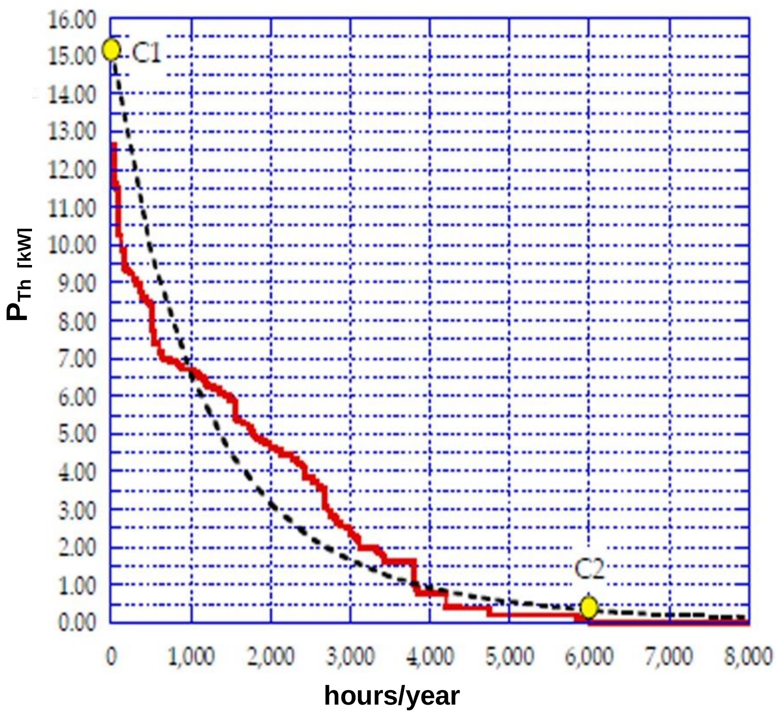

Fig. 4: Actual and modelled monotonic thermal demand curves for a residential user.

The introduced analytical expression of the modelled monotonic curve *S(t)* is:

$$S(t) = f_1 \cdot P_{Th,peak} \cdot \frac{K}{[(h_1 - h_2) + t]^n} = f_1 \cdot P_{Th,peak} \cdot \frac{K}{(h_2 + t)^n} \quad (6)$$

where：

$$K = h_2^n \tag{7}$$

$$n = \frac{\ln\left(\frac{f_1}{f_2}\right)}{\ln\left(\frac{h_2}{2h_2 - h_1}\right)} = \frac{\ln\left(\frac{f_1}{f_2}\right)}{\ln(0.5)} \tag{8}$$

Consequently, the curve *S(t)* can be used to estimate the thermal demand of a domestic user when no other information aside the peak thermal demand ($P_{Th,peak}$), the hours of request (h_2), and the total required energy are known.

In order to obtain a simplified operating cycle of a MCHP, the monotonic demand model *S(t)* and the part-load curve of the MCHP are used, according to the procedure described below and based on the graphs presented in Fig. 5.

In particular, Fig. 5(a) indicates the part-load performance curves of a MCHP in terms of normalized electric and thermal efficiency versus thermal output load (thermal and electric efficiencies assume unitary values for 100% thermal load). Fig. 5(b) indicates the model monotonic demand curve (dotted black line) and the assumed MCHP virtual cycle (red line and highlighted points).

Further details indicate that, according to the considered model, only four significant output loads of the MCHP are taken into account, namely 100, 75, 50, and 25% of the nominal thermal power. The considered thermal size of the MCHP is lower than the demand peak, as illustrated in Fig. 5(b) and, according to the assumed MCHP load curve, certain periods of the year show a deficit of thermal energy from the micro-cogenerator in comparison with the demand. Moreover, a minimum thermal power output of the MCHP (25%) is considered. Consequently, an external additional source (e.g., an auxiliary boiler) is taken into account in order to fulfil the residual demand. Using Fig. 5(b), it is possible to obtain the number of operating hours of the MCHP corresponding to a given load. For example, the MCHP operates for (h_{50} -h_{75}) hours at 50% of the peak load.

Based on the introduced model for the user demand given by the function *S(t)* and also based on the assumed virtual cycle of Fig. 5(b), the annual average thermal efficiency (η_{Th}) and average electrical efficiency (η_{El}) can be estimated as weighted average values of part-load efficiency, obtained fromFig. 5(a).

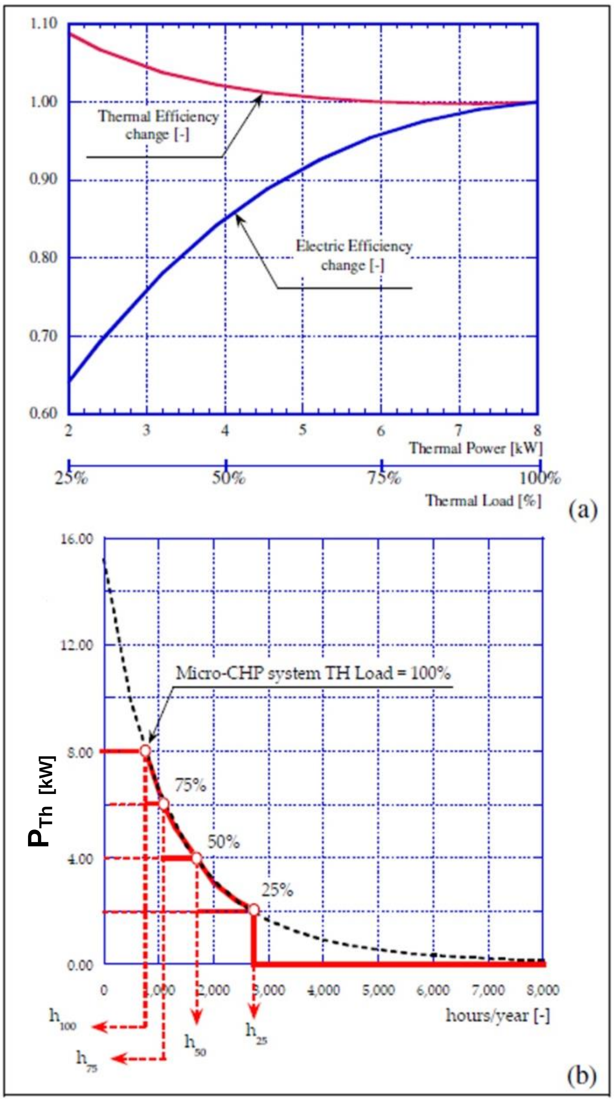

Fig. 5: MCHP part-load performance curves (a) and significant operating points (b)

This takes into account the four different thermal loads and that the weights used are the intervals of hours for each load step:

$$\eta_{Th} = \left. \begin{bmatrix} \eta_{Th,100} * h_{100} + 0.5 * (\eta_{Th,100} + \eta_{Th,75}) * (h_{75} - h_{100}) + \\ 0.5 * (\eta_{Th,75} + \eta_{Th,50}) * (h_{50} - h_{75}) + 0.5 * (\eta_{Th,50} + \eta_{Th,25}) * (h_{25} - h_{50}) \end{bmatrix} \middle/ h_{25} \right. \quad (9)$$

$$\eta_{El} = \left. \begin{bmatrix} \eta_{El,100} * h_{100} + 0.5 * (\eta_{El,100} + \eta_{El,75}) * (h_{75} - h_{100}) + \\ 0.5 * (\eta_{El,75} + \eta_{El,50}) * (h_{50} - h_{75}) + 0.5 * (\eta_{El,50} + \eta_{El,25}) * (h_{25} - h_{50}) \end{bmatrix} \middle/ h_{25} \right. \quad (10)$$

Where $\eta_{Th,i}$ and $\eta_{El,i}$ are the thermal and electric efficiency at the i-th load set point value of the MCHP. The average η_{Th} η_{Th} and the η_{El} η_{El}values can be used to calculate annual performance indices of the MCHP, such as the primary energy saving index.

As is evident from the equations given above, in each interval i-th of hours in which the MCHP thermal output is constant, the corresponding i-th thermal efficiency value is equal to the mean between $\eta_{Th,i}$ and $\eta_{Th,i+1}$, and is analogous for the electric efficiency.

2.3 UNI/TS 11300-4 Energy performance of buildings - Part 4: Renewable energy and other generation systems for space heating and domestic hot water production (ITALY)

This technical specification ([8]–[10]) calculates the primary energy requirement for winter space heating and domestic hot water (DHW) purposes for subsystems that provide useful thermal energy from renewable sources or generation devices that are considered different from conventional ones, such as cogenerators. A section of this specification is indeed dedicated to cogeneration, allowing the evaluation of the production of useful thermal and electric energy from cogeneration units and the corresponding primary energy input. Calculation methods have been developed for systems with electric power up to 1000 kW that are fed by liquid or gaseous fossil fuels, or by biogas or bio-liquids.

This specification requires that cogeneration units are connected in parallel to the grid and that the control of the cogeneration unit is exclusively performed in accordance with thermal energy needs of the distribution subsystem (thermal-following control). It also requires that all the thermal energy produced in cogeneration be utilized, which means that any systems for heat dissipation should operate in parallel to the grid during normal operation of the unit. Furthermore, the technical specification excludes cogeneration units intended for simultaneous generation of thermal and mechanical energy, as well as steam or organic fluid-based Rankine cycling for electric energy production and heat recovery.

For the purposes of this specification, the month is assumed to be that which provides the minimum interval for calculations.

First, the specification defines a dimensioning criterion for the storage tank and an index of adequacy, α, which is defined for each month as the ratio between thermal energy provided by the CHP to the storage tank and the heat storage capacity of the tank. This index depends on the average daily thermal energy requirements for DHW, for space heating (winter), and for absorption systems, if any, during the summer season, as well as on the nominal thermal power of the CHP. Therefore, if $\alpha \geq 1$ the storage is adequate, while if $0 < \alpha < 1$ the storage is present but inadequate; if $\alpha = 0$ the storage is not present.

The specification defines two different calculation procedures that depend on the type of operation of the CHP. The former method, referred to as "method of fractional contribution", applies to systems working at nominal conditions, i.e. at a fixed point and without load modulation. The latter method is named "method of monthly profile" and it applies to cogeneration units that operate at variable load, modulating the partial load factor, and to Stirling-based devices. Both methods can be applied to cogeneration plants consisting of either a single unit or multiple units, with slight modifications with respect to the below described procedures that refer to the case of a single cogeneration unit.

Method of fractional contribution

Useful thermal energy produced by the CHP on a monthly basis is given by the equation:

$$OE_{Th}^{CHP} = X^{CHP} \cdot \left(NE_{Th} + Q_{waste}^{ST} - Q_{waste}^{aux}\right) + X^{CHP-AHP} \cdot DE_{Th}^{AHP} \tag{11}$$

Where NE_{Th} is thermal energy for space heating, hot water production, and the heating coils of air handling units, if any, entering the distribution system. X^{CHP} is the fraction of NE_{Th} provided by the cogeneration unit, Q_{waste}^{ST} is the thermal energy losses of the storage tank, Q_{waste}^{aux} is the thermal energy losses recovered from electric auxiliaries, DE_{Th}^{AHP} is the thermal energy delivered to the absorption system for cooling purposes, and $X^{CHP-AHP}$ is the fraction of DE_{Th}^{AHP} supplied by the cogeneration section.

If the cooling energy provided by the absorption system is known, DE_{Th}^{AHP} can be evaluated from the knowledge of its coefficient of performance (COP). The specification provides a base COP value that has to be corrected in order to take into account the temperature of the water entering the condenser, the hot water feeding temperature, and the supply temperature of chilled water.

The primary energy input to the CHP can be evaluated simply as:

$$PE_{Fuel}^{CHP} = \frac{OE_{Th}^{CHP}}{\eta_{Th}^{CHP}} \tag{12}$$

where η_{Th}^{CHP} is the nominal thermal efficiency of the CHP.

The monthly net production of electric energy is given by:

$$OE_{El}^{CHP} = PE_{Fuel}^{CHP} \cdot \eta_{El}^{CHP} - DE_{El}^{aux} \tag{13}$$

where η_{El}^{CHP} is the net electric efficiency of the CHP and DE_{El}^{aux} is the fraction of OE_{El}^{CHP} delivered to auxiliaries of the system.

Finally, the primary energy input to the CHP is evaluated by subtracting the net electricity production from the overall effective consumption, considering a primary energy factor (2.18) for cogenerated electricity exported to the grid.

Obviously, the overall annual energy flows of the CHP are evaluated as a summation of the monthly contributions.

Method of monthly load profile

This method can be applied when the CHP is operated with a thermal-following control. Consequently, all the thermal energy produced in cogeneration is used and any system for heat dissipation operates during the normal operation of the unit in parallel to the grid, with the exception of a bypass on the exhaust-gases heat recovery. Furthermore, the performance data of the system as a function of load factor from nominal power to minimum technical should be available.

If the cogeneration unit can recover the condensation heat of the flue gases, thermal efficiency should be evaluated for two conditions of inlet water temperature, namely, high and low temperature. Preferentially, the values 60 and 35°C should be used, respectively.

The first step in this method is the determination of the load profile of the monthly day type. For each month, the amount of energy required during the day type of the month, as an input to the distribution system for space heating, space cooling and hot water production, is determined as:

$$NE_{Th,SH,day} = NE_{Th,SH,mon} / G \qquad (14)$$

$$NE_{Th,DHW,day} = NE_{Th,DHW,mon} / G \qquad (15)$$

$$DE^{AHP}_{Th,day} = DE^{AHP}_{Th,mon} / G \qquad (16)$$

where $NE_{Th,SH,mon}$ and $NE_{Th,DHW,mon}$ are thermal energy required for space heating and DHW on a monthly basis, and $DE^{AHP}_{Th,mon}$ is thermal energy delivered to the absorption system for cooling purposes on a monthly basis.

The total thermal power, as input to the distribution system at hour *h* of the monthly day type ($P_{Th,h}$), is determined, as:

$$P_{Th,h} = P_{Th,h,SH} + P_{Th,h,DHW} + P^{AHP}_{Th,h} - P^{aux}_{Th,h} \qquad (17)$$

where for each hour *h*, $P_{Th,h,SH}$ is the thermal power for space heating, $P_{Th,h,DHW}$ is the thermal power for DHW, $P^{AHP}_{Th,h}$ is the thermal power feeding the absorption system, and $P^{aux}_{Th,h}$ is the thermal power recovered by the electric auxiliaries.

With regards to $P_{Th,h,DHW}$, the specification defines the profile for DHW requirements as in Fig. 6.

The DHW profile plotted in Fig. 6 is quite similar to the DHW profile produced by Annex 42, [11], in that both exhibit the same typical morning and evening peaks, although with different percentage values. The Annex 42 profile was developed on the basis of the model designed to generate synthetic profiles produced by IEA Solar Heating and Cooling Programme Task 26.

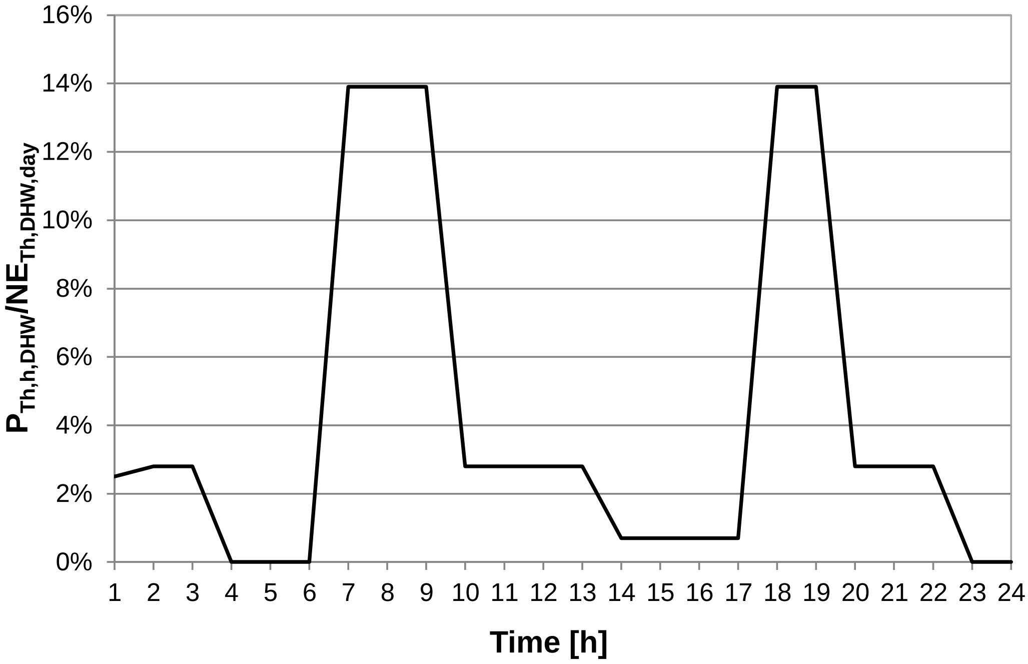

Fig. 6: Domestic hot water load profile as defined by UNI/TS 11300-4

With regards to the thermal-load profile for space heating requirements, from January to April and from October to December, the specification requires the calculation of the outdoor air temperature at hour *h* of each month, as:

$$T_{h,mon} = T_{avg,mon} + p_{h,mon} \cdot \Delta T_{mon} \quad (18)$$

where $T_{avg,mon}$ is the daily average temperature for the month, ΔT_{mon} is the daily excursion temperature for the month and $p_{h,mon}$ is a hourly correction coefficient of daily excursion temperature. $T_{avg,mon}$ and ΔT_{mon} are reported by the specification for the main Italian cities, whilst $p_{h,mon}$ is reported for the two climatic zones in which the Italian regions are divided.

Following this, the following quantity is calculated:

$$\sum_{h=1}^{24} \left(17\,^{\circ}C - T_{h,mon}\right) \quad (19)$$

Considering only positive values of the differences in the above summation, for each hour *h*, the percent contribution of thermal power for space heating $NE_{Th,SH,day}$ is given by:

$$\frac{17\,^{\circ}C - T_{h,mon}}{\sum_{h=1}^{24} \left(17\,^{\circ}C - T_{h,mon}\right)} \quad \text{if } 17°C - T_{h,nom} \geq 0 \quad (20)$$

$$0 \quad \text{if } 17°C - T_{h,nom} < 0 \quad (21)$$

As an example, the thermal-load profile for space heating requirements for the city of Milan during the month of October is presented in Fig. 7.

The load profile for space cooling requirements (from May to September) is determined in a very similar manner, calculating the following quantity:

$$\sum_{h=1}^{24} \left(T_{h,mon} - 23\,°C\right) \qquad (22)$$

The values 17 and 23°C are assumed to be the external balancing temperatures that annul the respective heating and cooling loads, with temperature set-points of 20 and 26°C, respectively. The balancing temperature depends on the building characteristics, as well as on solar and internal gains, and should be calculated analytically. However, for the purposes of the specification, the assumption of a conventional value is considered sufficient.

Subsequently, the thermal and electric energy output, as well as the primary input of the cogeneration system, is evaluated on a monthly basis; this is a procedure that depends on the presence of the storage tank.

For systems without thermal storage, and for each of the 24 time intervals in which the daily thermal-load profile is divided, the corresponding thermal partial-load ratio (PLR_{Th}) of the CHP is evaluated as:

$$PLR_{Th,h} = \frac{P_{Th,h}}{P_{Th,nom}^{CHP}} \qquad (23)$$

where $P_{Th,nom}^{CHP}$ is the nominal thermal power of the cogenerator. The partial load ratio can range from a minimum ($PLR_{Th,min}$), determined by the minimum available thermal power as declared by the manufacturer, to 1.

If $PLR_{Th,min} < PLR_{Th,h} < 1$, the performance of the cogeneration system at hour *h,* in terms of thermal power output ($P_{Th,h}^{CHP}$), electric power output ($P_{El,h}^{CHP}$), and primary power input ($P_{Fuel,h}^{CHP}$), is determined by means of a linear interpolation of the performance curves. If the manufacturer provides the rated (PLR_{Th} = 1) performance only, then the following relations that are reported from the specifications for internal combustion engine- and gas turbine-based CHPs, can be used:

$$P_{El}^{CHP} = PLR_{El} \cdot P_{El,nom}^{CHP} \qquad (24)$$

$$P_{Fuel}^{CHP} = \delta \cdot P_{Fuel,nom}^{CHP} \qquad (25)$$

$$P_{Th}^{CHP} = \gamma \cdot \delta \cdot \left(P_{El,nom}^{CHP} + P_{Th,nom}^{CHP}\right) - P_{El}^{CHP} \qquad (26)$$

where the coefficients δ and Υ are illustrated in Fig. 8 for internal combustion engine-based CHPs.

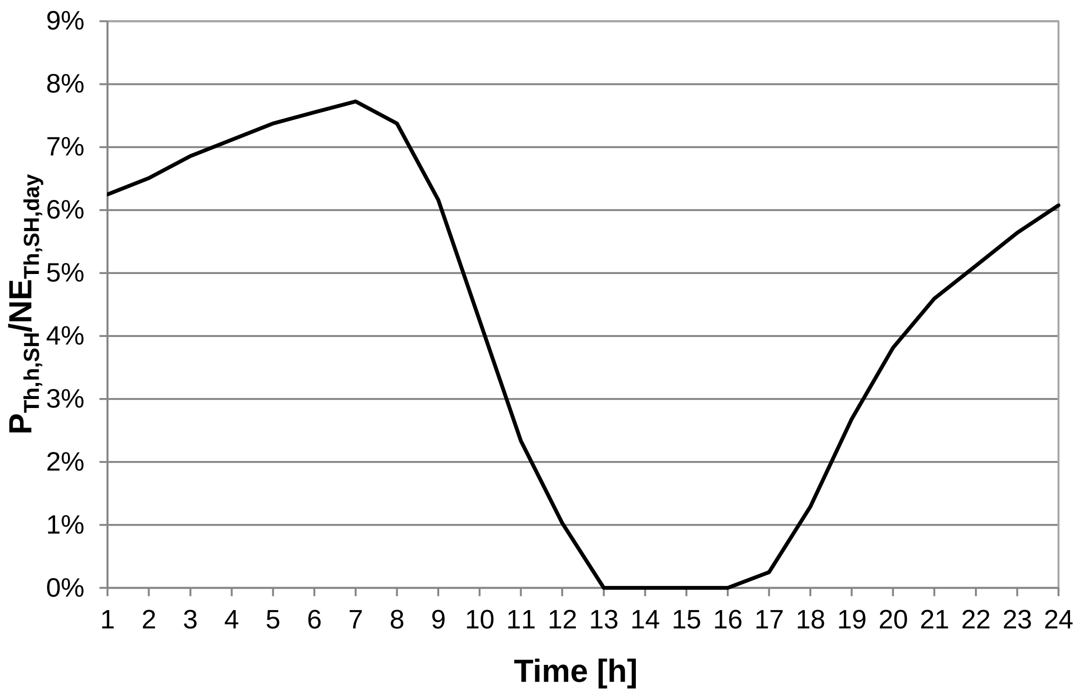

Fig. 7: Thermal-load profile for space heating requirements (Milan – October)

If the CHP can recover the condensed heat of the exhaust gases, the thermal efficiency or thermal power curve should be measured for two different water inlet temperatures, namely, high and low temperature, which are preferably 60 and 35°C, respectively. If the inlet water temperature to the CHP (T_R) can be accurately measured and the performance data for both high and low temperature are available, then these data should be linearly interpolated to calculate the thermal power output in the actual operating condition.

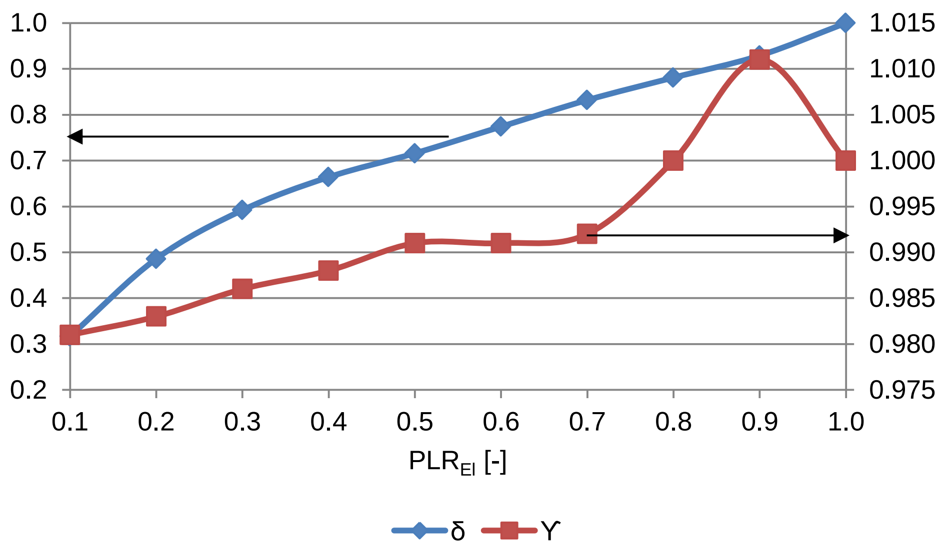

Fig. 8: Normalized performance curves for internal combustion engine-based CHPs

For example, if data at 60 and 35°C are available, then:

$$P_{Th}^{CHP} = P_{Th}^{CHP}\Big|_{T_R=35\,°C} + \left(P_{Th}^{CHP}\Big|_{T_R=60\,°C} - P_{Th}^{CHP}\Big|_{T_R=35\,°C} \right) \cdot \left({T_R - 35} \middle/ {60 - 35} \right) \tag{27}$$

Alternatively, if the performance data are known at a high temperature, such as 60°C, and the exhausts gas temperature is also known at a rated load, then it is possible to determine the low-temperature thermal efficiency. This is performed by using correction factors defined by the specification, which depends upon the temperature difference between exhaust gases and inlet water, on the location of the unit, whether outside or inside, and on the average temperature of water exiting the distribution system.

In the case of Stirling engines, the electric power output also varies considerably as a function of the inlet water temperature and it is necessary to consider this. For the purpose of the calculation method, the data for electric power and efficiency corresponding to at least two different inlet water temperatures should be available. Subsequently, an equation similar to the previous one is used (e.g. if data at 60 and 35°C are available):

$$P_{El}^{CHP} = P_{El}^{CHP}\Big|_{T_R=35\,°C} + \left(P_{El}^{CHP}\Big|_{T_R=60\,°C} - P_{El}^{CHP}\Big|_{T_R=35\,°C} \right) \cdot \left({T_R - 35} \middle/ {60 - 35} \right) \tag{28}$$

If $PLR_{Th,h} < PLR_{Th,min}$, the unit is switched-off and it is assumed that $PLR_{Th,h} = P_{Th,h}^{CHP} = P_{El,h}^{CHP} = P_{Fuel,h}^{CHP} = 0$.

If $PLR_{Th,h} > 1$, the unit operates at full load and it is assumed that $PLR_{Th,h} = 1;\ PLR_{Th,h}^{CHP} = P_{Th,nom}^{CHP}$; $PLR_{El,h}^{CHP} = P_{El,nom}^{CHP}$; $PLR_{Fuel,h}^{CHP} = P_{Fuel,nom}^{CHP}$; .

For systems with thermal storage, the parameter α (as above described) is first specified.

If α ≥ 1 (adequate storage), the partial-load ratio of the cogeneration unit can be assumed as constant during the day. PLR_{Th} has a unique value for each month, which is evaluated as:

$$PLR_{Th,mon} = \frac{P_{Th.mon}}{P_{Th,nom}^{CHP}} \tag{29}$$

where $P_{Th,mon}$ is the average thermal power entering the distribution system (on a monthly basis).

If $PLR_{Th,min} < PLR_{Th,mon} < 1$, the performance of the cogeneration system in terms of thermal power output ($P_{Th,mon}^{CHP}$), electric power output ($P_{El,mon}^{CHP}$), and primary power input ($P_{Fuel,mon}^{CHP}$), is determined by means of a linear interpolation of the performance curves. Following this, the corresponding energy flows are calculated:

$$OE_{Th,mon}^{CHP} = 24 \cdot G \cdot P_{Th,mon}^{CHP} \tag{30}$$

$$OE_{El,mon}^{CHP} = 24 \cdot G \cdot P_{El,mon}^{CHP} \tag{31}$$

$$PE_{Fuel,mon}^{CHP} = 24 \cdot G \cdot P_{Fuel,mon}^{CHP} \tag{32}$$

If $PLR_{Th,mon} < PLR_{Th,min}$, the unit intermittently operates at the minimum admissible load ratio. A parameter k is introduced to take into account the efficiency reduction during the start-up and cool-down periods:

$$OE^{CHP}_{Th,mon} = NE_{Th,SH,mon} + NE_{Th,DHW,mon} + DE^{AHP}_{Th,mon} \tag{33}$$

$$PE^{CHP}_{Fuel,mon} = \left(NE_{Th,SH,mon} + NE_{Th,DHW,mon} + DE^{AHP}_{Th,mon}\right)\cdot(1+k)\cdot\frac{P^{CHP}_{Fuel,\min}}{P^{CHP}_{Th,\min}} \tag{34}$$

$$OE^{CHP}_{El,mon} = \left(NE_{Th,SH,mon} + NE_{Th,DHW,mon} + DE^{AHP}_{Th,mon}\right)\cdot\frac{P^{CHP}_{El,\min}}{P^{CHP}_{Th,\min}} \tag{35}$$

where the parameter k is given by:

$$k = 0.005 \cdot \left(\frac{P^{CHP}_{Th,\min}}{P_{Th,mon}}\right) \tag{36}$$

and

$$\frac{P^{CHP}_{Th,\min}}{P_{Th,mon}} = \frac{PLR_{Th,\min}}{PLR_{Th,mon}} \tag{37}$$

ranging from 0 to 1.

If $PLR_{Th,mon} > 1$, then:

$$P^{CHP}_{Th,mon} = P^{CHP}_{Th,nom}\ ;\quad P^{CHP}_{El,mon} = P^{CHP}_{El,nom}\ ;\quad P^{CHP}_{Fuel,mon} = P^{CHP}_{Fuel,nom} \tag{38}$$

The corresponding energy flows are evaluated on the basis of the monthly hours of operation.

If 0 < α < 1 (inadequate storage), the energy flows of the CHP system are evaluated for both α = 0 and α = 1; this is followed by:

$$OE^{CHP}_{Th,mon} = (1-\alpha)\cdot OE^{CHP}_{Th,mon}\Big|_{\alpha=0} + \alpha\cdot OE^{CHP}_{Th,mon}\Big|_{\alpha=1} \tag{39}$$

$$OE^{CHP}_{El,mon} = (1-\alpha)\cdot OE^{CHP}_{El,mon}\Big|_{\alpha=0} + \alpha\cdot OE^{CHP}_{El,mon}\Big|_{\alpha=1} \tag{40}$$

$$PE^{CHP}_{Fuel,mon} = (1-\alpha)\cdot PE^{CHP}_{Fuel,mon}\Big|_{\alpha=0} + \alpha\cdot PE^{CHP}_{Fuel,mon}\Big|_{\alpha=1} \tag{41}$$

2.4 prEN 50465:2011: Gas appliances – Combined heat and power appliance of nominal heat input inferior or equal to 70 kW (EUROPE)

This document is the second edition of EN 50465:2008 that only dealt with fuel-cell systems. It has been modified as follows:

- Inclusion of requirements for Stirling engines and internal combustion engines
- Modification of the requirements for fuel-cell heating appliances
- Modification of the total efficiency calculation

Owing to the change in scope to include technologies in addition to fuel cells, the title of this EU standard has been changed from, “fuel cell gas heating appliances” to, “combined heat and power appliances”.

This draft EU standard was submitted to members for CENELEC enquiry.

The central and most fundamental principle of a MCHP is that, in order to maximize the many benefits that arise from it, systems should be sized according to the heat demands of the applications.

This EU standard specifies the requirements and test methods for the construction, safety, fitness for purpose, rational use of energy, and the marking of a MCHP. It applies to MCHPs that have the following characteristics:

- That use one or more combustible gases
- Where the temperature of the heat-transfer fluid does not exceed 105°C during normal operation
- Where the maximum operating pressure in the heating-water circuit does not exceed 6 bar
- Where DHW circuit (if installed) has a maximum pressure of 10 bar
- Which can give rise to condensation under certain circumstances
- Which are intended to produce hot water either by the instantaneous or storage principles
- Which have a maximum primary input (based on net calorific value) not exceeding 70 kW.

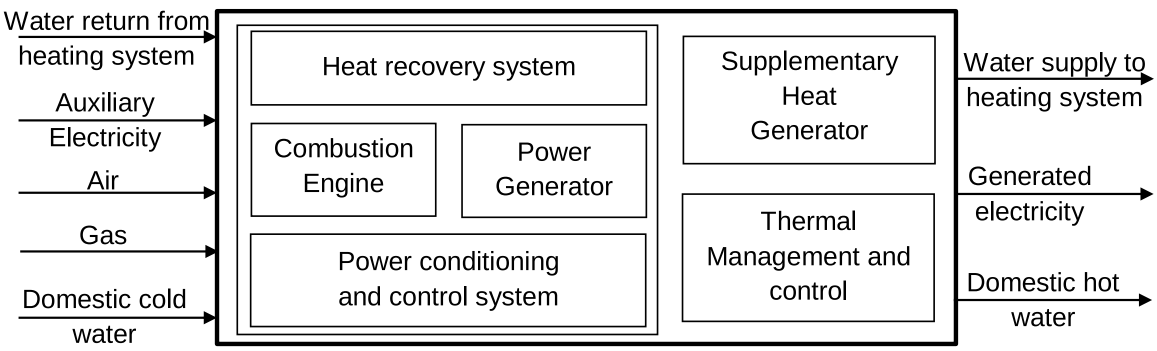

Fig. 9: Typical set-up for an internal combustion engine MCHP appliance

The standard refers, in the case of an internal combustion engine MCHP, to the typical set-up in Fig. 9. In the case of a fuel-cell MCHP, the “combustion engine” and the “power generator” are substituted by the “fuel-processing system” and the “fuel-cell module”. In the case of a Stirling engine MCHP appliance, the engine and generator are substituted by the “engine burner” and the “Stirling engine module”, respectively.

With regards to the overall efficiency requirements of the standard, it defines the overall efficiency as the total of the electric net AC output and the supplied thermal output, referred to as the primary input, based on the lower heating value. Furthermore, it specifies that an overall efficiency of no less than 80% should be reached at nominal primary input.

The tests at nominal conditions should be performed at a water temperature regime of 50/30°C for condensing appliances and at 80/60°C for non-condensing units.

The measurement uncertainties are selected so that a ±2% total uncertainty in the efficiency measurement is ensured.

2.5 DIN 4709 (2011-11): Determination of the Standard Efficiency Factor for Micro-CHP appliances of Nominal Heat Input not Exceeding 70 kW (GERMANY)

DIN 4709 has been prepared at the Heating and Ventilation Standards Committee (NHRS) by Working Committee NA 041-01-68 AA "Mikro KWK Anlagen" ("micro-CHP units”).

This standard specifies a method for determining the standard efficiency of MCHPs for domestic use for space heating and hot water production. It establishes a test procedure that is performed with different thermal loads for heating operation. Moreover, it specifies how the energy demand for the production of hot water, determined in accordance with other standards, is taken into account in order to evaluate a standard efficiency for hot water production.

This standard applies to MCHPs that do not exceed a nominal primary input of 70 kW and are fuelled by natural gas or other fuels. Furthermore, testing is performed on the complete system (CHP + thermal storage + control unit). This yields a more realistic measure in efficiency because transient losses are taken into account, as well as thermal losses from the storage tank. This measure also takes the effect of the control strategy for loading and unloading the thermal storage tank of the CHP plant into consideration.

For the application of the procedure, the use of VDI 4655, which details reference-load profiles of single- and multi-family dwellings for CHPs, among other regulations, is indispensable.

The standard specifies the reference conditions for the test:

- Ambient air temperature (20 ± 3)°C;
- Temperature of the combustion air (20 ± 3)°C;
- Electrical voltage: (230/400 ± 2%) V;
- The system is installed in a well-ventilated space, free of drafts (air velocity lower than 0.5 m/s). The system is also protected from direct sunlight;

In addition, the required instrument uncertainties are:

- Fuel flow rate ±1%;
- Water flow rate ±1%;

- Time: ±10 s;
- Ambient temperature: ±1 K;
- Water temperature: ±0.5 K;
- Fuel temperature: ±0.5 K;
- Pressure: ±2%;
- Calorific value of fuel ±1%;
- Fuel density: ±0.5%;
- Amount of electrical energy: ±2%;
- Fuel mass: ±0.5%.

The assessment is based on lower heating value (LHV_{Fuel}) of gas and the standard requires the evaluation of primary energy input to the MCHP as:

$$PE_{Fuel}^{MCHP} = m_{Fuel} \cdot LHV_{Fuel} \text{ or } PE_{Fuel}^{MCHP} = \int \dot{m}_{Fuel} \cdot LHV_{Fuel}\, dt \qquad (42)$$

where PE_{Fuel}^{MCHP} is primary energy input of the MCHP, and m_{Fuel} and $\dot{m}_{Fuel}$ are the mass and flow rate of fuel, respectively. See also section 3 for definition of energy flows and nomenclature.

The useful amount of thermal energy provided by the micro-CHP is evaluated as:

$$OE_{Th}^{MCHP} = \int \dot{m}_{cw} \cdot c_p (T_S - T_R) dt \qquad (43)$$

where OE_{Th}^{MCHP} is thermal energy provided by the MCHP, $\dot{m}_{cw}$ is the cooling water mass flow rate, c_p is the isobaric specific heat capacity of water, and T_S and T_R are the supply and return temperature of water, respectively. In particular, during the test, the MCHP and hydraulic scheme are set so that the supply and return temperatures of 50 and 30°C, respectively, are maintained.

To determine the standard efficiency of MCHPs, it is necessary to measure the electric energy output of the plant (OE_{El}^{MCHP}). Some examples of MCHPs are illustrated in Fig. 10.

As indicated by the arrows in both directions at the electricity meter, any auxiliary power consumed by the CHP is taken into account. Hence, the electricity output measured refers to the net output. The consumption of the external circulation pump is also taken into account owing to it being connected at the generator output. However, the standard also contemplates further schemes, where the circulation pump does not affect the auxiliary power, because it is connected to the main line in front of the electricity meter.

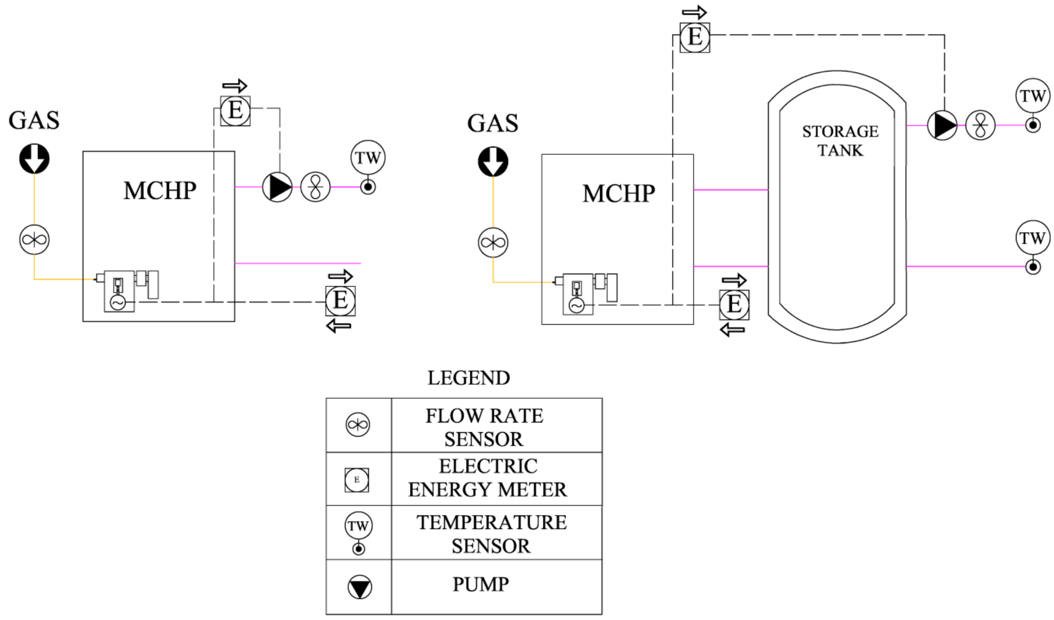

Fig. 10: Schematic representations of two equipment options with measuring points: left – MCHP without thermal storage; right - MCHP with thermal storage

To perform the tests, the plant is set for heating purposes only. Any existing facility for the preparation of sanitary hot water is not taken into account.

With regards to the operation of the MCHP for heating purposes, measurements for determining the standard efficiency occur with a variable thermal load, as indicated in Fig. 11 according to VDI 4655. The detailed data for each phase are listed in Tab. 3. The Y-axis indicates the heat demand as a percentage of the nominal thermal output of the CHP.

Owing to the return and supply temperatures being maintained at constant levels of 30 and 50°C, respectively, the heat rejection can be only adjusted by the volume flow rate in the heating circuit.

Evidently, this profile of thermal load does not match the profile of a day in winter for a properly designed CHP because the mean ratio of heat demand to nominal thermal power of the CHP 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. In conclusion, the DIN 4709 profile of thermal load refers to a day in spring or in fall or, in other words, to a transition time during the year. The intention of selecting such a profile can be understood when referring to the evaluation of the primary energy savings according to Directive 2004/8/EC of the EU Parliament, which is based on annual efficiency factors. Since it is not feasible to test cogeneration units for a period of one full year, any short-cut method should represent the variable heat demand during the year as best as possible. Obviously, neither winter days nor summer days can serve as a meaningful profile to this aim [12].

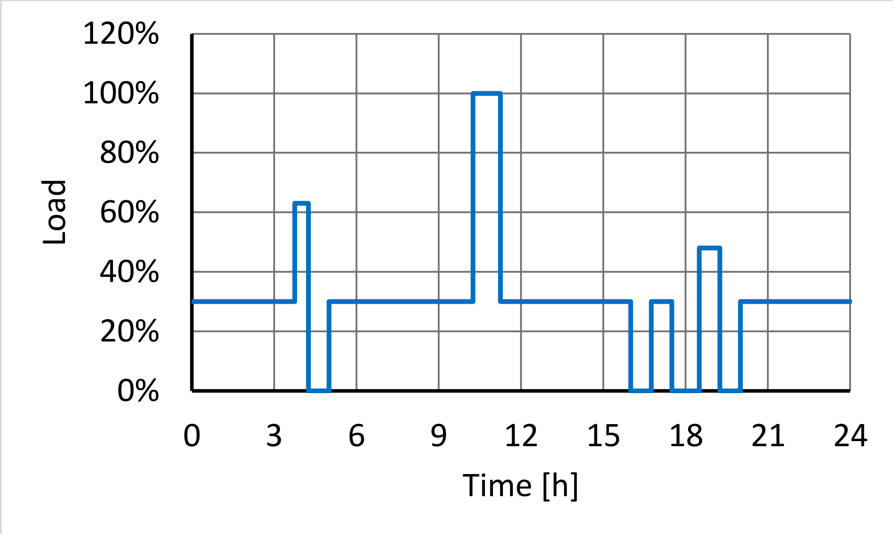

Fig. 11: DIN 4709 Thermal-Load Profile – X is the time [h] and Y is the ratio between thermal output and rated output [%]

Tab. 3: DIN 4709 Test Program

Phase	Cumulative Time [h]	Thermal Output/rated Output [%]
1	3.75	30
2	4.25	63
3	5.00	0
4	10.25	30
5	11.25	100
6	16.00	30
7	16.75	0
8	17.50	30
9	18.50	0
10	19.25	48
11	20.00	0
12	24.00	30

In the case of MCHPs with thermal storage (Fig. 10, right), the interaction of the cogenerator and the storage tank is managed by the control unit. Consequently, the thermal-load profile presented in Fig. 11 does not coincide with the operation of the CHP because its operation is determined by the internal control unit with respect to the level of thermal energy in the storage tank. If the level is low and this is detected by the temperature sensors placed in the tank, the CHP is forced to start; if the level is high, the CHP is forced to shut down. The level of thermal energy in the storage tank is affected by the thermal-load profile because the heat demanded is delivered by the storage tank and is fed into the heating circuit by the circulation pump (illustrated in Fig. 10, right).

Fig. 12 is an illustration of the test process in schematic form, where 1 is the beginning of test, 2 is the end of test, 3 is the default setting of the MCHP, 4 is the pre-test phase, and 5 is the test phase (max 24 hours + 30 minutes). As can be seen in the figure, before starting the test procedure, the conditions at the test stand should be prepared with respect to the first phase of the load profile.

In the beginning and at the end of the test, in order to ensure equal energy states in the MCHP, the unit is powered up until steady state is reached. Subsequently, the test is performed. The test begins as soon as the MCHP, with or without a buffer, has achieved steady state. The steady state is reached when the average value of the fuel mass flow within 30 minutes changes by no more than ±2% and the return temperature varies by no greater than ±1°C of the 30°C set point. During the test, the average variation of the supply and return temperatures over the entire measurement cycle is no greater than ±2°C of the set value. For each phase within the test cycle, a maximum deviation from the thermal energy profile of 5% is permitted.

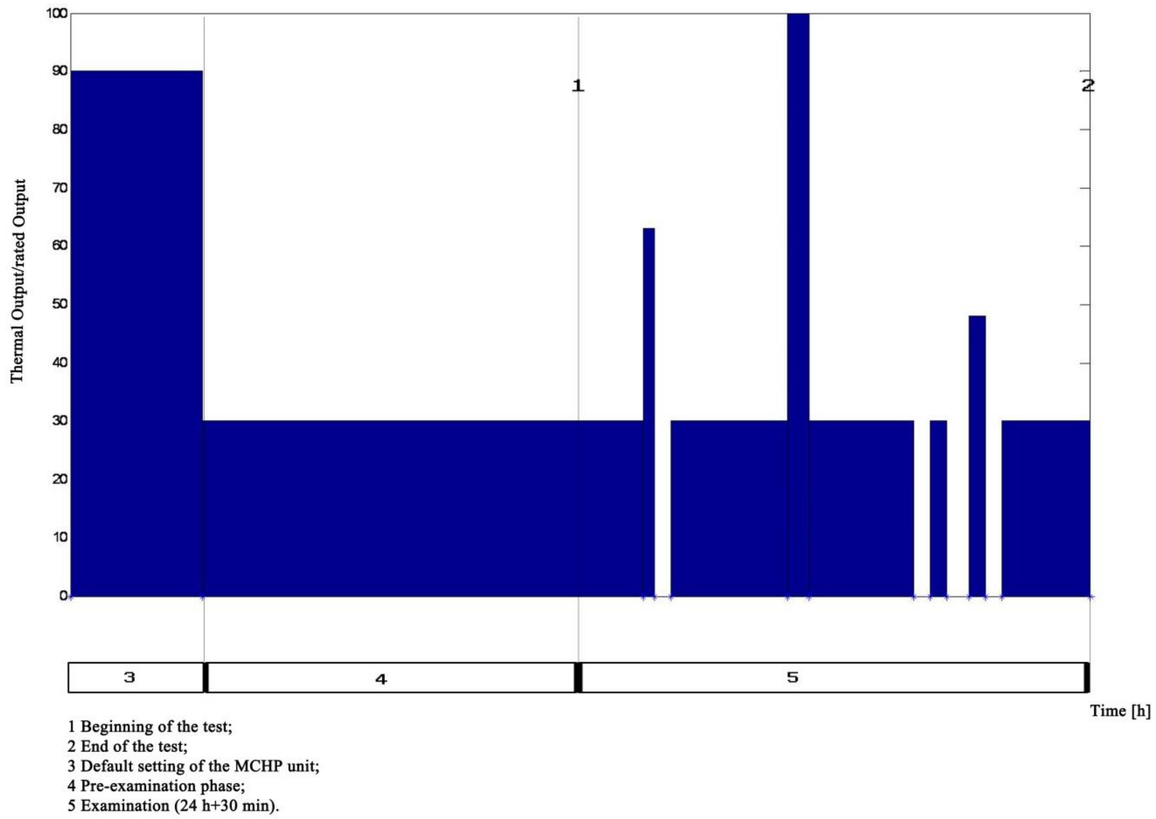

Fig. 12: Schematic representation of the test process

If the unit is equipped with a thermal storage, the testing period starts and ends with full thermal storage. In the pre-test phase, the heat rejection from the storage tank to the heating circuit needs to be tuned to 30% of the nominal thermal output of the CHP.

For the sake of accuracy and consistency, the level of thermal energy in the storage tank must be the same at the beginning and the end of the test procedure. According to the standards set by DIN 4709, a storage tank at maximum energy level forcing the CHP to shut down by the internal control is used as an indicator for the start and the end of the test procedure.

Obviously, the end of the test procedure should be triggered by the same event. In other words, the storage tank at its maximum level of energy forcing the CHP to shut down signals the end of the test procedure after 24 h. However, because the operation of the CHP is generally independent of the heat rejection to the heating circuit, which is due to the thermal decoupling by the storage tank as stated earlier, then it will mere coincidence if the end of the test procedure after 24 hours and the shutdown of the CHP occur at the same time. Consequently, the standard defined by DIN 4709 allows the shutdown of the CHP unit in a time slot between 24 and 24.5 hours after the test procedure started. Evidently, this requires the prolonging of phase 12 of the test procedure (Tab. 3) from 4 up to 4.5 h. If the CHP does not shut down within this 0.5-hour time slot, another 24-hour test procedure should be added; this can easily be achieved because the conditions for phase 12 at the end of the test cycle are the same as for phase 1 at its beginning. If the end of this second test procedure between 48 to 48.5 hours after start still does not coincide with the shutdown of the CHP, a third 24h-test procedure should be added. If this does not resolve the testing procedure, the entire test must be aborted and the test should be recorded as being “inconclusive”.

With the measured amounts of energy during the test, thermal, electrical, and overall standard efficiencies can be determined.

The thermal standard efficiency during heating operation is the ratio of thermal energy generated and the fuel primary energy input:

$$\eta_{Th}^{MCHP} = \frac{OE_{Th}^{MCHP}}{PE_{Fuel}^{MCHP}} \tag{44}$$

The electrical standard efficiency is the ratio of electrical energy output and the amount of primary energy input:

$$\eta_{El}^{MCHP} = \frac{OE_{El}^{MCHP}}{PE_{Fuel}^{MCHP}} \tag{45}$$

The overall efficiency for heating purposes is defined as the sum of the thermal efficiency and a corrected electrical efficiency:

$$\eta_{tot} = \eta_{Th}^{MCHP} + \eta_{El}^{MCHP} \cdot \frac{PEF_{El}}{PEF_{Fuel}} \tag{46}$$

where PEF_{El} and PEF_{Fuel} are primary energy factor of electricity mix and fuel used, respectively. Similar equations apply to evaluate standard thermal, electric, and overall efficiencies if the MCHP is used for hot water production. In this case, the standard efficiency is determined by the results of a specific profile calculated according to DIN EN 13203-4.

2.5.1 Results from tests according to the standard DIN 4709 for evaluation of micro-CHPs

The test procedure provided from standard DIN 4709 was applied to two CHPs at Reutlingen University, as described in [12]. This study addresses a major drawback of the test procedure proposed in DIN 4709; this is that the test period should end between 24 and 24.5 hours after that start and that the end of the period should coincide with a shutdown of the CHP. Both conditions are rarely achieved simultaneously during practical testing. Instead of repeating the complete test, as proposed by the standard, an alternative method is suggested.

Both tested units are based on a four-cylinder internal combustion engine. The first unit runs on a lean air-to-fuel mixture delivering 15 kW_{El}, the second unit operates at stoichiometric conditions, delivering 20 kW_{El}. Both units are capable of variable power output. In Tab. 4, the nominal performance data of the two tested micro-cogenerators are reported.

Tab. 4: Nominal performance data of the tested micro-cogenerators

	Unit 1	**Unit 2**
Rated electric power	15 kW	20 kW
Rated electric efficiency	30%	32%
Rated thermal power	30 kW	40 kW
Rated thermal power including condensing heat exchanger	33 kW	44.5 kW
Thermal efficiency (without condensation)	62%	64%

The hydraulic setup for the tests is illustrated in Fig. 13. The CHP is connected to a heat distributor, and the supply line leaving the heat distributor is connected to a storage tank with a capacity of 0.5 m^3 as well as to the heating system, which is simulated by a primary pump and a water-cooled heat exchanger (cooler). The three-way mixing valve controls the supply temperature, maintaining a constant supply temperature of 50°C at the cooler during the test. The constant return temperature of 30°C is achieved after the cooler by the flow rate of the water within itself, which serves as a final heat sink. A further control regulates the speed of the circulation pump and, consequently, the heat rate rejected by the heating circuit occurs according to the load profile presented in Fig. 11.

The condensing heat exchanger is located in the return line in order to allow the lowest temperatures for optimal condensation of the exhaust gases. The condensing heat exchanger can be set to be active or inactive using the two-way valves; this enables tests to be performed with and without the condensation of exhaust gases. The natural gas from the local utility grid has a lower heating value of 10.14 kWh/Nm^3.

As required by the standard, at the start and at the end of the test procedure the energy level in the thermal storage tank needs to be identical in order to achieve consistent results for the required efficiency. To this aim, the maximum energy level in the tank, indicated by the shutdown of the CHP, serves as an appropriate measure. Consequently, at the first shutdown of the unit the test procedure is started. According to the DIN 4709 standard, the shutdown to end the test procedure should occur between 24 and 24.5 hours after the start. For the test with unit one (without a condensing heat exchanger) two shutdowns occur, one at 21.7 hours (“End 1”) and one at 25.4 hours after the start (“End 2”).

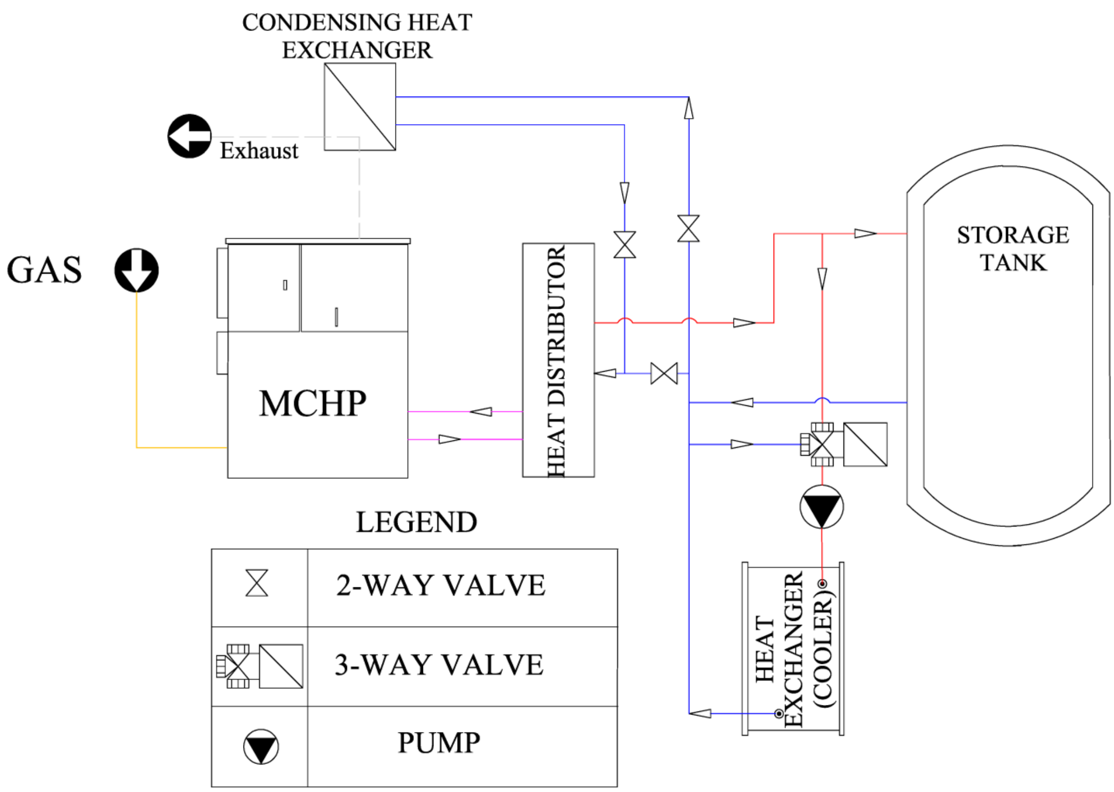

Fig. 13: The hydraulic setup for the tests according to DIN 4709

The energies measured during the test allow the evaluation of the thermal, electric, and overall efficiency for the two shutdowns events (Tab. 5).

Tab. 5: Efficiency factors for the test with unit one without a condensing heat exchanger

Efficiency	Section Start – End 1	Section Start – End 2
Thermal	55.2%	55.6%
Electric	30.5%	30.4%
Overall	85.7%	86.0%

The data from Tab. 5 shows almost identical results for the two test sections analysed, which implies that the efficiency factors for the 24-hour test profile can be derived using linear interpolation. The final results achieved with this procedure for all the tested configurations are reported in Tab. 6.

The results indicate that the efficiency factors for the intended test length of 24 hours can effectively be derived using linear interpolation from the two shutdown events.

Tab. 6: Efficiency factors for all the tested configurations

Efficiency	Unit 1	Unit 2

Thermal	55.5%	59.0%
Electric	30.4%	30.9%
Overall	85.9%	89.9%
Including condensing heat exchanger		
Thermal	60.5%	64.8%
Overall	90.9%	95.7%

2.6 VDI 4656:2011-04: Design and dimensioning of micro-combined-heat and power-plants (GERMANY)

In the future, it is assumed that MCHPs will supply power and heat for single- and multi-family houses. Special claims are made by the planners and installers of the plants with regards to designs and dimensioning. This, in particular, includes the design of the electrical and thermal performance of the MCHP and the supplementary heater, as well as the size of the heat storage unit and other required components, which must all be considered.

This standard specifies the rules for the planning and design process of the components of MCHPs, using methods that are based on reference load profiles according to VDI 4655. This enables the comparison of different MCHP technologies and different dimensions of components with the same framework conditions in the planning and dimensioning process.

The necessary calculations, including the generation of reference-load profiles, are supported using a calculation program. However, it can also generate also the real load profiles for the MCHPs under investigation.

This standard applies to MCHPs for use in multi-family houses or for small commercial business applications that do not exceed a nominal primary input of 70 kW. When the reference load profile is used according to VDI 4655, the single-family house can extend to a maximum of twelve persons and to apartment buildings with up to 40 units.

The standard refers to a MCHP consisting of:

- CHP;
- Optional additional heater;
- Storage tank.

The standard defines the steps for the selection of the appropriate MCHP for practical applications, of which the following are important:

- Design heat load for sizing the MCHP;
- The annual energy requirement;
- The objectives and aims of the planning process (that typically are to meet the energy demands of the user and to obtain a higher number of operating hours of the MCHP);

- The different available technologies for MCHPs and their technical parameters.

In addition to this, it is necessary to know the maximum annual operating time of the MCHP ($t_{\max}^{MCHP}$), which is defined as follows:

$$t_{\max}^{MCHP} = \frac{E_{Th}}{P_{Th,\min}^{MCHP}} \tag{47}$$

where E_{Th} is the annual energy requirement (including DHW) and $P_{Th,\min}^{MCHP}$ is the minimum thermal power of the MCHP. In practical applications, the annual operating time is always smaller than $t_{\max}^{MCHP}$.

With these input data, it is possible to select a group of MCHPs that are based on different technologies and are suitable for the analysed application. It is then possible to select one of the solutions, among the previous choices, following these steps:

Step 1: The reference load profiles (for heating, electric energy and DHW requirements) are designed according to VDI 4655;

Step 2: The appropriate parameters for each solution are chosen (including the control methods);

Step 3: A yearly simulation is performed and this is based on the previously defined load profiles for electric energy, DHW and heating energy, the characteristics of the plant, and the control method of the CHP. The results of the calculations are stored in a worksheet and they include:

1) The thermal and electrical energy generated by the micro-cogeneration unit (this is in addition to the associated thermal and electrical efficiency, and the resulting total efficiency);
2) The thermal energy generated in the optional auxiliary heater and the related thermal efficiency;
3) The amount of fuel required by each device;
4) The electrical energy used by the plant;
5) The resulting exchange of energy with the electrical grid;
6) The thermal losses of the heat storage system;
7) The number of start-ups and the operating hours (divided into normal operation, start-up, and cool-down) for the micro-cogeneration unit and the additional heater.

Finally, the results of all the investigated MCHPs are evaluated and the best investment option, based on environmental, economic, and energy performance, is then selected.

2.7 RAL-UZ-108: 06-2011: Small-Scale Gas-Fired Cogeneration Modules – Basic Criteria for Award of the Environmental Label: Der Blaue Engel (GERMANY)

The environmental label defined by this standard, [13], may be awarded to small-scale cogeneration modules that make a rational use of fuel and emit less nitrogen oxides and carbon monoxides in comparison with conventional systems (CSs). Aside from engine-driven cogeneration systems powered by diesel, gasoline, or gas engines, plants driven by Stirling engines also fall within the scope of the standard. The MCHP must have an electric power no higher than 30 kW.

The basic criteria specify the emission requirements for the MCHPs. The emission limits stated below are related to the exhaust gases under standard conditions (0°C, 1013 mbar) with an oxygen volumetric content of 5% for engine-powered systems and 0% for other units.

The nitrogen monoxide and nitrogen dioxide content of the exhaust gas must not exceed 250 mg/Nm³.

The carbon monoxide content of the exhaust gas must not exceed 300 mg/Nm³.

In terms of energy performance requirements, efficiencies are to be determined at a supply temperature of 75°C and a return temperature of 55°C. The efficiencies of units powered by Stirling engines are to be determined at a supply temperature of 50°C and a return temperature of 40°C.

The total efficiency must not fall below 89% at full load and at minimum power level, if adjustable.

In the case of cogeneration modules that can be operated at partial load, the total efficiency at minimum power or at 50% partial load must be not lower than 87%.

The electrical efficiency should be determined at full load, and at minimum power or at 50% partial load, if adjustable; the efficiency must meet the following requirements:

a. for cogeneration modules with a permanently adjustable electrical power

$$\eta_{El} \geq 2.5 * \ln(P_{El}) + 21.5 \tag{48}$$

b. for cogeneration modules with modulation of electrical power

$$\eta_{El} \geq 2.5 * \ln(P_{El}) + 20.5 \tag{49}$$

In the case of cogeneration modules that can be operated at partial load, for a partial load <50% in relation to full load, the measurements must not be taken at minimum electrical power but at 50% partial load. The electrical efficiency at 50% partial load must not fall more than 3% below the value determined at full load.

If the cogeneration module is designed for only one electrical power level, the measurement only needs to be taken at this power level.

2.8 Japanese Industrial Standards JISC8841-3 - Small solid oxide fuel cell power systems – Part 3: Performance testing methods and environment testing methods (JAPAN)

Performance and environmental testing methods are regulated for stationary small solid-oxide fuel-cell power systems contained in packages for which the rated transmission output is under 10 kW.

More specifically, the performance testing methods correspond to:

1) Fuel consumption thermal test;
2) Start-up test (measurement of the start-up time of the generating unit, the energy measurement necessary for start-up, and of the receiving power under a storage and suspension state);
3) Electric output test;
4) Efficiency test (power generation, heat recovery, and comprehensive test);
5) Load-change characteristics test;
6) Stop test (measurement of the stop time of the generating unit, and of the energy for stopping).

Environmental testing methods correspond to:

1) Noise test;
2) Exhaust-gas measurement test;
3) Drainage measurement test (measurement of the quality of the water discharged from the generating unit).

2.9 Japanese Industrial Standards JIS B8122 - Test Methods for Measuring Performance of Cogeneration Units (JAPAN)

This Japanese industrial standard specifies the test methods for measuring the performance of CHPs that supply both electric power and heat by means of a diesel engine, a gas engine, or a gas turbine as a prime mover.

The range of CHPs includes a prime mover, a generator, a heat recovery facility, and pollution abatement equipment for exhaust gases. It also includes a cooling facility that is required for the operation of the prime mover, and is required by the control and monitoring devices for their operation.

Specifically, this standard provides for the following:

1) Start-up testing;
2) Testing the performance of protective devices;
3) Testing the speed-control performance and voltage fluctuation properties;
4) Load testing;
5) Continuous operation testing;
6) Heat output measurement and testing;
7) Testing the properties of exhaust-gas emissions;
8) Noise measurement and testing;
9) Vibration measurement and testing;
10) Parallel operation testing (testing in parallel with grids);
11) Methods of making performance conversions between various motors.

This regulation only defines the method for testing.

For example, in continuous operation testing, regulations stipulate that the test should be performed at rated power over a continuous 3-hour period, without any adjustment. Performance checks should be performed every 1 hour.

The points to be checked are as follows:

- Generating voltage;
- Current and frequency;
- Power factor;
- Fuel heating value;
- Fuel consumption;
- Lubricant oil temperature and pressure;
- Exhaust gas temperature;
- Cooling water temperature;
- Exhaust gas flow;
- Heat output (cooling water flow rate and supply/return temperatures).

2.10 PAS 67: Laboratory tests to determine the heating and electrical performance of heat-led micro-cogeneration packages primarily intended for heating dwellings (UK)

This publicly available specification (PAS) has been developed by the Energy Saving Trust in collaboration with the British Standards Institution (BSI), [14]. This description relates to the 2008 version of the standard, but a more recent revision (PAS 67:2013) is now available, [15].

The purpose of PAS 67 is to determine by measurement, under a variety of load conditions, the data needed to calculate the energy performance of a micro-cogeneration unit. It specifies a comprehensive set of test conditions for determining the heating and electrical performance of heat-led micro-cogeneration systems that are primarily intended for use in dwellings. The tests are designed in order to be reproducible.

The PAS is suitable for testing MCHPs with a thermal output up to 70 kW that are fuelled by natural gas, LPG, biogas, hydrogen, mineral oil, and bio-oil. All the calculations should be determined using gross calorific values of the fuels, measured with an uncertainty lower than 0.5%. The specification also defines the maximum permitted uncertainties for fuel energy input, thermal energy output, as well as electric energy input and output measurements.

The following classifications of MCHPs are used:

RegPK – category of micro-cogeneration package for providing space and water heating, intended for connection to a separate DHW storage tank of standard specification, Fig. 14.

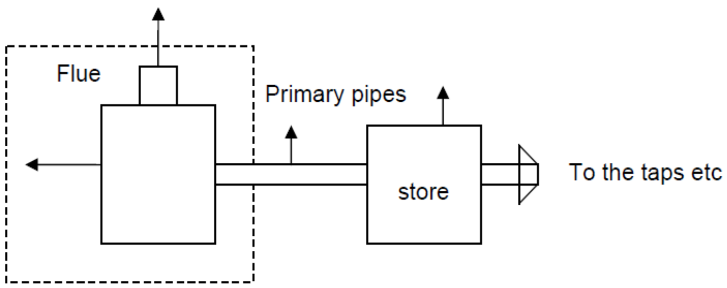

Fig. 14: Regular package MCHP

CombiPK – category of micro-cogeneration package for providing space and water heating in which DHW service is provided wholly from within the package, Fig. 15.

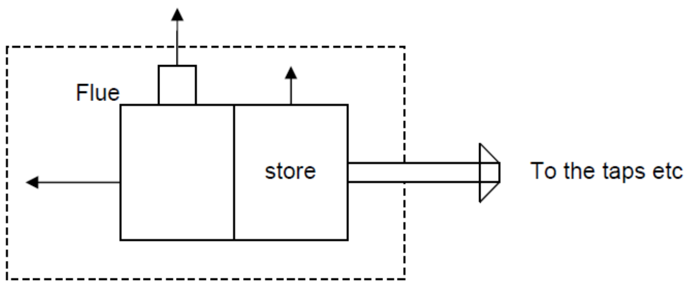

Fig. 15: Combined package MCHP

HeatPK – category of micro-cogeneration package for providing space heating only (no DHW service), Fig. 16.

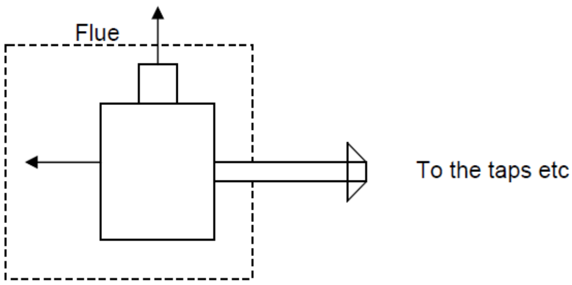

Fig. 16: Heat package MCHP

The specification defines the test laboratory conditions adjacent to the MCHP unit:

- the ambient air temperature in the test laboratory should be 20 ± 5°C;
- the maximum air velocity adjacent to the unit should be 0.5 m/s (except where the air velocity is inherently generated by the unit itself);
- the unit should be shaded from sunlight;
- the laboratory temperature, humidity, and pressure should be recorded hourly during the test at a height of 1.5 m and at a distance of between 1 and 3 m horizontally from the micro-cogeneration unit. The thermometer shall be protected from direct radiation from the MCHP;
- wherever possible, the relative humidity should be controlled between 50 and 70%.

The test laboratory should perform the following energy-balance calculation for each test period:

$$Q_{bal} = \left(PE_{Fuel}^{MCHP} + DE_{El}^{MCHP}\right) - \left(NE_{SH} + NE_{El} + Q_{waste} + \Delta h^{MCHP} + \Delta h^{ST}\right) \quad (50)$$

Where Q_{bal} represents the energy balance, that is, the total measured energy input minus the total measured energy output. PE_{Fuel}^{MCHP} and DE_{El}^{MCHP} are the primary and electric energy entering the MCHP, respectively, NE_{SH} and NE_{El} are net useful thermal energy for space heating and electric energy, respectively, Q_{waste} is thermal energy wasted through case and flue losses, Δh^{MCHP} and Δh^{ST} are the energy content difference at the beginning and end of the test for the MCHP and storage tank, respectively.

The absolute value of Q_{bal}, expressed as a percentage of PE_{Fuel}^{MCHP}, should not exceed a discrepancy limit (in the range 2.0–6.0%) that depends on the value of the partial load ratio (*PLR*) for which the unit is tested.

The specification requires a minimum of three operating tests (full output, 30%, and 10% tests). The full output test is a test of the system at its nominal rated heat output for space heating. The 30% output test is a test of the system for 24 hours with a suitable space heating demand, such that the space heating output should be equivalent to 30% of the space heating output produced during the full output test. The 10% output test is a test of the system for 24 hours with a suitable space heating demand, such that the space heating output should be equivalent to 10% of the space heating output produced during the full output test. A maximum deviation from the test value is permitted.

A test to determine stand-by loss (given by $PE_{Fuel}^{MCHP} + DE_{El}^{MCHP} - NE_{El}$) should also be performed, under conditions where the system is ready for service. This means that it should supply its nominal rated heat output within half an hour of a call for thermal energy. In the case of a CombiPK package, ready for service also requires readiness for hot water draw-off.

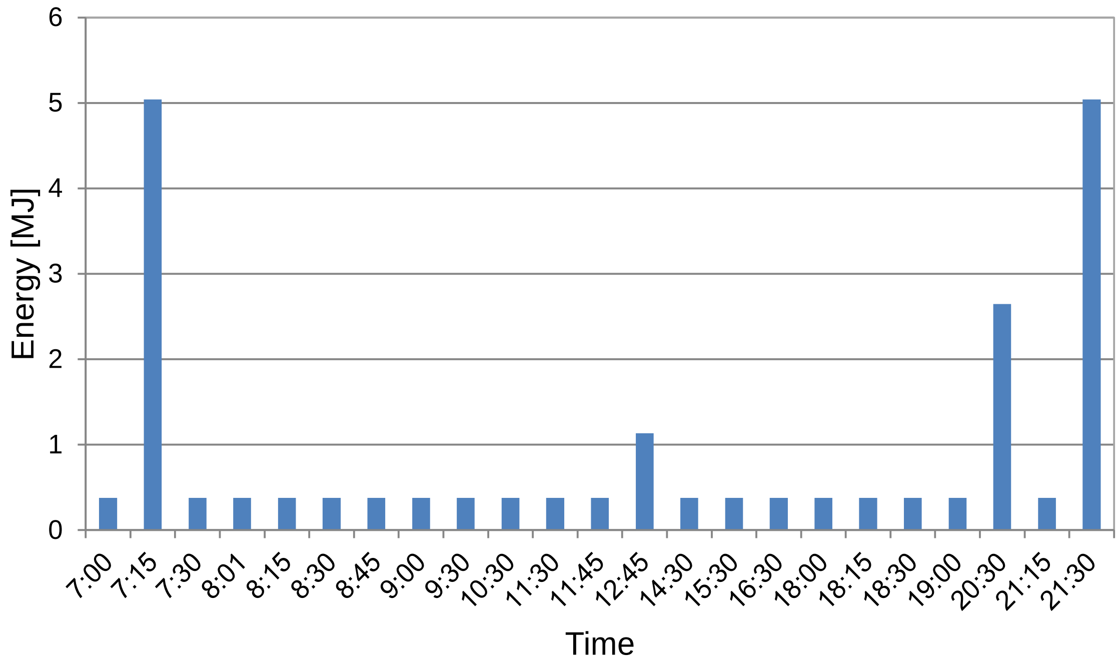

Fig. 17: EU reference DHW cycle

Finally, the specification defines a DHW test, applicable to RegPK and to CombiPK (with hot water storage less than 15 L) with slightly different testing procedures. The test for the production of DHW is a test of the unit for 24 hours considering the EU DHW tapping cycle (Fig. 17). The specification also defines, for each of the 23 tappings detailed in Fig. 17, the minimum and desired temperature differences between the cold and the hot water, the water flow rate, the allowable energy deviation, and a tolerance of the total energy content of the DHW drawn off.

The results obtained from testing with the requirements of PAS 67 are not intended for use as a tool for direct comparative assessment of MCHPs. However, the PAS results can be used as an input to procedures that calculate annual energy performance, such as the "Method to evaluate the annual energy performance of micro-cogeneration heating systems in dwellings", detailed in section 4.7. This evaluation method enables the estimation of the annual energy performance and derivation of a single index of performance for product comparison.

2.11 Product Certification Scheme Requirements: Electricity-led micro-cogeneration packages in dwellings (UK)

This document identifies the evaluation and assessment requirements, and practices for the purposes of the certification and listing of electricity-led micro-cogeneration packages [16]. It relates to the UK's micro-cogeneration certification procedure, which also makes use of PAS 67, according to the methodology described in section 4.7. Certification is required before a user of the micro-cogeneration equipment can apply for the UK feed-in tariff.

This scheme deals with electricity-led micro-cogeneration packages intended for installation in dwellings, where the package:

- has a thermal and electrical output of less than 45 kW or 50 kW, respectively;
- is fuelled by any of the following second and third family fuels, namely, gas from a bespoke source, hydrogen, mineral oil, other liquid fuels that are principally bio-oils, and other fuels including unconventional fuels and solid fuels;
- is intended to maximize electricity production in response to an electrical demand;
- includes all the co-generated heat recovered being utilized on site.

For compliance with this scheme, the micro-cogeneration unit or package must be able to demonstrate some performance criteria. Specifically, it must have a carbon emissions value 10% lower than that measured in an identical test on a condensing boiler with 90% rated efficiency [17].

If the MCHP consists of a prime mover, such as a fuel cell, that is intended only for the production of electricity and DHW (i.e. not space heating), it should be tested in accordance with the methods outlined in [16] and the PAS67 DHW test methodology. In particular, the DHW draw-off patterns should be those specified in PAS67.

The carbon emission value should be calculated using the following formula:

$$C = Fuel \times CIF_{Fuel} + \left(Elec_{out} - Elec_{in}\right) \times CIF_{El} + \left(H_1 - H_2\right) \times CIF_{El} \quad (51)$$

where:

- *Fuel* is the total gas fuel consumption during the 24-hour test period;
- CIF_{Fuel} is the carbon intensity factor (see section 4.7);
- $Elec_{out}$ is the electricity production during the 24-hour test period;
- $Elec_{in}$ is the electricity consumption during the 24-hour test period;
- H_1 is the heat content of DHW draw off required as per the specified hot water draw-off pattern in kWh;
- H_2 is the heat content of DHW draw off delivered in kWh.

Note that if $H_2 > H_1$, then H_1 will be deemed to equal H_2 so that ($H_1 - H_2$) can never give a result that is less than zero.

2.12 Summary

In this chapter, several available standard national testing procedures for MCHPs have been described. From a comparison of these standards, it was observed 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 (MCHP, integration boiler, and storage tank);
- 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, especially in terms of sensor accuracy;
- they define the reference testing conditions (supply and return water temperatures, ambient air temperature, etc.).

Nevertheless, some major differences can be observed; for example, considering the EU standards, they differ in terms of:

- the limiting value of power (electric, thermal or primary) for applicability;
- the thermal-load profile for testing; the Italian standard defines four day types, the German standard defines a single profile, which is representative of an intermediate day, while in the UK standard, the heat-load profile is represented by the number of days per heating season at 13 part-load bands;
- the type of energy performance parameter; the Italian and German standards use energy-based performance indices, while the UK procedure is based on an environmental-based performance-assessment parameter.

However, in conclusion, the analysed national standard methodologies seem to be based on the same fundamental elements. These common general elements can also be applied to the performance evaluation of micro-cogeneration systems. This application occurs with the parameters described in the subsequent chapter, either for experimentally based assessment studies, or for experimental calibration and validation of models to be used in simulative analysis

3 Performance Indices

To evaluate the performance of micro-generation systems, several performance indices can be used. This variety of indices is strictly related to the high complexity of hybrid micro-generation systems, which can perform bidirectional interactions with the external electric grid, as well as district heating and cooling networks. In addition, they can also be activated by both fossil- and renewable-energy sources, either contemporary or alternative.

Furthermore, the performance indices may or may not assume the same quality for the different energy outputs (exergy analysis). The indices can also require the evaluation of the system at nominal conditions or during dynamic operation. Finally, the performance indices can be relatively comprehensive, either taking all energetic inputs and outputs into account or neglecting some of them.

In this section, an overview of the performance indices that can be used to assess the performance of micro-cogeneration and micro-trigeneration systems is provided, taking into account the symbols and parameters defined in [1]. The time frame over which these indices are applied should be clearly defined when they are used. They should be typically evaluated on an annual basis; however; shorter time frames such as a heating season, a month, or even a week, can be acceptable.

In particular, the following nomenclature is used in Fig. 18, with reference to the boundary system of the building:

- Net energy (*NE*) is the energy provided by heating ventilation and air conditioning (HVAC) and electric systems (including renewable energy technologies) to cover the energy demand for space heating/cooling, DHW, and electricity consumption;

- Delivered energy (*DE*) is the energy represented individually for each energy carrier (fuel, electricity, heat/cold) that is entering the individual building envelope (the system boundary) in order to be used for heating, cooling, mechanical ventilation, hot water, lighting systems, and appliances. This may be expressed in energy units or in units of the energy carrier (kg, m^3, etc.). Locally generated renewable energy sources are not considered as delivered energy, but are accounted for as a separate contribution (renewable energy [*RE*]) to the net energy demand;

- Output energy (*OE*) is the energy output (electric, thermal, or cooling) from an energy conversion device;

- *RE* is the renewable energy “generated” on the building premises (e.g. electricity by PV, heat by solar thermal system, or using a stove fired with sustainably grown wood);

- Exported energy (*XE*) is the energy (heat/cold, or electricity) “generated” within the building envelope and exported to an external grid; this can include part of the renewable energy;

- Primary energy (*PE*) is the energy usage associated with the delivered energy that is embodied in natural resources (e.g. coal, crude oil, natural gas, sunlight, uranium) and that has not yet undergone any anthropogenic conversion or transformation.

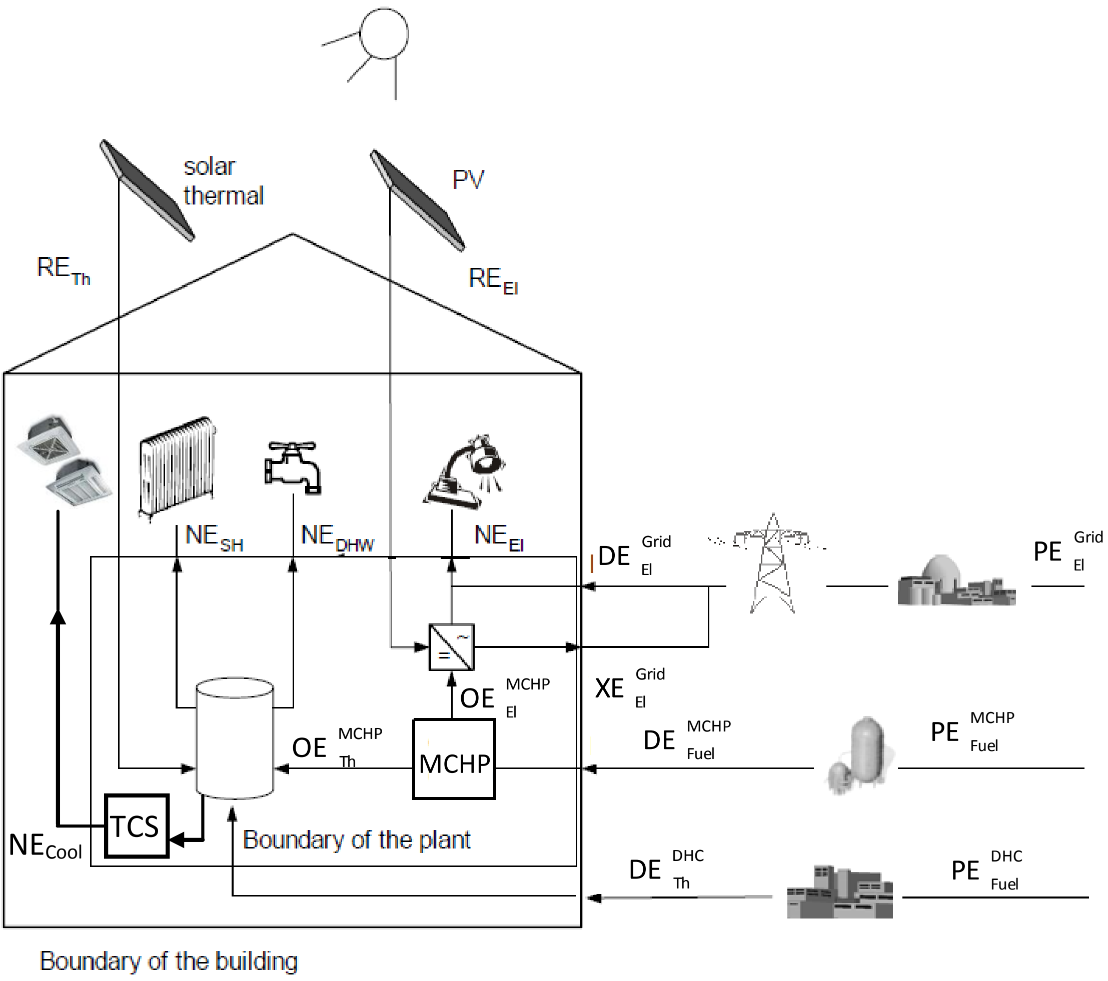

Fig. 18: Control volumes and related energies (updated from [1])

Moreover, specific superscripts, referring to energy conversion devices involved in energy flow have been used. Instead, subscripts refer to energy vectors.

3.1 Micro-cogeneration devices

The energy flows of a MCHP are illustrated in Fig. 19. Energy losses related to processing and distribution of the primary energy sources are not taken into account in this scheme. This is because there is high complexity in estimating these losses, and because they are external to the main energy conversion device (i.e. the MCHP) and to the building envelope. In this case, DE_{Fuel}^{MCHP} is assumed equal to PE_{Fuel}^{MCHP}, in other words, delivered energy is assumed as primary energy.

The following indices, based on the first law of thermodynamics, can be defined:

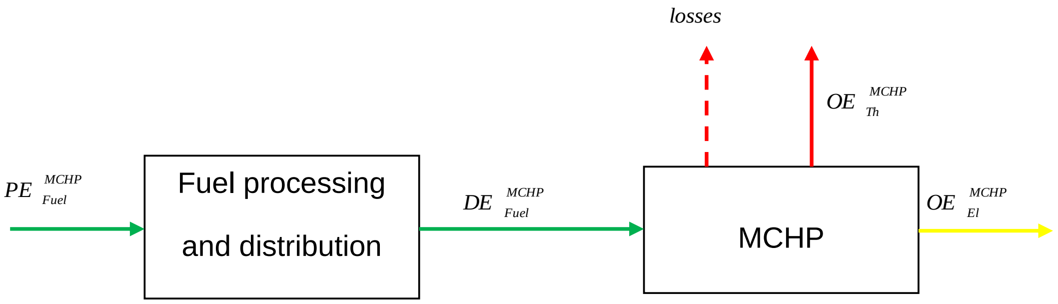

Fig. 19: Energy flows for a MCHP

- Primary energy factor of fuel

$$PEF_{Fuel} = \frac{PE_{Fuel}^{MCHP}}{DE_{Fuel}^{MCHP}} \tag{52}$$

This parameter takes into account the energy losses of fuel processing and distribution processes [1].

- Electric efficiency

$$\eta_{El}^{MCHP} = \frac{OE_{El}^{MCHP}}{DE_{El}^{MCHP}} \tag{53}$$

- Thermal efficiency

$$\eta_{Th}^{MCHP} = \frac{OE_{Th}^{MCHP}}{DE_{Fuel}^{MCHP}} \tag{54}$$

- Primary energy ratio

$$PER^{MCHP} = \frac{OE_{El}^{MCHP} + OE_{Th}^{MCHP}}{DE_{Fuel}^{MCHP}} = \eta_{El}^{MCHP} + \eta_{Th}^{MCHP} \tag{55}$$

- Cogeneration ratio [18]

$$\lambda = \frac{OE_{Th}^{MCHP}}{OE_{El}^{MCHP}} = \frac{\eta_{Th}^{MCHP}}{\eta_{El}^{MCHP}} \tag{56}$$

- Electric Index

$$EI^{MCHP} = \frac{OE_{El}^{MCHP}}{OE_{El}^{MCHP} + OE_{Th}^{MCHP}} \tag{57}$$

Beyond a first-law approach, exergy theory clearly suggests that electric energy has a higher thermodynamic quality with respect to thermal energy, [19]–[22].

Exergy analysis is not involved in the goals of Annex 54; nevertheless, an index that attempts to overcome the intrinsic limits of the above defined first-law indices has been proposed on an economic basis. Although the economic "value" of electric and thermal energy is not necessarily related to the exergetic value of that energy, this index weighs the individual contributions of energy flows by means of their respective average selling prices, to arrive at the so-called value-weighted primary energy ratio, PER_{VW}, [18]:

$$PER_{VW}^{MCHP} = \frac{\xi_{El} OE_{El}^{MCHP} + \xi_{Th} OE_{Th}^{MCHP}}{\xi_{Fuel} DE_{Fuel}^{MCHP}} \tag{58}$$

where ξ_{El} is the selling price of 1 kWh_{El}, ξ_{Th} is the selling price of 1 kWh_{Th}, and ξ_{Fuel} is the selling price of 1 kWh_{Fuel}.

The previous equation can be rewritten as:

$$\begin{aligned} PER_{VW}^{MCHP} &= \frac{\xi_{El}}{\xi_{Fuel}} \left[\left(OE_{El}^{MCHP} + \frac{\xi_{Th}}{\xi_{El}} OE_{Th}^{MCHP} \right) \frac{1}{DE_{Fuel}^{MCHP}} \right] = \\ &= \frac{\xi_{El}}{\xi_{Fuel}} \left(\eta_{El}^{MCHP} + \frac{\xi_{Th}}{\xi_{El}} \eta_{Th}^{MCHP} \right) = \frac{\xi_{El}}{\xi_{Fuel}} \eta_{eq,VW} \end{aligned} \tag{59}$$

Where

$$\eta_{eq,VW} = \eta_{El}^{MCHP} + \frac{\xi_{Th}}{\xi_{El}} \eta_{Th}^{MCHP} \tag{60}$$

is the equivalent value-weighted efficiency.

Moreover, it is possible to introduce a further index that is based on an incremental approach that separates the fuel primary energy entering the MCHP, from the share related to the cogenerated thermal energy that would be produced from the reference boiler. Therefore, the electrical incremental heat rate (*EIHR*) can be defined as [23]:

$$DE_{Fuel}^{MCHP} = \frac{OE_{Th}^{MCHP}}{\eta_{Th,ref}} + EIHR \cdot OE_{El}^{MCHP} \tag{61}$$

or

$$EIHR = \frac{DE_{Fuel}^{MCHP}}{OE_{El}^{MCHP}} - \frac{OE_{Th}^{MCHP}}{\eta_{Th,ref} \cdot OE_{El}^{MCHP}} = \frac{1}{\eta_{El}^{MCHP}} - \frac{\eta_{Th}^{MCHP}}{\eta_{El}^{MCHP} \eta_{Th,ref}} \tag{62}$$

The inverse of the *EIHR* is defined as the "artificial efficiency", because it separates the fuel primary energy entering the MCHP (DE_{Fuel}^{MCHP}) from the share that would be used from a reference boiler to produce the cogenerated thermal energy ($OE_{Th}^{MCHP} / \eta_{Th,ref}$):

$$\eta_{a}^{MCHP} = \frac{OE_{El}^{MCHP}}{DE_{Fuel}^{MCHP} - \dfrac{OE_{Th}^{MCHP}}{\eta_{Th,ref}}} \tag{63}$$

If $\eta_{El,ref} > \eta_a^{MCHP}$, it is better to produce electric energy by means of the reference system, rather than using the MCHP.

Similarly, it is possible to define the thermal incremental heat rate (*TIHR*), [23], [24]:

$$TIHR = \frac{DE_{Fuel}^{MCHP}}{OE_{Th}^{MCHP}} - \frac{OE_{El}^{MCHP}}{\eta_{El,ref} \cdot OE_{Th}^{MCHP}} = \frac{1}{\eta_{Th}^{MCHP}} - \frac{\eta_{El}^{MCHP}}{\eta_{El,ref} \cdot \eta_{Th}^{MCHP}} \tag{64}$$

by which it is possible to evaluate the effective efficiency in producing thermal energy by cogeneration, taking into account that, simultaneously, electric energy is being produced from the same amount of fuel energy.

MCHPs often perform bidirectional interactions with external electric grids and thermal/cooling networks; consequently, a methodology to calculate the primary energy share in relation to on-site use of “produced” useful energies should be defined.

To evaluate the amount of cogenerated electricity consumed on-site and the amount exported to an external electric grid, the related surplus factor can be introduced, [25]:

$$\psi_{El} = \frac{XE_{El}^{MCHP}}{OE_{El}^{MCHP}} \tag{65}$$

Obviously, a similar indicator can also be defined with respect to thermal energy output of the MCHP (in Fig. 18, the interaction of the MCHP with an external thermal grid, such as a district heating network, is not considered for the purpose of simplicity):

$$\psi_{Th} = \frac{XE_{Th}^{MCHP}}{OE_{Th}^{MCHP}} \tag{66}$$

Finally, if the micro-trigeneration system interacts with an external cooling grid, such as a district cooling network, the corresponding surplus factor is:

$$\psi_{Cool} = \frac{XE_{Cool}^{TCS}}{OE_{Cool}^{TCS}} \tag{67}$$

While a thermally activated cooling system (TCS) is included in Fig. 18, in general, the cooling equipment can also be electrically driven in trigeneration systems.

A surplus factor of zero means that all the energy remains within the system boundaries, while a surplus factor of one signifies that all the energy leaves the system.

If an energy vector leaves the boundary system (e.g. it is fed into the electrical or thermal grid), the corresponding primary energy demand has to be evaluated in order to obtain the primary energy demand related to the products remaining within the system. To achieve this, the allocation procedure should be used; this aims to partition the input of a process (i.e. primary energy) to one or more outputs (i.e. electric and thermal energy). The electrical and thermal allocation factors distribute the primary energy demand to the final products [25]. One possible method for evaluating them is:

$$\xi_{El} = \frac{\eta_{El}^{MCHP}}{\eta_{El}^{MCHP} + \eta_{Th}^{MCHP}} \quad (68)$$

$$\xi_{Th} = \frac{\eta_{El}^{MCHP}}{\eta_{El}^{MCHP} + \eta_{Th}^{MCHP}} \quad (69)$$

The allocation factor is in the range between 0 and 1. It takes into account only the useful exported energy, whereas, if the energy vector leaves the system boundaries without energetic usage (e.g. waste heat), the corresponding allocation factor is set to zero.

To provide an example of the application of surplus and allocation factors, it is assumed that a certain amount of the electric and thermal energy produced is exported and used outside the building envelope. In this case, the effective primary energy consumption (PE_{Fuel}^{*MCHP}) ascribed to the MCHP is:

$$PE_{Fuel}^{*MCHP} = PE_{Fuel}^{MCHP}\left(1 - \psi_{El}\xi_{El} - \psi_{Th}\xi_{Th}\right) \quad (70)$$

3.2 Cooling devices

The demand for air conditioning is known to be increasing in the commercial, tertiary (shops, warehouses, offices, schools, etc.) and residential sectors. This is resulting in an increase in primary energy consumption in these sectors, especially in industrialized countries where people spend the majority of the day indoors, making it very important to ensure high indoor-air quality (IAQ) and thermal comfort. This trend encourages new strategies for exploiting renewable energy sources and for achieving higher levels of efficiency in order to reduce the energy input of cooling devices. In this framework, high efficiency air-conditioning and refrigerating systems, as well as hybrid technologies, represent a potential solution in the near future.

The aim of this section is not to deeply analyse the wide topic of refrigeration technologies, for which the following references can be useful, [26]–[28], but to provide some useful indices that characterize the performance of the different devices. This is aimed at research groups dealing with cooling equipment and CCHP systems, with respect to the technologies investigated by the same research groups in Annex 54.

3.2.1 Electric vapour compression Heat Pump (EHP)

The vapour compression heat pump is a mechanically driven system, in which the energy input is mechanical energy that is provided by a prime mover or electric energy, which is obtained from an electric generator or from the grid. In the latter case, the unit is typically referred to as an electric heat pump (EHP), which is currently the most widespread and cheapest type of heat pump available on the market, thanks to the wide availability of electric energy, as well as the cost–effectiveness and reliability of electric motors.

The EHP can be used for both heating and cooling purposes. The main indices used to characterize the performance of an EHP are the COP and the energy efficiency ratio (EER). The former is defined as:

$$COP^{EHP} = \frac{NE_{Th}^{EHP}}{DE_{El}^{EHP}} \tag{71}$$

Where NE_{Th}^{EHP} is the thermal energy provided by the EHP (during the heating season), while DE_{El}^{EHP} is the electric energy delivered to the EHP.

The *EER* is defined as:

$$EER = \frac{NE_{Cool}^{EHP}}{DE_{El}^{EHP}} \tag{72}$$

Where NE_{Cool}^{EHP} is the cooling energy provided by the EHP (during the cooling season). MCHP/EHP systems are among the most widely diffused trigeneration configurations. MCHP/EHP systems consist of an EHP powered by a micro-cogenerator, Fig. 20.

By means of the re parameter that varies in the range between 0 and 1, different operating modes could be considered, [1]:

a) MCHP mode: the system operates in cogeneration mode, delivering all electric and thermal energy to the user, $r_e = 0$;

b) EHP mode: the electric energy output of the MCHP is used completely to activate the EHP ($r_e = 1$) that meets the summer cooling load. During winter, the thermal load is covered by both the condenser of the EHP and the thermal recovery system of the MCHP;

c) MCHP/EHP mode: the electric energy delivered by the MCHP is used to both activate the EHP (cooling or heating) and to supply electricity, $0 < r_e < 1$.

The significant reason for the MCHP/EHP system being widely used is the possibility of driving the EHP from the electric grid whenever an engine failure occurs or when a more convenient energy cost is achievable from the grid. Another reason is the opportunity to use widely diffused and commercialized units, reducing the first cost of the system.

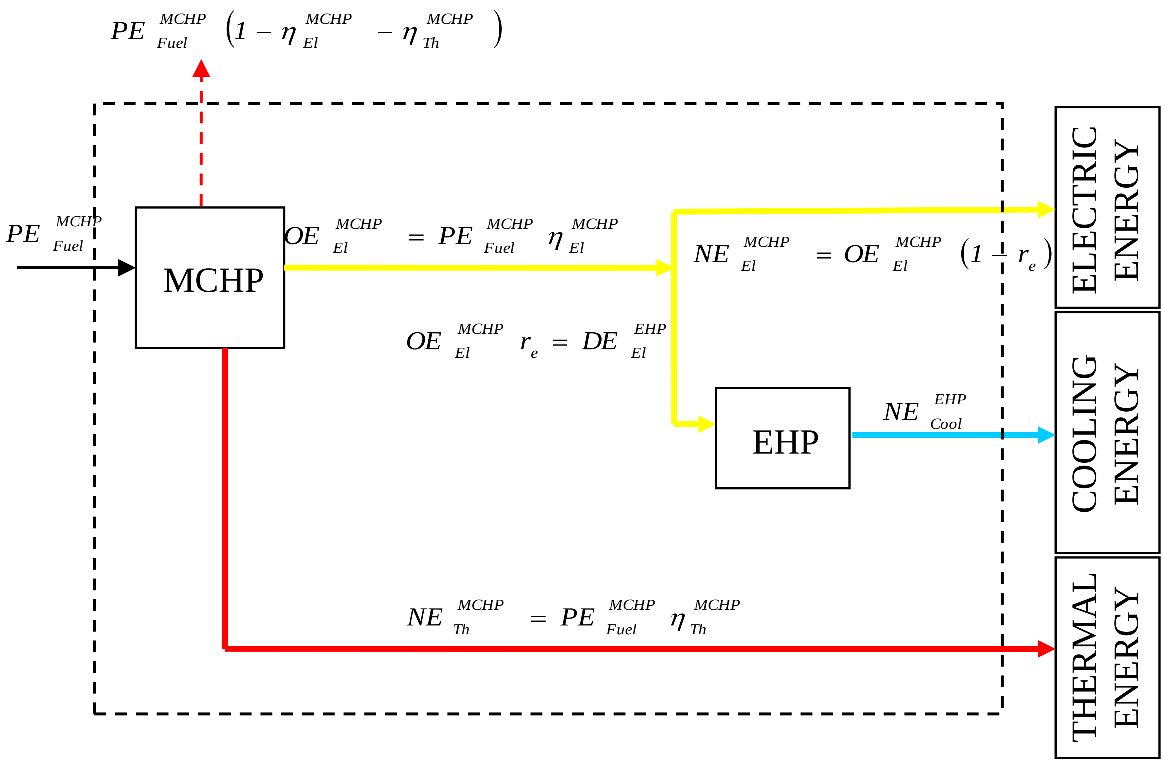

Fig. 20: Energy flows of the MCHP/EHP system in summer operation.

The significant reason for the MCHP/EHP system being widely used is the possibility of driving the EHP from the electric grid whenever an engine failure occurs or when a more convenient energy cost is achievable from the grid. Another reason is the opportunity to use widely diffused and commercialized units, reducing the first cost of the system.

The overall efficiency of the MCHP/EHP system can be evaluated by means of its *PER*:

$$PER^{MCHP/EHP}=\frac{NE_{El}^{MCHP}+NE_{Th}^{MCHP}+NE_{Cool}^{EHP}}{PE_{Fuel}^{MCHP}} \quad (73)$$

In the simpler case of EHP powered from the electric grid, Fig. 21, the *PER* is given by:

$$PER^{Grid/EHP}=\frac{NE_{Cool}^{EHP}}{PE_{Fuel}^{Grid}} \quad (74)$$

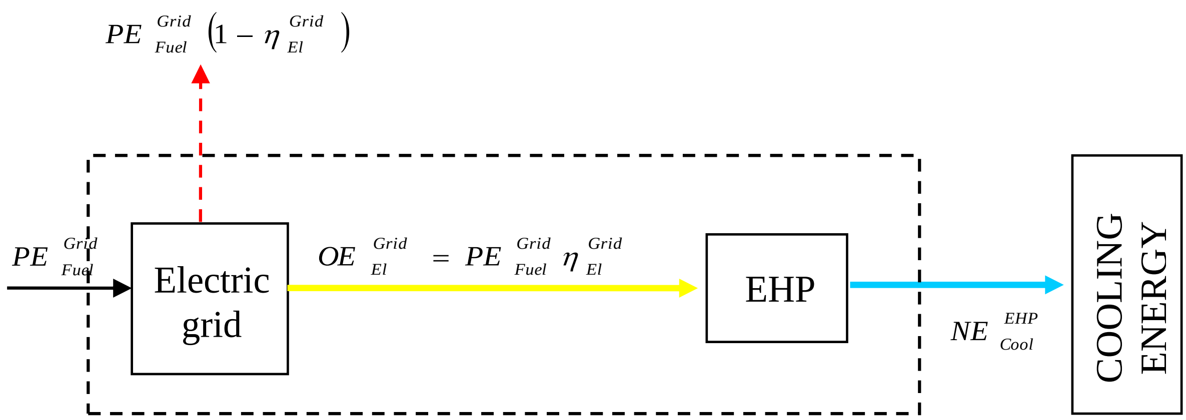

Fig. 21: Energy flows of the EHP system powered from the electric grid during summer operation.

3.2.2 Absorption Heat Pump (AHP)

AHPs are one of most widely applied commercialized thermally activated technologies in existing CCHP systems [26]. Typically, they are used in only cooling mode; consequently, the term 'absorption chillers' has also been applied. The basic difference between an absorption chiller and a vapour compression heat pump, which uses a rotating device (the compressor) to raise the pressure of refrigerant vapours, is that with an absorption chiller, the main energy input is not mechanical or electric energy, but thermal energy. In the basic cycle, a volatile liquid refrigerant evaporates in the evaporator vessel at a low pressure, producing a cooling effect at low temperature. It is then absorbed by a diluted solution (refrigerant/absorbent) in an adjacent absorber. The concentrated solution is then pumped, by means of a pump that requires a very small amount of mechanical energy, to the high temperature and pressure generator. Here, the refrigerant evaporates by means of a heat input before a condenser closes the refrigerant cycle. Usually, during the absorption process, the condensation and mixing heat is rejected to the ambient heat sink.

The most common working pairs are N_{H3}/water and water/LiBr, operating in single- or double-effect systems using steam, liquid hot water (indirectly fired), or the combustion of fossil fuels (directly fired) as a heat source [1].

The *EER* of an AHP is defined as:

$$EER^{AHP} = \frac{NE_{Cool}^{AHP}}{DE_{Th}^{AHP}} \tag{75}$$

Where NE_{Cool}^{AHP} is the cooling energy provided by the AHP, while DE_{Th}^{AHP} is the thermal energy delivered to the generator of the AHP.

AHPs are the most common thermally activated technology in existing CCHP systems (hotels, hospitals, commercial buildings, etc.), [29]. In Fig. 22, the energy flows of an MCHP/AHP system are illustrated.

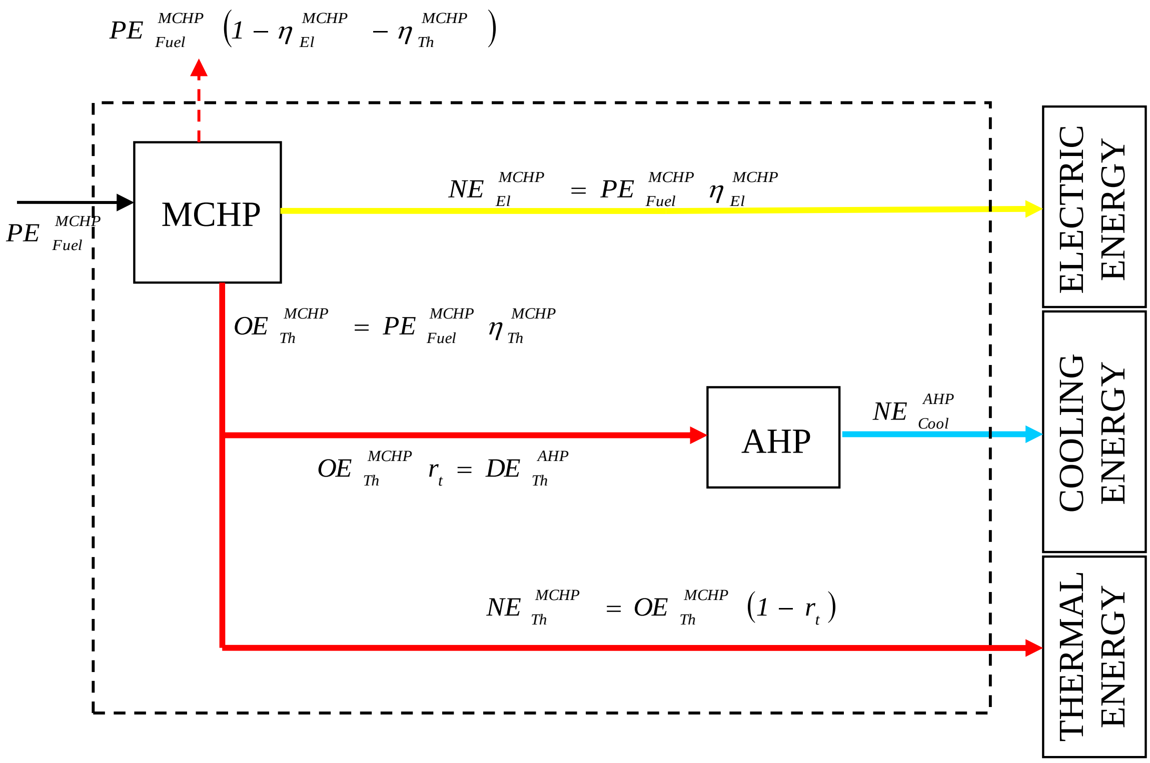

Fig. 22: Energy flows of an MCHP/AHP system during summer operation.

Cogenerated thermal energy can be split between the absorption system and direct use (DHW, space heating). Through the inclusion of an r_t parameter, [0-1], different operating modes can be considered:

a) MCHP mode: the system operates in cogeneration mode, supplying electric and thermal energy to users without AHP operation, $r_t = 0$;

b) AHP mode: all of the thermal energy is used to activate the AHP, $r_t = 1$;

c) MCHP/AHP mode: thermal energy is used both to activate the AHP and to meet the energy demands of users, $0 < r_t < 1$, (CCHP).

The PER of the MCHP/AHP system can be evaluated as:

$$PER^{MCHP/AHP}=\frac{NE_{El}^{MCHP}+NE_{Th}^{MCHP}+NE_{Cool}^{AHP}}{PE_{Fuel}^{MCHP}} \tag{76}$$

AHPs can be effectively activated by means of thermal energy originating from renewable-based technologies, such as solar thermal collectors. The use of solar energy for space cooling requirements (“solar cooling”) is highly advantageous because its availability coincides with the need for cooling; consequently, the summer peak demand of electricity due to the extensive use of electric air conditioners, which occurs simultaneously with the peak solar irradiance, can be lowered.

The main components of a solar cooling plant are the solar collectors, the absorption chiller, and a thermal integration system (typically a natural gas-fuelled boiler); the overall system efficiency depends on the coupling between these components, illustrated in Fig. 23. Additionally, in this case, the delivered energy is assumed to be the primary energy for the boiler, neglecting both processing and distribution losses. Q_{waste} represents thermal energy lost at the absorber and condenser of the AHP.

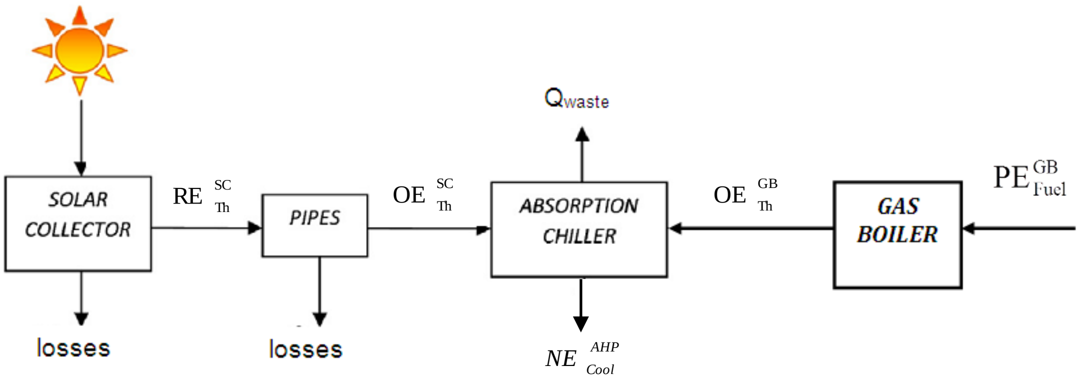

Fig. 23: Diagram illustrating the energy flows of a solar/gas absorption cooling plant.

To evaluate the performance of solar absorption cooling, two ratios should be calculated. First, the solar cooling ratio (*SCR*), which represents the efficiency of the solar system and is the ratio between the useful cooling and the insolation on the solar field, can be calculated. The second ratio is the solar heat fraction (*SHF*), which represents the heat injected into the absorption machine generator; this is covered by the solar energy, [30]:

$$SCR = \frac{NE_{Cool}^{AHP}}{RE_{Th}^{SC}} \tag{77}$$

$$SHF = \frac{OE_{Th}^{SC}}{OE_{Th}^{SC} + OE_{Th}^{GB}} \tag{79}$$

Where NE_{Cool}^{AHP} is the net cooling energy.

In this case, the *EER* can be evaluated as:

$$EER = \frac{NE_{Cool}^{AHP}}{OE_{Th}^{SC} + OE_{Th}^{GB}} \tag{79}$$

Finally, the solar COP (*SCOP*) can be evaluated as:

$$SCOP = \frac{NE_{Cool}^{AHP}}{AG} \tag{80}$$

Where *A* is collector area and *G* is the solar radiation intensity. To be consistent with the previous nomenclature, the term solar *EER* should be used instead of *SCOP*; however, in the literature, the latter is used more widely.

3.2.3 Adsorption Heat Pump (ADHP)

The adsorption cycle occurs when a gas or liquid phase, called solute (usually water), accumulates on the surface of a solid, called the adsorbent (usually silica gel); this forms a film, called the adsorbate [31]–[33].

The main components of ADHPs are an evaporator, a condenser, and two adsorbing beds. The refrigerant (typically water) evaporates in the evaporator, providing a useful cooling effect; following this, the vapour refrigerant is adsorbed by one of the two beds, while the adsorbent material in the second bed is regenerated by means of a thermal energy input. The operation of the two beds is then reversed periodically in order to obtain the continuous operation of the system. Both the adsorption and condensation heats are wasted in the environment.

In comparison with a liquid absorption system, ADHP has the advantage of being powered by a larger range of heat source temperatures (50–500°C).

Concerning the *EER*, the same definition that was used for AHP applies, eq. 75. Similarly, the same energy flow diagram used for an MCHP/AHP system (Fig. 22) applies for the MCHP/AHP system, as well as the *PER* defined in eq. 76.

The same energy flows diagram presented in Fig. 23 can also be used for solar-assisted adsorption chillers, Fig. 24, [34]. The same indices as section 3.2.2 can also be calculated.

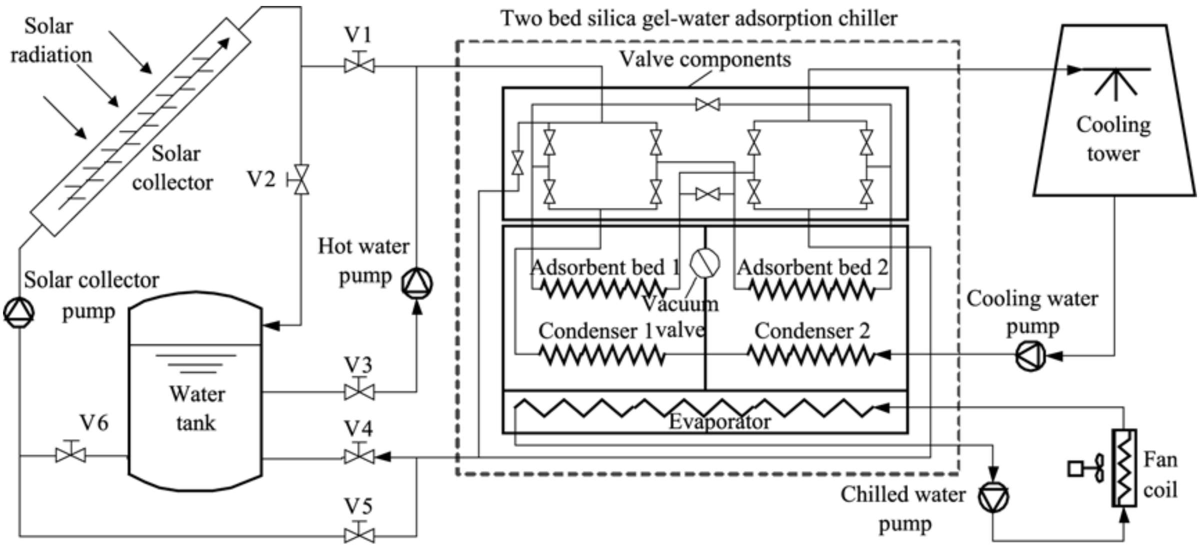

Fig. 24: Schematic diagram of a solar-powered adsorption cooling system

3.2.4 Desiccant Cooling System (DCS)

An alternative to balancing latent loads by cooling the air below the dew-point (cooling dehumidification) is represented by the sorptive cooling cycle, also referred to as the desiccant cooling system (DCS). In the DCS cycle, air dehumidification is performed using a sorptive component, such as a DW.

The process air stream flows through the desiccant material (such as silica gel, activated alumina, lithium chloride salt, or molecular sieves), which retains the moisture of the air. The desiccant capacity of the material can be restored through its regeneration via a heated air stream (typically, within the temperature range 50–120°C, depending on the desiccant material and the desired humidity reduction). Usually, thermal energy for this heated air stream is supplied by a gas-fired boiler. To ensure continuous operation of the system, the DW slowly rotates between the process and the regeneration air flows.

The temperature decrease of the process air exiting the DW can be achieved by either direct, indirect or combined (direct + indirect) evaporative cooling.

A schematic representation of a desiccant cooling cycle, with the corresponding psychrometric diagram, is provided in [35] and Fig. 25. However, a different layout has also been described [35], [36].

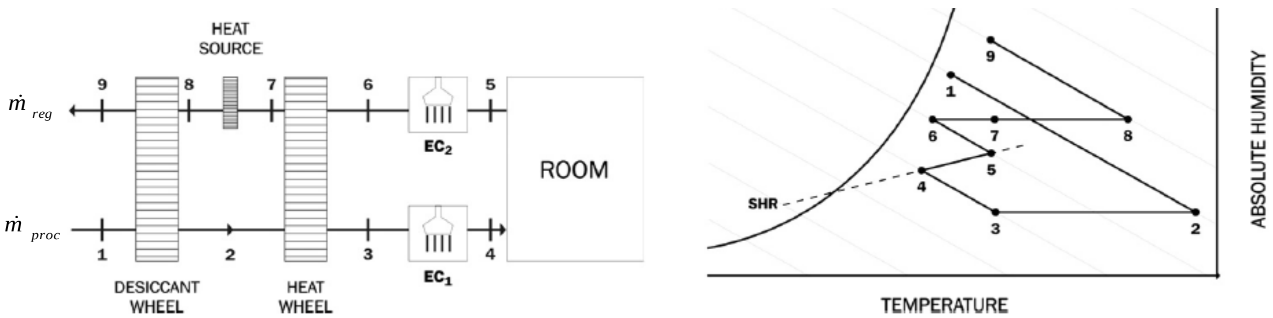

Fig. 25: Schematic representation of a desiccant cooling cycle.

The layout illustrated in Fig. 25 includes two evaporative coolers (supply air evaporative cooler, EC_1, and return air evaporative cooler, EC_2), a sensible heat wheel, and a DW. The heat required to regenerate the DW is supplied by a thermal energy source.

The core component of the cycle is the DW, which consists of the same structure as the heat wheel, except that it is coated with a desiccant material layer. The purpose of this component is to promote a thorough dehumidification of the air stream, allowing a more significant temperature drop across the evaporative cooler.

The total cooling energy, NE_{Cool}^{DCS}, is defined as the time integral of the enthalpy difference between the ambient air and the supply air, multiplied by the air mass flow rate:

$$NE_{Cool}^{DCS} = \int \dot{m}_{proc} \cdot (h_1 - h_4) dt \tag{81}$$

Where $\dot{m}_{proc}$ is the process air mass flow rate.

Other authors have represent the cooling effect as the enthalpy difference between the supply and indoor conditions. In this case, the total cooling energy can be expressed as:

$$NE_{Cool}^{DCS} = \int \dot{m}_{proc} \cdot (h_5 - h_4)dt \qquad (82)$$

The thermal COP of the desiccant cycle is then determined using [37]:

$$COP_{Th}^{DCS} = \frac{NE_{Cool}^{DCS}}{\int \dot{m}_{reg} (h_8 - h_7)dt} \qquad (83)$$

In eq. 83, (h_8 - h_7) is the specific regeneration thermal power and $\dot{m}_{reg}$ is the regeneration mass flow rate. Generally, $\dot{m}_{proc}$ and $\dot{m}_{reg}$ are not equal, and they coincide only in the case of balanced flows.

The electrical COP of the desiccant cycle is determined by [39]:

$$COP_{El}^{DCS} = \frac{NE_{Cool}^{DCS}}{DE_{El}^{aux}} \qquad (84)$$

Where DE_{El}^{aux} accounts for the total electric energy delivered to auxiliaries (fans and pumps).

The standard desiccant cooling cycle described above, which for instance, is installed in temperate climates such Central Europe, is not able to efficiently operate in the conditions encountered in warm and humid climates, such as in the coastal zones of Mediterranean countries. Consequently, the application of desiccant technology in such climates using sorptive rotors requires specific configurations. The following modified cycles, which use cooling coils in addition to the DW, have been studied in terms of their energy performance:

The scheme of a standard cycle with a cooling coil added behind the heat recovery wheel on the supply-air side is illustrated in Fig. 26 with the corresponding air states. The DW realises a pre-dehumidification (air states 1 - 2) and the cooling coil controls the air to achieve the final desired humidity (air states 3 - 4). A re-heater (air states 4 - 5) is required if the supply temperature is to enter the room with a comfortable temperature, i.e., a temperature not below 18°C.

In order to compare the performance of the different cycles, the following performance figures have been defined [40]:

- The conventional cooling energy, $NE_{Cool,conv}^{DCS}$, denotes the cooling effect supplied by the cooling coils, for instance using chilled water from a compression chiller:

$$NE_{Cool,conv}^{DCS} = \int \dot{m}_{proc} \cdot (h_3 - h_4)dt \qquad (85)$$

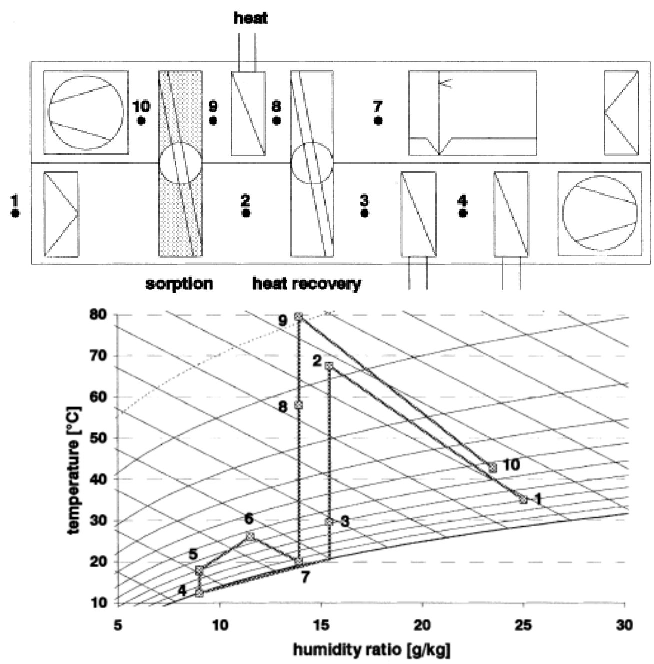

Fig. 26: Standard cycle with an additional cooling-coil behind a heat recovery wheel

- The sorptive cooling energy, $NE^{DCS}_{Cool,sorpt}$, defines the amount of the total cooling that is not covered by the cooling coils:

$$NE^{DCS}_{Cool,sorpt} = NE^{DCS}_{Cool} - NE^{DCS}_{Cool,conv} \tag{86}$$

- The electric energy required by the chiller (DE^{chil}_{El}) is defined by the ratio between the conventional cooling energy and the chiller COP:

$$DE^{chil}_{El} = \frac{NE^{DCS}_{Cool,conv}}{COP^{chil}} \tag{87}$$

- The total electricity demand, $DE_{El,tot}$ is defined as the electric energy delivered to both the chiller and the auxiliaries (fans and other eventual electric components):

$$DE_{El,tot} = DE^{chil}_{El} + DE^{aux}_{El} \tag{88}$$

The electric COP of the DCS is defined as the ratio between the total cooling power and the total electricity demand [41]:

$$COP^{DCS}_{El} = \frac{NE^{DCS}_{Cool}}{DE_{El,tot}} \tag{89}$$

- The sorptive thermal COP, $COP^{DCS}_{Th,sorpt}$, is defined as the ratio between the sorptive cooling and the required heat for regeneration of the desiccant:

$$COP_{Th,sorpt}^{DCS} = \frac{NE_{Cool,sorpt}^{DCS}}{\int \dot{m}_{reg}\left(h_9 - h_8\right)dt} \qquad (90)$$

- The total energy input, DE_{tot}, is the sum of the delivered thermal energy for regeneration, and the electric energy for auxiliaries and the chiller. The overall COP is then defined as the ratio between the total cooling power and the total power input to the system [42]:

$$COP^{DCS} = \frac{NE_{Cool}^{DCS}}{DE_{tot}} \qquad (91)$$

The primary energy ratio is defined as the ratio between the total cooling energy and the total primary energy input:

$$PER^{DCS} = \frac{NE_{Cool}^{DCS}}{PE_{Fuel}^{DCS}} \qquad (92)$$

where PE_{Fuel}^{DCS} is the total primary fuel input related to both regeneration thermal energy and total electric energy.

In a MCHP/HVAC-DW system, the waste heat of a micro-cogeneration unit is used to regenerate the desiccant material, while the cogenerated electricity can operate the chiller to meet the room sensible load, the auxiliaries, and the requirements of further electric appliances (computer, lights, etc.), as illustrated in Fig. 27 ([1]).

Electric energy can be split between the chiller and direct use (lights, appliances, etc.) by means of the re parameter. In a similar manner, thermal energy can be split between the regeneration of the DW and the direct use (space heating, DHW) by varying the r_t parameter.

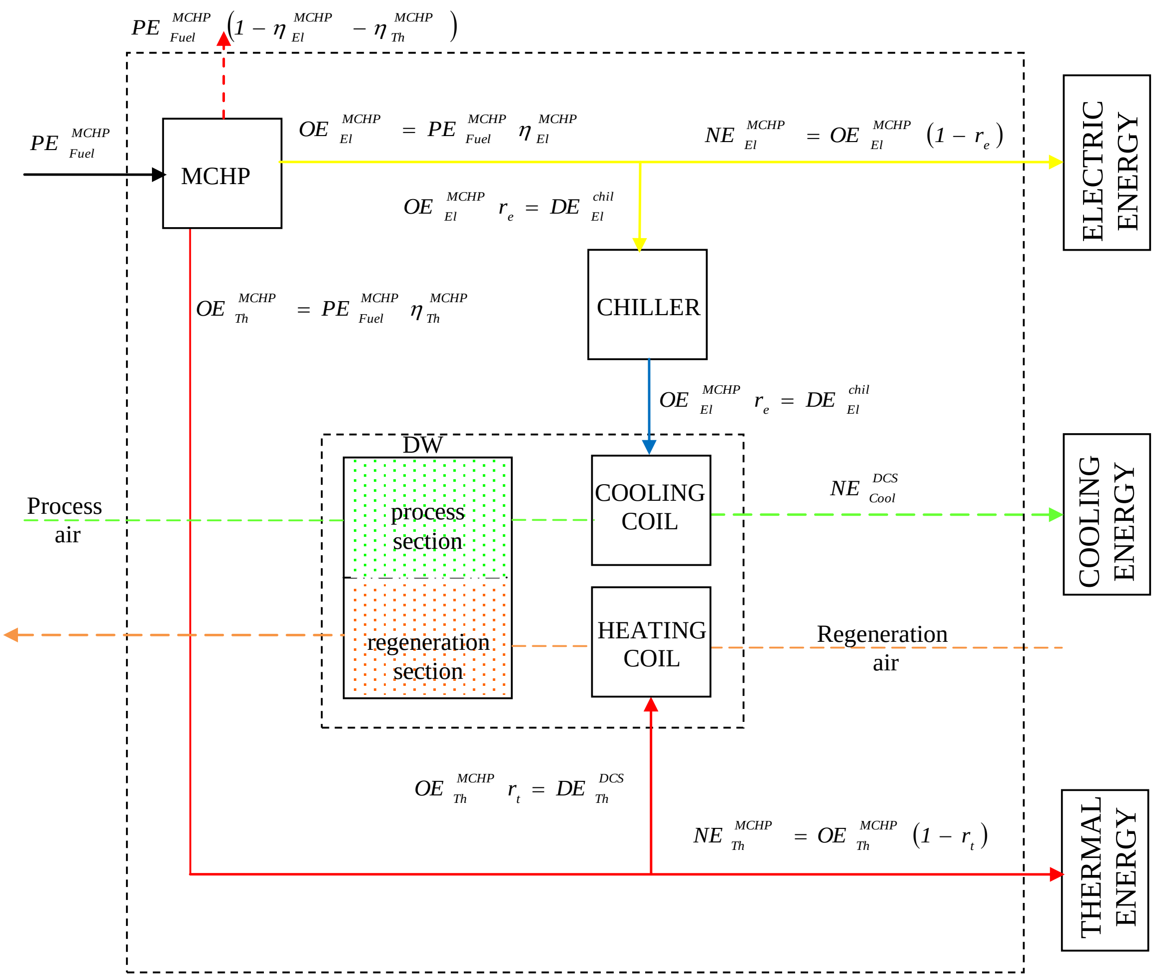

Fig. 27: Energy flows of an MCHP/HVAC-DW system.

Consequently, the system can operate in different modes:

a) MCHP mode: the cogenerator supplies electricity and thermal energy to the end-user. The HVAC system does not operate, $r_t = r_e = 0$;

b) HVAC-DW mode: the electric and thermal energy delivered by MCHP are used completely to activate the desiccant-based HVAC system, $r_t = r_e = 1$;

c) MCHP/HVAC-DW mode: this configuration allows electric, heating and cooling energy requirements to be met, $0 < r_t < 1$, $0 < r_e < 1$.

The PER of the MCHP/HVAC-DW system can be evaluated as:

$$PER^{MCHP/HVAC-DW} = \frac{NE_{El}^{MCHP} + NE_{Th}^{MCHP} + NE_{Cool}^{DCS}}{PE_{Fuel}^{MCHP}} \tag{93}$$

Thermal energy for DW regeneration can be also obtained by means of solar collectors [43], [44]. A schematic representation of a solar DCS is illustrated in Fig. 28, [45].

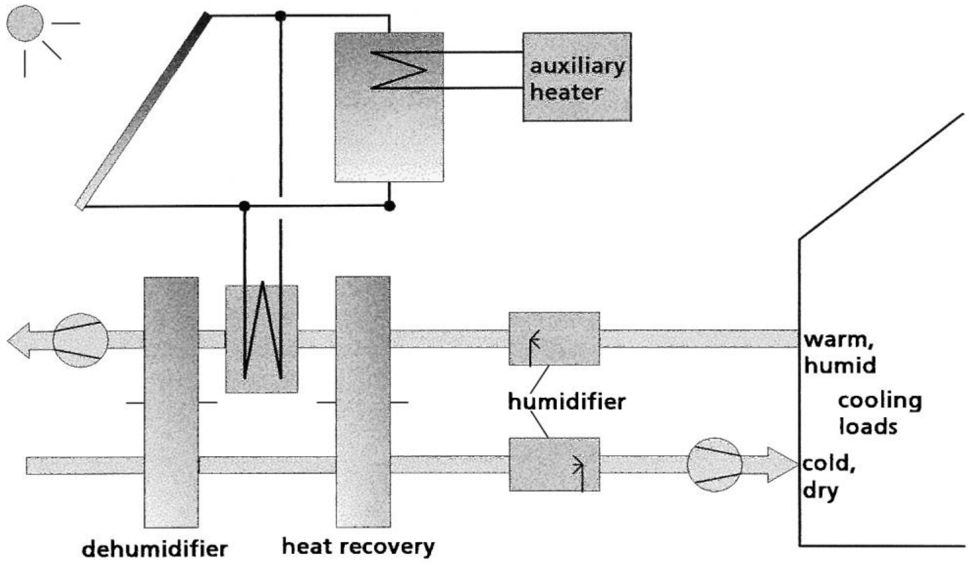

Fig. 28: Schematic representation of a solar desiccant cooling cycle.

With regards to the performance assessment of a solar DCS, the same definitions introduced for the solar absorption cooling system can be used.

4 Evaluation Methods for Small-Scale Cogeneration and Polygeneration Systems

The general purpose of this section, considering the common elements of the standard national testing procedures identified in section 2, and the performance indices defined in section 3, is to review the methodologies available in different countries for evaluating the performance of small-scale cogeneration and polygeneration systems in terms of their energy, emissions, technical, and economic criteria.

The performance assessment methodologies focus on decentralized small-scale polygeneration systems applied in the residential sector. In particular, these systems interact with individual buildings, or a cluster of buildings connected via a local electric grid, and/or district heating and cooling networks.

The interaction of a cogeneration device with the other components of the system (e.g. water storage), and with other energy supply components such as heat pumps, or with renewable energy technologies, is evaluated in terms of selected criteria, such as the primary energy demand, CO_2 emissions, and operating costs.

The final aim is to define a common approach that the Annex 54 participants can apply in their countries' specific performance assessment studies. Based on the results of these studies, the objective is to identify critical issues in the context of micro-generation technologies and to demonstrate the influence of building, occupant, and system parameters on their performance by means of sensitivity analysis.

4.1 3-E Analysis

A simplified approach to evaluate the energy, environmental, and economic (3-E) performance of a micro-generation system (alternative system [AS]) is through comparing, with respect to a specific time period (typically an annual basis), the primary energy demand (*PE*), operating costs (*OC*), and emissions (for example in terms of equivalent CO_2 emission, m_{CO_2}) with those of a reference system (CS). CSs are based on the separate production of the same amount of useful energy, for a given electric demand, a given heat demand for space heating, and DHW, as well as a given cooling demand for space cooling, [1] [46]. It is noteworthy that the operating costs of an AS can "exit" the system itself (i.e. a cash-flow output) if costs are higher than revenues, or, alternately, they can "enter" the system (i.e. a cash-flow input). For example, in a MCHP fuelled by pellets, revenues arising from green certificates or feed-in tariffs can be higher than the operating costs due to fuel purchase and system maintenance.

Consequently, in the 3-E analysis approach, the primary energy, greenhouse gas emissions, and operating costs of the polygeneration system have to be calculated and compared with those of the CS. This is performed while taking into account the delivered and renewable energy amounts, as well as the output energy and user requirements, as illustrated in Fig. 29.

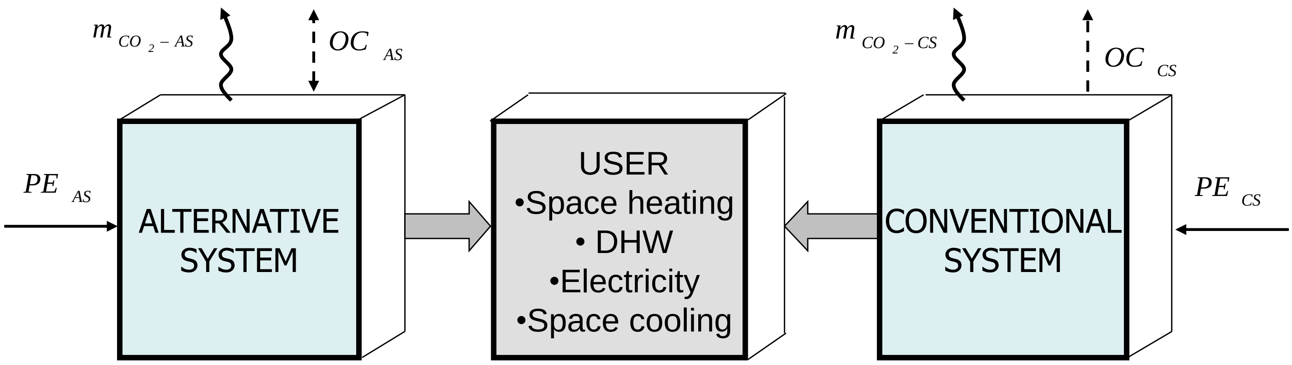

Fig. 29: Energy flows of alternative and CSs

This conventional (reference) system could, for example, be based on traditional and widely used technologies that separately supply the same amounts of electric, thermal, and cooling energy as a micro-generation system.

For example, in Fig. 30, an example of the comparison between a trigeneration system and a reference system is shown. Energy losses from fuel (natural gas) due to processing and distribution are not taken into account in this scheme; consequently, the delivered energy is assumed to be equal to the primary energy.

As proposed in section 3, specific superscripts that refer to energy conversion devices involved in an energy flow (such as thermally driven heat pump [THP]) have been used in order to avoid misunderstanding, [3], while subscripts refer to energy vectors. Furthermore, when two superscripts are present, the former refers to the output device and the latter to the input device. Further subscripts referred to AS or CS; however, this was only in case of possible misunderstanding. For example, they are not used for energy flows related to a MCHP, which is not present in the CS, while they are used for the boiler, which is present both in ASs and CSs.

The following systems are suggested as a possible reference energy system ([3]):

- 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.

4.1.1 Energy analysis

As the main benefit of a polygeneration system is the possibility of saving primary energy with respect to the separate "production" of equal energy outputs, the natural approach would be to quantify the primary energy saving by means of the fuel energy saving ratio (*FESR*), [47]:

$$FESR = \frac{PE_{CS} - PE_{AS}}{PE_{CS}} = 1 - \frac{PE_{AS}}{PE_{CS}} \tag{94}$$

Where PE_{CS} and PE_{AS} are the primary energy input to CS and AS, respectively; they can both be evaluated as:

$$PE_{AS} = PE_{Fuel}^{MCHP} + PE_{Fuel-AS}^{GB} + PE_{El-AS}^{Grid} \tag{95}$$

$$PE_{CS} = PE_{Fuel-CS}^{GB} + PE_{El-CS}^{Grid} \tag{96}$$

In the case of Fig. 30, this can be expressed as:

$$FESR = 1 - \frac{PE_{Fuel}^{MCHP} + PE_{Fuel-AS}^{GB} + PE_{El-AS}^{Grid}}{PE_{Fuel-CS}^{GB} + PE_{El-CS}^{Grid}} \tag{97}$$

EU Directive 2004/8/EC adopts the index primary energy saving to compare the primary energy consumption of cogeneration with the reference system, while defining the reference values of separate electric and thermal "production" ($\eta_{El,ref}$ and $\eta_{Th,ref}$). In this report, the *FESR* parameter is used in order to distinguish between the technical analysis carried out in the present work and regulatory constraints.

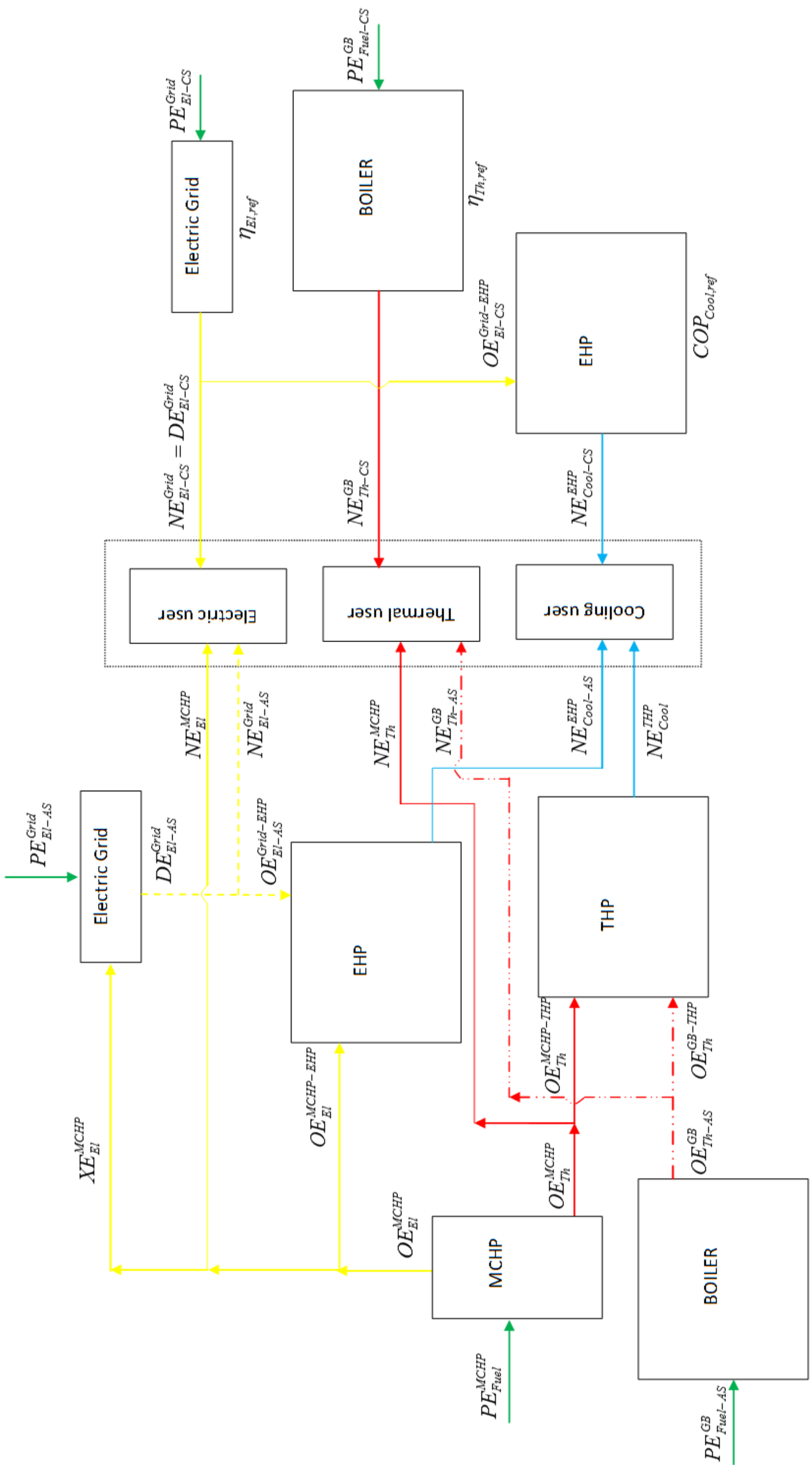

Fig. 30: Comparison between a trigeneration system and the reference system

4.1.2 Environmental analysis

In terms of the energy saving, with respect to micro-generation emissions, the natural term for comparison is the separate "production" system. However, an emission analysis to evaluate the performance of a distributed polygeneration system, particularly when installed in urban areas, is somehow difficult to perform. In fact, a global balance seems correct only with respect to greenhouse gas and ozone depletion emissions. Conversely, emissions that have a local impact (within a radius of hundreds of kilometers from the source) on the surrounding environment and people's health, such as NO_x, CO, SO_x and PM, require a special analysis and a specific model to examine local impact.

If all the separate "production" emission sources are included in the analysis, aside from their location, the global emission reduction of the mass of a generic pollutant "z" that the AS can achieve with respect to the CS can be evaluated, typically on an annual basis, as:

$$\Delta m_{glo} = \frac{m_{z-CS} - m_{z-AS}}{m_{z-CS}} = 1 - \frac{m_{z-AS}}{m_{z-CS}} \qquad (98)$$

Where m_z is the mass of the pollutant.

The terms in eq. 98 can be easily determined by means of the following equation:

$$m_z = \mu \cdot K \qquad (99)$$

Where μ is the specific emission factor, typically expressed as kg per kWh of primary, delivered, or output energy type, while K is the related energy quantity. By way of example, in the case of a combustion-based device (boiler or CHP), K represents the primary energy input of the fuel and it should be multiplied by the fuel-specific emission factor, μ_{Fuel}. Obviously, a correct determination of the specific emission factors is crucial in order to achieve an accurate analysis.

However, in most cases, separate electric "production" occurs in a centralized power plant, far from urban areas, and far from the location of the micro-generation system, which is typically located in an urban district. Consequently, it is possible to formulate a local-emissions balance, in which only the emissions from the separate thermal energy "production" are taken into account. In fact, thermal energy "production" occurs in distributed boilers, which should be substituted by cogeneration systems, located in the city perimeter.

The local emission reduction that the micro-generation system can achieve is therefore evaluated as:

$$\Delta m_{loc} = \frac{m_{z-CS} - m_{z-AS}}{m_{z-CS}} = 1 - \frac{m_{z-AS}}{m_{z-CS}} \qquad (100)$$

Where "z" is a local impacting pollutant.

However, equation 100 significantly underestimates the impact of ozone or NOx emissions, to which centralized power plants contribute significantly. Nevertheless, the use of a local emission balance seems more appropriate than a global emission balance. This is because small-scale cogeneration plants have emissions characteristics, such as a chimney's location and height, that are more similar to domestic boilers than large centralized power plants located in industrial districts.

As discussed previously, the global balance appears adequate when global environmental problems are concerned, such as the greenhouse effect. The main constituent of greenhouse gases is the carbon dioxide that is emitted by combustion-based devices.

The global CO_2 emission reduction that can be achieved using micro-generation systems can be calculated as:

$$\Delta CO_2 = \frac{m_{CO_2-CS} - m_{CO_2-AS}}{m_{CO_2-CS}} = 1 - \frac{m_{CO_2-AS}}{m_{CO_2-CS}} \tag{101}$$

It is possible to extend the previous equation in order to take into account other greenhouse gas emissions. For example, methane is emitted, for the most part unburned, in exhaust gases. It has a global warming potential (GWP) of 23, meaning that it has a greenhouse effect impact that is 23 times higher than that of CO_2.

It is possible to extend the index defined in eq. 101 using the emission factors model in order to consider the equivalent CO_2-specific emission factor by multiplying the specific emission factor of the pollutant, μ, and the *GWP*:

$$\mu_{CO_2,eq} = GWP \cdot \mu \tag{102}$$

In this case, the comparison index is the equivalent CO_2-avoided emissions:

$$\Delta CO_{2,eq} = \frac{m_{CO_2,eq-CS} - m_{CO_2,eq-AS}}{m_{CO_2,eq-CS}} = 1 - \frac{m_{CO_2,eq-AS}}{m_{CO_2,eq-CS}} \tag{103}$$

4.1.3 Economic analysis

The economic analysis focuses on the comparison of the total costs (both investment and operating costs) for the different systems. It also focuses on the influence of time-dependent prices of purchased electricity and fuel on the optimization of the system in terms of size, control, and operation.

In Annex 42, only a very limited amount of economic assessments were performed owing to a lack of knowledge about the investment, and the operation, and maintenance (O&M) costs of micro-cogeneration devices, as well as a lack of knowledge regarding the complexity of energy cost structures.

Presently, this information is available for small-scale cogeneration units, which are based on the reciprocating internal combustion engine, and the Stirling engine and fuel cell. This is due to the diffusion of these devices into the Japanese, European, and American commercial markets.

Consequently, one of the aims of Annex 54 is to promote the introduction of a simplified economic analysis in performance-assessment studies. A more detailed analysis can be found in [48].

However, it should be noted that the results of an economic analysis depend on several variables (energy prices, taxation, energy market regulations, etc.).

By way of example, the possibility of selling the surplus electricity, or of receiving incentives for the use of energy efficient technologies, varies between countries. In order to evaluate, with a simplified approach, the economic performance of ASs and CSs, the parameters most commonly used include the simple pay back (*SPB*), the net present value (*NPV*), the profitability index (*PI*), and the internal rate of return (*IRR*).

Using the SPB method, the number of years required in order to recover the higher investment cost of the micro-generation system in comparison with a conventional system are evaluated:

$$SPB = \frac{EC}{\sum_{k=1}^{n} F_k} \tag{104}$$

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 a CS and AS.

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

$$NPV = \sum_{k=1}^{n} \frac{F_k}{(1+a)^k} - EC \tag{105}$$

Where '*a*' is the discount rate.

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

$$PI = \frac{\sum_{k=1}^{n} \frac{F_k}{(1+a)^k}}{EC} \tag{106}$$

In both the *NPV* and *PI* indices, the discount rate '*a*' is *a-priori* fixed. As an alternative, the *IRR* method evaluates the value of '*a*' that annuls the *NPV*:

$$\sum_{k=1}^{n} \frac{F_k}{(1+a)^k} = EC \tag{107}$$

The *IRR* represents the value of the interest rate over which the project is no longer economically profitable, as an investment for which a banking loan is utilized.

Several others economic indicators can be defined to optimize the operation of CHP systems. By way of example, the spark spread (SS) is useful in assessing the profitability of the "power production operation mode", and how it compares with the unitary price of grid electricity (UP_{El}^{Grid}, typically expressed as €/kWh or $/kWh) and the production cost of 1 kWh_{El} from the cogenerator; it is defined as [49]:

$$SS = \frac{UP_{El}^{Grid}}{\frac{1}{\eta_{El}^{MCHP}} \cdot \frac{1}{LHV_{Fuel}^{MCHP}} \cdot UP_{Fuel}^{MCHP}} \quad (108)$$

Where UP_{Fuel}^{MCHP} and LHV_{Fuel}^{MCHP} are the unitary price (expressed as €/Sm^3 or \$/Sm^3) and the lower heating value (expressed as kWh/Sm^3 or kWh/Nm^3) of cogenerator fuel, respectively. Values higher than 1 indicate the profitability of self-producing electricity (even wasting any heat coming from the engine) with respect to the option ‘‘switch the engine off and buy electricity”.

A second indicator, named the total supply spread (TSS), is defined for “heating” and “cooling” hours (i.e. for hours where the recovered heat is used for heating or cooling purposes, respectively), as follows [50]:

$$TSS_{hs} = \frac{UP_{El}^{Grid} + UP_{Fuel,\ ref} \cdot \frac{1}{\eta_{Th,\ ref}\, LHV_{Fuel,\ ref}\, PHR^{MCHP}}}{\frac{1}{\eta_{El}^{MCHP}} \cdot \frac{1}{LHV_{Fuel}^{MCHP}} \cdot UP_{Fuel}^{MCHP}} \quad (109)$$

$$TSS_{sum} = \frac{\left(\frac{EER^{AHP}}{EER^{EHP} \cdot PHR^{MCHP}} + 1\right) \cdot UP_{El}^{Grid}}{\frac{1}{\eta_{El}^{MCHP}} \cdot \frac{1}{LHV_{Fuel}^{MCHP}} \cdot UP_{Fuel}^{MCHP}} \quad (110)$$

Where PHR^{MCHP} is the power-to-heat ratio of the cogeneration unit, and $UP_{Fuel,ref}$ and $LHV_{Fuel,ref}$ are the unitary price and lower heating value of fuel used by the reference system for thermal energy “production”, respectively. EER^{AHP} and EER^{EHP} are the EER of the absorption chiller and one of the EHPs that are used in the ASs and CSs for cooling production, respectively.

TSS represents the ratio of the “economic value” of the amounts of heating/cooling and electricity, produced in cogeneration mode, to the economic value of the natural gas consumed as fuel by the prime mover. When *TSS* is higher than 1, this indicator suggests that the combined production is economically convenient in comparison with separate production.

However, the values assumed by SS and TSS may vary on an hourly basis (when energy prices also vary).

4.1.4 Reference energy/environmental performance index

One of the most important issues in the evaluation of the primary energy and greenhouse gas emissions savings that micro-generation system can offer is the energy performance and CO_2-specific emissions factors of the reference system. Owing to the complex and constantly changing generation park, it is very difficult to state which primary energy consumption and CO_2 specific emissions factors the micro-generation system should be compared with.

Energy/Environmental performance of the separate "production" system

The aim of this section is to provide a broad overview of the energy and environmental performance of the separate "production" reference systems used by Annex 54 participants; in particular, in terms of the following parameters:

- $\eta_{El,ref}$: energy performance factor of the reference system for supplying electricity (ratio of electric energy output to primary energy input, [kWh_{El}/kWh_{PE}]);

- $\mu_{El,ref}$: equivalent carbon dioxide specific emission factors of the reference system for supplying electricity (ratio of equivalent CO_2 emissions to electric energy output, [$kg_{CO2,eq}/kWh_{El}$]);

- $\eta_{Th,ref}$: energy performance factor of the reference system for supplying heat (ratio of thermal energy output to primary energy input, [kWh_{Th}/kWh_{PE} or kWh_{Th}/kWh_{DE}]);

- $\mu_{Th,ref}$: equivalent carbon dioxide emission factor of the reference system for supplying heat (ratio of equivalent CO_2 emissions to primary energy input, [$kg_{CO2,eq}/kWh_{PE}$ or kWh_{Th}/kWh_{DE}]). Typically, a natural gas boiler is used for thermal energy production in the reference system; consequently, a specific $CO_{2,eq}$ emission factor of natural gas, μ_{NG} , is assumed;

- $EER_{Cool,ref}$: energy efficiency ratio of the reference system for supplying cooling (ratio of cooling energy output to electric energy input, [kWh_{Cool}/kWh_{El}]).

For estimating the energy and environmental performance of the reference system based on separate "production", three different approaches can be used.

The first approach is to use energy performance and CO_2 factors on the basis of a national/regional technological mix. In this approach, different time references can be adopted, namely, average annual, monthly, or even hourly values. The last frame of reference is used, in particular, when renewable energy sources, which can be thought of as having very random availability, contribute significantly to separate energy "production".

The second approach is to use the best available and economically justifiable technology, for example, a combined-cycle, natural gas-fired power plant for supplying electricity.

The third approach is to use values provided by some national or international directives. An example of this is EU Directive 2004/8/EC for the promotion of cogeneration; this is based on a useful heat demand that defines reference values for separate electricity "production", varying with, among other factors, the year of construction of the cogeneration plant, the fuel used, and the average national temperature.

Emission factors are coefficients that quantify the emission per unit of energy consumed and/or supplied. The emissions are estimated by multiplying the emission factor with the corresponding energy consumptions data. Two different approaches may be followed when selecting the emission factors:

- Using 'standard' emission factors. This approach is in line with the Intergovernmental Panel on Climate Change (IPCC) principles, which cover all the CO_2 emissions that occur owing to energy consumption, either directly through 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, as in the context of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto protocol. In this approach, CO_2 is the most important greenhouse gas; however, other greenhouse gases can be included in the analysis. For example, the decision may be made to use emission factors that also take into account CH_4 and N_2O emissions from combustion. In this case, the emission unit is quantified as 'CO_2 equivalent emissions' and emissions of greenhouse gases other than CO_2 are converted to CO_2 equivalents by using the GWP values. For example, 1 kg of CH_4 has a similar impact on global warming to 21 kg of CO_2 when the impact is considered over an integration time horizon of 100 years; consequently, the GWP value of CH_4 is 21. Furthermore, the CO_2 emissions from the sustainable use of biomass/biofuels, as well as emissions of certified green electricity, are considered to be zero.

- Using life cycle assessment (LCA) emission factors. This approach takes the overall life cycle of the energy carrier into consideration and includes not only the emissions of the final combustion but also all emissions of the supply chain. It includes emissions from the exploitation, transportation, and processing (e.g. refinery) stages, in addition to the final combustion; consequently, it includes emissions that are produced outside the location where the fuel is used. In this approach, the greenhouse gas 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_2 may play an important role. Consequently, it was decided that the Annex participants that would use the LCA approach should report emissions in the form of CO_2 equivalents.

With regards to $\eta_{El,ref}$, it should be taken into account that micro-generation systems generate electricity near the point of use, allowing for a reduction in transmission and distribution losses, thereby minimizing the use of the electricity network in comparison with larger/centralized electricity production. Typically, a large CHP plant connected to a high-voltage network would avoid loses of approximately 2.5%, whilst a MCHP plant in a house connected to a low-voltage network would avoid losses of approximately 10%. Electricity grid systems, both transmission and distribution, demonstrate considerable loss variation across each country; consequently, it will be necessary to use a simple and workable method to correct for a central power plant's energy performance in order to take into account national circumstances. A simple approach to this issue defines a standard grid loss for each voltage level of the network system. Therefore, depending on the voltage level that a CHP unit is connected to, it is easy to determine the total avoided grid losses arising from using the unit.

With regards to $\eta_{Th,ref}$, the real-life operational efficiencies of boilers can differ significantly from their nominal values, depending on load conditions and the supply and return water temperature. For instance, the nominal operating efficiency of a condensing gas boiler can increase by more than 8% if the return temperature decreases from 60 to 30°C.

With regards to $EER_{Cool,ref}$, the real-life operational efficiencies of vapour compression cooling devices can differ significantly from their nominal values, depending on the climatic and load conditions, as well as the supply and return water temperatures.

By way of example, the *EER* of a small-size air-cooled vapour compression chiller can be reduced by more than 30% when the condenser temperature is increased from 30 to 40°C.

Moreover, different values of efficiency can be used depending on whether the auxiliary electric consumption of the vapour compression cooling device is accounted for. Finally, the efficiency of vapour compression cooling devices is strongly dependent on their load condition. In fact, during real-life operation, the cooling unit works at full load for only a limited number of hours and it works at a partial load with a reduced efficiency for the remaining time. By way of example, the Eurovent standard introduced the European seasonal energy efficiency ratio (*ESEER*), which is defined as:

$$ESEER = A \times EER(100\%) + B \times EER(75\%) + C \times EER(50\%) + D \times EER(25\%) \quad (3)$$

where the coefficients A, B, C, and D are weighting coefficients that are dependent on the partial load ratio. The fundamental hypothesis applied in this method is that the thermal source temperature for the condensation varies according to a pre-determined mode with the load.

Economic performance of separate "production" system

The aim of this section is to provide a broad overview of the economic figures used by Annex 54 participants to characterize the reference system based on separate "production", particularly concerning the following parameters:

- UP_{El}^{Grid} : unitary price of electricity from the grid, which is the reference system for supplying electricity (ratio of electric energy cost to delivered electric energy, [€/kWh_{DE} or \$/kWh_{DE}]);
- UP_{NG}: unitary price of natural gas (ratio of natural gas cost to its standard volume, [€/Sm^3, €/Nm^3, \$/Sm^3 or \$/Nm^3]). This parameter is used for the natural gas consumption of the reference boiler, the integration boiler of the AS, and the micro-cogenerator. However, a reduced price can be often assumed for MCHP use, owing to specific supporting mechanisms. Additionally, to convert energy quantities to volumetric quantities, a suitable lower heating value of natural gas (LHV_{NG}, [kWh/kg], [kWh/Sm^3] or [kWh/Nm^3]) must be used.

In Tab. 7, the parameters for the method of characterizing reference systems used by some Annex 54 participating groups are detailed.

Tab. 7: parameters for reference system characterization used by some Annex 54 participating groups

UK										0.17 [51]			0.424[5] [51]		LHV of 9.99 kWh/Sm^3; SB = Standard Boiler; CB =

			TUM (Germany)	NIST (USA)	UNISANNIO/SUN (Italy)	JAPAN
Reference Separate "Production" System	Heating	Type of device	SB – CB	Natural gas furnace (NC) A/A Heat Pump (SC)[1]	SB CB	
		$\eta_{Th,ref}$	SB = 80% CB = 95%	AFUE = 94% (NC) HSPF = 8.5 (SC)	SB = 85-90% CB = 95-102%	73.5%[4]
	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)	
	Electricity	$\eta_{El,ref}$	38.5%	Vary by region	42.0%[3] (Italian mix) 54.3%[3] (BAT)	36.1%[4] (daytime) 38.8%[4] (nighttime)
		$\mu_{El,ref}$ [g/kWh$_{El}$]	540	Vary by region (both marginal and overall)	573 (Italian mix) 400 (BAT)	559
		T&D losses		7 % (US average)	6.23% (average)	
		$P_{el,Grid}$ [€/kWh$_{El}$]			0.243 peak hours 0.225 off-peak hours	0.1 (industrial) 0.2 (domestic)
	Natural gas	PEF_{NG} [kWhPE/kWh$_{DE}$]	1.1			
		UP_{NG} [€/Sm^3]			0.941[2] 0.771 for MCHP use	0.5 (industrial) 1.2 (domestic)
		μ_{NG} [gCO_2/kWh$_{DE}$]	205		207	205
		LHV_{NG} [kWh/Nm^3]			9.52	

4.2 Directive 2004/8/EC

Directive 2004/8/EC [2] on the promotion of cogeneration introduces the energy index primary energy saving (*PES*), which is similar to *FESR* and is defined as (see Fig. 19):

$$PES = 1 - \frac{DE_{Fuel}^{MCHP}}{\dfrac{OE_{El}'^{MCHP}}{\eta_{El,ref}} + \dfrac{OE_{Th}^{MCHP}}{\eta_{Th,ref}}} \tag{112}$$

where $OE_{El}^{'MCHP}$ is the cogenerated electricity. It is only equal to the global "production" (OE_{El}^{MCHP})if the cogenerator has an annual overall efficiency (*PER*) higher than a limit value, depending on the technology (80% for combined cycle gas turbines and condensing steam turbines, 75% for other types of prime movers). If the PER is lower than this limiting value, the cogenerated electricity has to be evaluated as:

$$OE_{El}^{'MCHP} = PHR^{MCHP} \cdot OE_{Th}^{MCHP} \qquad (113)$$

where PHR^{MCHP} is the power-to-heat ratio of the cogenerator, and OE_{Th}^{MCHP} is the amount of useful heat from cogeneration.

The calculation of electricity from cogeneration must be based on the actual power-to-heat ratio. If this is not known, the following default values can be used (Tab. 8):

Tab. 8: Default values of the power-to-heat ratio

Type of the unit	Default *PHR*
Combined cycle gas turbine with heat recovery	0.95
Steam backpressure turbine	0.45
Steam condensing extraction turbine	0.45
Gas turbine with heat recovery	0.55
Internal combustion engine	0.75

EU Directive 2004/8/EC and its associated commission decision [52] provide a method for evaluating the harmonised efficiency reference values for the separate production of electricity ($\eta_{El,ref}$) and heat ($\eta_{Th,ref}$).

In particular, to define $\eta_{El,ref}$ the methodology first defines a base value (Tab. 9), which is dependent on the year of construction of the unit and the type of fuel it uses.

Tab. 9: Base values of $\eta_{El,ref}$ as a function of the year of construction and the type of fuel

	Year of construction: Type of fuel	2001 and before	2002	2003	2004	2005	2006-2011	2012-2015
Solids	Hard coal/coke	42,7	43,1	43,5	43,8	44,0	44,2	44,2
	Lignite/lignite briquettes	40,3	40,7	41,1	41,4	41,6	41,8	41,8
	Peat/peat briquettes	38,1	38,4	38,6	38,8	38,9	39,0	39,0
	Wood fuels	30,4	31,1	31,7	32,2	32,6	33,0	33,0
	Agricultural biomass	23,1	23,5	24,0	24,4	24,7	25,0	25,0
	Biodegradable (municipal) waste	23,1	23,5	24,0	24,4	24,7	25,0	25,0
	Non-renewable (municipal and industrial) waste	23,1	23,5	24,0	24,4	24,7	25,0	25,0
	Oil shale	38,9	38,9	38,9	38,9	38,9	39,0	39,0
Liquids	Oil (gas oil + residual fuel oil), LPG	42,7	43,1	43,5	43,8	44,0	44,2	44,2
	Biofuels	42,7	43,1	43,5	43,8	44,0	44,2	44,2
	Biodegradable waste	23,1	23,5	24,0	24,4	24,7	25,0	25,0
	Non-renewable waste	23,1	23,5	24,0	24,4	24,7	25,0	25,0
Gaseous	Natural gas	51,7	51,9	52,1	52,3	52,4	52,5	52,5
	Refinery gas/hydrogen	42,7	43,1	43,5	43,8	44,0	44,2	44,2
	Biogas	40,1	40,6	41,0	41,4	41,7	42,0	42,0
	Coke oven gas, blast furnace gas, other waste gases, recovered waste heat	35	35	35	35	35	35	35

Following this, the value is corrected to take into account the annual average temperature in the member state (0.1% efficiency reduction for every degree above 15°C; 0.1% efficiency increase for every degree below 15°C) and the avoided grid losses, which depend on the voltage and the share of electric energy exported to the grid (Tab. 10).

Tab. 10: Correction coefficients for $\eta_{El,ref}$ to take into account avoided grid losses

Voltage	For electricity exported to the grid	For electricity consumed on-site
> 200 kV	1	0,985
100-200 kV	0,985	0,965
50-100 kV	0,965	0,945
0,4-50 kV	0,945	0,925
< 0,4 kV	0,925	0,860

With regards to $\eta_{Th,ref}$, the methodology for evaluating its value is simpler because it only depends on the type of fuel and on how the cogenerated thermal energy is used (direct use of exhaust gases or “production” of steam/hot water) Tab. 11.

Tab. 11: Values of $\eta_{Th,ref}$ as a function of type of fuel and type of heat recovery

	Type of fuel	Steam/hot water	Direct use of exhaust gases (*)
Solids	Hard coal/coke	88	80
	Lignite/lignite briquettes	86	78
	Peat/peat briquettes	86	78
	Wood fuels	86	78
	Agricultural biomass	80	72
	Biodegradable (municipal) waste	80	72
	Non-renewable (municipal and industrial) waste	80	72
	Oil shale	86	78
Liquids	Oil (gas oil + residual fuel oil), LPG	89	81
	Bio-fuels	89	81
	Biodegradable waste	80	72
	Non-renewable waste	80	72
Gaseous	Natural gas	90	82
	Refinery gas/hydrogen	89	81
	Biogas	70	62
	Coke oven gas, blast furnace gas, other waste gases, recovered waste heat	80	72

(*) Values for direct heat should be used if the temperature is 250 °C or higher.

4.3 Application of small-scale cogeneration systems for summer and winter air conditioning and DHW production in Italy.

The technical form 21T, produced by the Italian Authority for Electric Energy and Gas (AEEG, [53]), provides a procedure for evaluating the white certificates for new small-scale cogeneration and trigeneration installations within the residential sector.

The methodology refers to Fig. 31; it does not take energy losses resulting from fuel processing and distribution processes into account. Consequently, in order to comply with the nomenclature defined in previous chapters, the energy of the fuel entering the CCHP system should be denoted as delivered energy (*DE*) and not as primary energy (*PE*). However, it was decided that *PE* be used, instead of *DE*, in order to better conform to the nomenclature used in the technical form.

The methodology requires the evaluation of the net primary energy saving (*NS*), measured in tonnes of oil equivalent (toe), as:

$$NS = NS_{Th} + NS_{Cool} + NS_{El} \tag{114}$$

where:

$$NS_{Th} = IRE_{mod} \cdot PE_{Th} \tag{115}$$

NS_{Th} is the net primary energy saving related to the corresponding net thermal energy.

$$PE_{Th} = f_T \cdot \frac{OE_{Th}^{CCHP}}{\eta_{Th,ref}} = f_T \cdot \frac{OE_{Th}^{CCHP}}{0.75 + 0.03 \cdot Log_{10} P_{nom}} \tag{116}$$

where f_T = 0.086 toe/MWh is the conversion factor from MWh to toe, P_{nom} is the nominal power in kW of the boiler that would produce thermal energy without the CHP.

$$NS_{Cool} = IRE_{mod} \cdot PE_{Cool} \tag{117}$$

NS_{Cool} is the net primary energy saving related to corresponding net cooling energy.

$$PE_{Cool} = PEF_{El} \cdot \frac{OE_{Cool}^{CCHP}}{SEER_{Cool,ref}} \tag{118}$$

where PEF_{El} is the primary energy of grid electricity – the inverse of the reference efficiency of the electric mix ($\eta_{El,ref}$) – and is equal to:

0.220 toe/MWh for year 2005	$\eta_{El,ref}$ = 39.1%
0.210 toe/MWh for year 2006	$\eta_{El,ref}$ = 40.9%
0.207 toe/MWh for year 2007	$\eta_{El,ref}$ = 41.5%
0.204 toe/MWh for year 2008	$\eta_{El,ref}$ = 42.1%
0.201 toe/MWh for year 2009	$\eta_{El,ref}$ = 42.8%
0.187 toe/MWh for successive years	$\eta_{El,ref}$ = 46.0%

$SEER_{Cool,ref}$ is the seasonal energy efficiency ratio for cooling "separate" production; it is equal to 2.7 or 3.0, depending on the Italian climatic zone.

$$NS_{El} = IRE_{mod} \cdot PE_{El} \tag{119}$$

NS_{El} is the net primary energy saving related to the corresponding net electric energy.

where

$$PE_{El} = PEF_{El} \cdot OE_{El}^{CCHP} \tag{120}$$

and $OE_{El,GC}^{CCHP}$ is the share of OE_{El}^{CCHP} for which green certificates have been obtained. Green certificates are the mechanism by which electric production from renewable energy source is encouraged.

IRE_{mod} is an index similar to *FESR* that compares the primary energy requirement of CCHP and the reference systems. It is defined as:

$$IRE_{\mathrm{mod}} = \frac{PE - PE_{Fuel}^{CCHP\ *}}{PE} \tag{121}$$

where $PE = PE_{Th} + PE_{Cool} + PE_{El}$ (122)

and $PE_{Fuel}^{CCHP\ *} = PE_{Fuel}^{CCHP} \cdot f_T$ (123)

The quantities (expressed as MWh) presented in Fig. 31 must be measured.

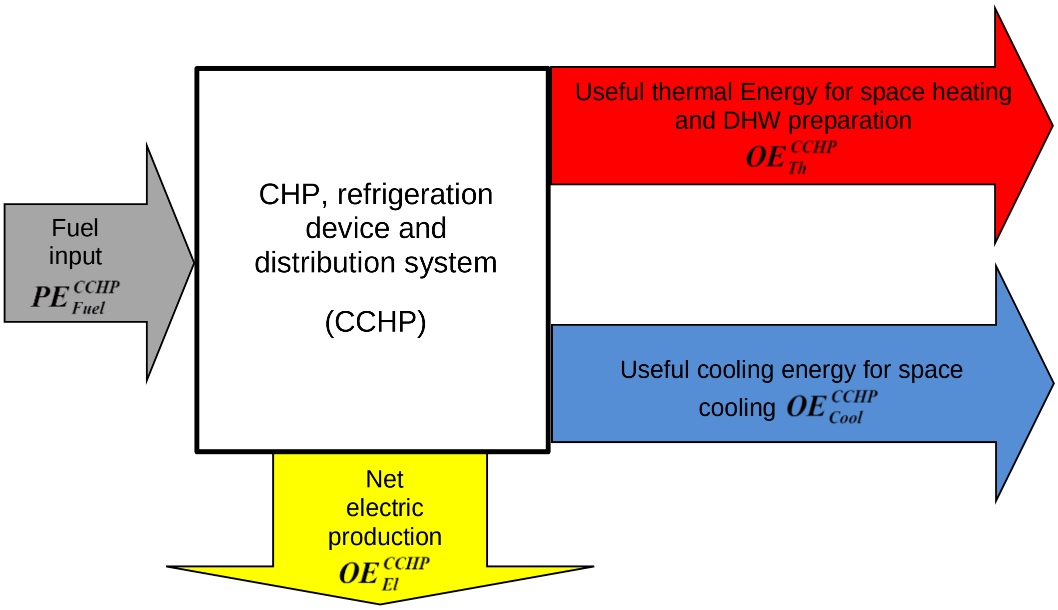

Fig. 31: Energy flows for the application of technical form n. 21T of the AEEG

The mechanism defined by the AEEG requires that a minimum number of white certificates must be achieved; this quantity can be very difficult to obtain using small-scale systems. For this reason, an alternative procedure, the Ministerial Decree of 5th September 2011, provides a further methodology for calculating the white certificates that an MCHP unit can obtain. This new procedure is based on the following equation, which evaluates the net primary energy saving of the cogenerator with respect to a reference system:

$$NS = \frac{OE_{El}^{'MCHP}}{\eta_{El,ref}} + \frac{OE_{Th}^{MCHP}}{\eta_{Th,ref}} - PE_{Fuel}^{MCHP} \tag{124}$$

$\eta_{El,ref}$ is the average efficiency of a reference system for supplying electricity in Italy; it is equal to 0.46 multiplied by the correction factor defined in Tab. 10, while $\eta_{Th,ref}$ is as defined in Tab. 11.

The number of white certificates to which the system is entitled is calculated using:

$$WC = NS \cdot f_T \cdot K \tag{125}$$

where K is a correction factor depending on the size of the MCHP, which is equal to 1.4 for MCHPs.

The necessary condition to obtain white certificates is that the MCHP is recognized as having a high efficiency, as defined by Directive 2004/8/EC. For MCHPs with electric power lower than 50 kW_{El}, the criterion for high efficiency certification is that $PES > 0$.

4.4 Japanese Method for detached houses

This method [54] applies in the case of detached houses supplied by cogeneration systems; it estimates the primary energy consumption by a single-family house equipped with a micro-cogeneration system.

The estimation formula is as follows:

$$PE_{Fuel}^{MCHP} = E_{El} C_1 + \left(E_{Th,hw,rh} + E_{Th,hw,DHW}\right) C_2 + C_3 - E_s \tag{126}$$

where

- PE_{Fuel}^{MCHP} is the primary energy consumption of the MCHP (GJ/y);
- E_{El} is the electricity consumption of the house for heating, cooling, ventilation, and lighting (GJ/y). Consumption of electric appliances is not included;
- $E_{Th,hw,rh}$ is the hot water supply for room heating (GJ/y);
- $E_{Th,hw,DHW}$ is the hot water supply for DHW preparation (GJ/y);
- C_1, C_2, C_3 are empirical coefficients that depend on the type of cogeneration system employed (GJ/GJ);
- E_s is an adjusting factor that takes the electric consumption of electric appliances into account (GJ/y).

The procedure for the method is as follows:

1. The MCHP is evaluated experimentally for six day types, which are representative of three or four seasons, in order to measure the primary energy consumption (PE_{Fuel}^{MCHP});
2. The building is modelled to estimate the daily and annual energy consumption of the house (E_{El}, $E_{Th,hw,rh}$, $E_{Th,hw}$), which depends on the region (eight types of regions, from cold to semi-tropical);
3. A regression analysis on primary energy consumption is performed (see for example Fig. 32) in order to determine the empirical coefficients C_1, C_2, and C_3 (see Tab. 12 for an example).

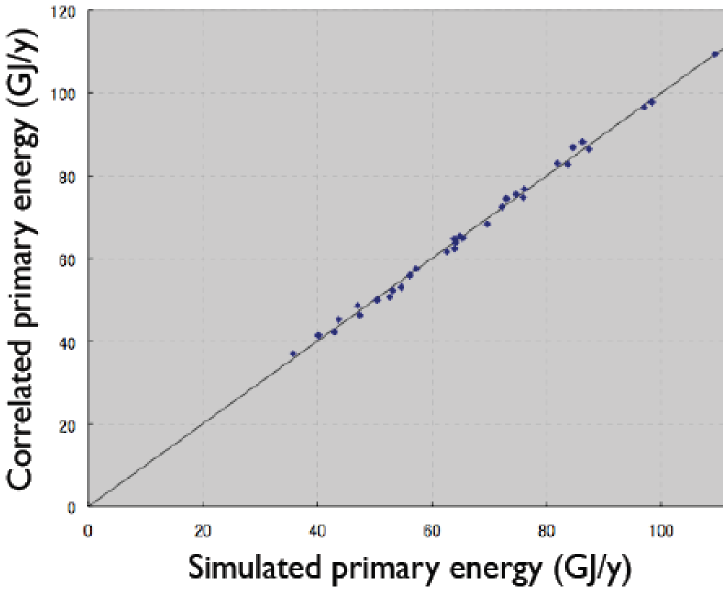

Fig. 32: Regression analysis for an ICE

Tab. 12: Empirical coefficients for FC and ICE MCHPs with 1 kW electric power output

Coefficient	Unit	FC	ICE
C_1	GJ/GJ	0.836	0.9499
C_2	GJ/GJ	1.048	1.1158
C_3	GJ	-1.003	1.4838

With regards to the adjusting factor, a share of the cogenerated electricity is consumed by electric appliances; however, this method only takes into account the primary energy consumption, which is related to the electricity consumption of the HVAC system. Consequently, a part of the MCHP fuel consumption, represented by the adjusting factor E_s, has to be deducted from the overall primary energy consumption ($PE_{Fuel,0}^{MCHP}$) in order to estimate the primary energy consumption for the HVAC and hot water supply (PE_{Fuel}^{MCHP}).

$$PE_{Fuel,0}^{MCHP} = E_{El} C_1 + \left(E_{Th,hw,rh} + E_{Th,hw}\right) C_2 + C_3 \tag{127}$$

$$PE_{Fuel}^{MCHP} = PE_{Fuel,0}^{MCHP} - E_s \tag{128}$$

The adjusting factor E_s can be determined as:

$$E_s = \left(PE_{Fuel,0}^{MCHP} - PE_{\text{standard}}\right) R \tag{129}$$

where R is the ratio of electric appliance in total electricity consumption and $PE_{standard}$ is the standard primary energy consumption in a detached house (excluding energy for electric appliances); this is dependent on the climatic region (very cold, cold, warm, hot, and semi-tropical).

4.5 Japanese method for District Heating/Cooling (DHC) systems with CHP

The Tokyo provincial government defines the energy efficiency index for DHC systems utilizing waste heat produced by a cogenerator [55], [56]. The energy efficiency of a DHC plant, for example on an annual basis, is defined as:

$$\eta = \frac{NE_{Th/Cool}^{DHC}}{PE_{Fuel}^{GB} + DE_{El}\theta_p + PE_{Fuel\_Th}^{CHP}} \tag{130}$$

where

- DE_{El} is the electricity consumption of the plant (GJ/year)
- PE_{Fuel}^{GB} is the primary fuel consumed by the boiler (GJ/year)
- $PE_{Fuel\_Th}^{CHP}$ is the primary energy consumption of the CHP for producing waste heat (GJ/year)
- $NE_{Th/Cool}^{DHC}$ is the net thermal/cooling energy production of the DHC system (GJ/year)
- θ_p is the conversion coefficient of electricity to primary energy (2.71 GJ/GJ)

The gas consumption of the CHP for thermal energy production is evaluated as:

$$PE_{Fuel\_Th}^{CHP} = \frac{\alpha OE_{Th}^{CHP}}{\alpha OE_{Th}^{CHP} + \beta OE_{El}^{CHP}} PE_{Fuel}^{CHP} = \frac{OE_{Th}^{CHP}}{OE_{Th}^{CHP} + \beta/\alpha \, OE_{El}^{CHP}} PE_{Fuel}^{CHP} = \frac{OE_{Th}^{CHP}}{OE_{Th}^{CHP} + 2.17\, OE_{El}^{CHP}} PE_{Fuel}^{CHP} \tag{131}$$

where

- OE_{Th}^{CHP} is the cogenerated heat used in the DHC plant (GJ/year)
- OE_{El}^{CHP} is the electricity generated by the CHP (GJ/year)
- PE_{Fuel}^{CHP} is the total primary energy consumption of the CHP (GJ/year)
- α is the fuel-to-thermal energy ratio for a conventional boiler (1.26 GJ/GJ)
- β is the fuel-to-electric energy ratio for the electric grid (2.73 GJ/GJ)

4.6 The UK Quality Assurance for Combined Heat and Power (CHPQA)

The CHPQA is an initiative of the UK Government for monitoring, assessing, and improving the quality of CHP plants. It provides a practical, robust and deliberate methodology for defining 'good quality' CHP, in terms of the energy efficiency and environmental performance [57].

Self-assessment and certification under CHPQA provides the principal evidence required for determining eligibility of CHP systems for "Climate Change Levy" exemption, for "Enhanced Capital Allowances" (both subject to EU state aids clearance), and for the exemption of the plant and machinery from a business rating.

4.6.1 Methodology

This methodology refers to Fig. 33 and in this case, it does not take the energy losses from fuel processing and distribution into account. Consequently, the energy of fuel entering the CHP system should be denoted as delivered energy (*DE*) and not as primary energy (*PE*). However, the decision was made to use *PE*, instead of *DE*, in order to better conform to the nomenclature used in the related documentation.

The methodology is based on threshold criteria that must be met or exceeded in order to qualify a CHP as 'good quality'. The threshold criteria are set for quality index (*QI*) and power efficiency, and both can be determined from just three sets of data, namely, fuel used, power generated, and heat supplied.

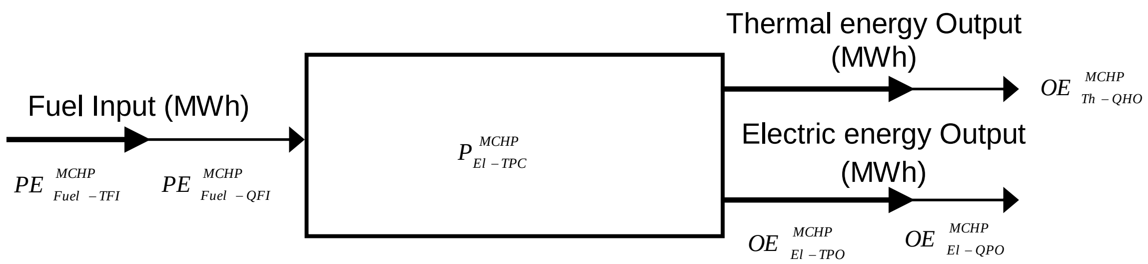

Fig. 33: Energy flows for the application of CHPQA methodology

Normally, the main threshold criteria are *QI* = 100 and power efficiency = 20%, under annual operation. However, the threshold criteria can vary under certain circumstances, such as during the initial period of operation, which starts when the unit has begun operating and ends after the first complete year of operation, for a plant serving an individual user or site. For a system serving community heating, the initial operation ends after the first two complete years of operation. In a situation where either or both the power efficiency or QI threshold criterion are not met, only a portion of fuel input or power output of the CHP qualifies as being of "good quality".

4.6.2 Nomenclature

CHP qualifying fuel input ($PE^{MCHP}_{Fuel-QFI}$) is the registered annual fuel input to a CHP scheme qualifying as input to a "good quality" CHP (MWh); this is based on the gross calorific value. If the scheme meets the threshold power efficiency criterion for a "good quality" CHP under annual operation, $PE^{MCHP}_{Fuel-QFI}$ is the total annual fuel input ($PE^{MCHP}_{Fuel-TFI}$). For a scheme that does not achieve the threshold power efficiency criterion for a "good quality" CHP, $PE^{MCHP}_{Fuel-QFI}$ is the portion of the annual fuel input to a scheme that would have achieved the power efficiency criterion, based on the actual annual power generated (OE^{MCHP}_{El-TPO}).

CHP qualifying heat capacity (P^{MCHP}_{Th-QHC}) is the registered maximum heat supply capacity of a CHP scheme (MW_{Th}). It is the maximum rate of heat supply that is utilized to displace heat that would otherwise be supplied from other energy sources.

CHP qualifying heat output (OE^{MCHP}_{Th-QHO}) is the registered amount of useful heat that is supplied annually by a CHP (MWh_{Th}). It is the heat output that is utilized to displace heat that would otherwise be supplied from other sources. OE^{MCHP}_{Th-QHO} excludes any heat discharged to the environment without any beneficial use. Examples include, inter alia, heat lost from chimneys or exhausts, and heat rejected in equipment such as condensers and radiators.

CHP qualifying power capacity (P^{MCHP}_{El-QPC}) is the registered power generation capacity of a CHP scheme (MW_{El}) that qualifies as a "good quality" CHP. If a scheme meets the relevant threshold QI criterion for "good quality" CHP capacity, P^{MCHP}_{El-QPC} is the same value as the total power capacity (P^{MCHP}_{El-TPC}). Where a scheme includes mechanical power output, this should be converted to an equivalent electrical power output before being included in P^{MCHP}_{El-TPC} . For a scheme that does not achieve the threshold QI criterion for a "good quality" CHP, P^{MCHP}_{El-QPC} is that portion of the total generation capacity that would achieve the threshold QI criterion, under maximum heat output under normal operating conditions.

CHP qualifying power output (OE^{MCHP}_{El-QPO}) is the registered annual power generated by a CHP scheme (MWh_{El}) that qualifies as a "good quality" CHP. If a scheme meets the relevant threshold QI criterion for a "good quality" CHP during annual operation, OE^{MCHP}_{El-QPO} is the total power output, OE^{MCHP}_{El-TPO} , that is the total annual power generation from a CHP scheme as measured at the generator terminals plus the electrical equivalent of any qualifying mechanical power supplied by the scheme. Where mechanical power is provided by a scheme, this should be included in the self-assessment of OE^{MCHP}_{El-TPO} as an equivalent electrical output by multiplying the mechanical energy by a factor of 1.05. For a scheme that does not achieve the threshold QI criterion for a "good quality" CHP, OE^{MCHP}_{El-QPO} is the portion of the annual power output from a scheme that would have achieved the threshold QI criterion; this is based on the actual annual heat supplied (OE^{MCHP}_{Th-QHO}).

Heat efficiency (η_{Th}^{MCHP}) is the qualifying heat output divided by the total fuel input over the period in question.

Power efficiency (η_{El}^{MCHP}) is one of two key parameters for assessing a CHP scheme and it is defined as the total power output divided by the total fuel input.

QI is one of two key parameters for assessing a scheme. QI is an indicator of the energy efficiency and environmental performance of a scheme, relative to the generation of the same quantities of heat and power by separate and alternative means.

4.6.3 Procedure

The QI is one of two key parameters for assessing a CHP scheme. QI is an indicator of the energy efficiency and environmental performance of a scheme.

The general form of the QI definition is:

$$QI = \left(X \cdot \eta_{El}^{MCHP}\right) + \left(Y \cdot \eta_{Th}^{MCHP}\right) \tag{132}$$

X is a coefficient related to alternative power supply options. Similarly, Y is a coefficient for the generation of heat from alternative options for supplying heat. The values of X and Y vary for different sizes and types of scheme.

With regards to the basis for the X and Y factors, and considering electrical efficiency first (the X factor), small CHP schemes are not compared exclusively with a combined cycle gas turbine (CCGT), but are also compared with existing mid-merit steam turbine plants (coal, gas or oil-fired). These plants incur transmission and distribution losses. Additionally, small CHP schemes are compared with new embedded gas turbines, which achieve electrical efficiency of approximately 36%, based on gross calorific value. In order to supply 100 units of electricity, it would require 180–370 units of fuel, Tab. 13.

For supplying heat (the Y factor), the alternative to CHPs is heat-only boilers, which exhibit different efficiency depending on the technology utilized. In order to supply 100 units of heat, it would typically require between 115 and 120 units of fuel, Tab. 13.

In Tab. 13, the QI definitions for new CHP schemes with an electric power lower than 1 MW_{El} are reported.

Where a scheme utilizes both conventional and alternative fuels, weighted mean values for X and Y should be used for the definition and calculation of QI.

QI is normally calculated on an annual basis where:

$$\eta_{El}^{MCHP} = \frac{OE_{El-TPO}^{MCHP}}{PE_{Fuel-TFI}^{MCHP}} \tag{133}$$

$$\eta_{Th}^{MCHP} = \frac{OE_{Th-QHO}^{MCHP}}{PE_{Fuel-TFI}^{MCHP}} \tag{134}$$

Tab. 13: QI definition for new CHP schemes

CONVENTIONAL FOSSIL FUELS NEW CHP SCHEMES (≤1 MW$_{El}$)	
Natural gas, oil, and coal	$QI = 249 \cdot \eta_{El}^{MCHP} + 115 \cdot \eta_{Th}^{MCHP}$
Fuel cell schemes	$QI = 180 \cdot \eta_{El}^{MCHP} + 120 \cdot \eta_{Th}^{MCHP}$
ALTERNATIVE FUEL NEW CHP SCHEMES (≤1 MW$_{El}$)	
By-product gases	$QI = 294 \cdot \eta_{El}^{MCHP} + 120 \cdot \eta_{Th}^{MCHP}$
Biogas	$QI = 285 \cdot \eta_{El}^{MCHP} + 120 \cdot \eta_{Th}^{MCHP}$
Waste gas or heat	$QI = 329 \cdot \eta_{El}^{MCHP} + 120 \cdot \eta_{Th}^{MCHP}$
Liquid biofuels	$QI = 275 \cdot \eta_{El}^{MCHP} + 120 \cdot \eta_{Th}^{MCHP}$
Liquid waste	$QI = 275 \cdot \eta_{El}^{MCHP} + 120 \cdot \eta_{Th}^{MCHP}$
Biomass or solid waste	$QI = 370 \cdot \eta_{El}^{MCHP} + 120 \cdot \eta_{Th}^{MCHP}$
Wood fuels	$QI = 329 \cdot \eta_{El}^{MCHP} + 120 \cdot \eta_{Th}^{MCHP}$

The threshold criteria for a "good quality" CHP are:

- For fuel inputs under annual and initial operation: a scheme that qualifies as a "good quality" CHP for its entire annual energy inputs is one where the power efficiency equals or exceeds 20%.
- For power outputs under annual operation: a scheme that qualifies as a "good quality" CHP for its entire annual energy outputs is one where the QI equals or exceeds 100. A scheme with a QI of 100 will typically make primary energy savings of 16–26% over current alternative-electricity and heat-only supply systems. Normally, the threshold QI criterion is based on annual operation but it can also be based on other periods, such as the heating season, as is the case in the case of residential community heating schemes.
- For power outputs under initial operation: a scheme that qualifies as a "good quality" CHP for its entire annual energy outputs is one where the QI equals or exceeds 95.

CHP Qualifying Fuel Input

Where the power efficiency meets or exceeds the threshold criterion, all of the fuel input to the scheme qualifies, $PE_{Fuel-QFI}^{MCHP} = PE_{Fuel-TFI}^{MCHP}$. Where the power efficiency for a scheme is less than the threshold criterion, the fuel use that qualifies as input to a "good quality" CHP ($PE_{Fuel-QFI}^{MCHP}$) should be calculated. $PE_{Fuel-QFI}^{MCHP}$ is the portion of the fuel input that would have provided a power efficiency equal to the threshold criterion, based on the annual power output (OE_{El-TPO}^{MCHP}).

$$PE_{Fuel-QFI}^{MCHP} = PE_{Fuel-TFI}^{MCHP} \cdot \frac{\eta_{El}^{MCHP}}{\eta_{El(threshold)}^{MCHP}} \tag{135}$$

CHP Qualifying Power Output

For schemes that meet the threshold QI criterion, the qualifying power output is the same as the total power output, $OE_{El-QPO}^{MCHP} = OE_{El-TPO}^{MCHP}$. For schemes that do not qualify as a "good quality" CHP for the whole of their output, the power output is considered in two portions:

(i) The portion represented by the CHP qualifying power output, OE_{El-QPO}^{MCHP}. This is the portion of the actual annual electrical (or mechanical) energy supplied that would result in the CHP achieving a QI equal to 100, given that the actual annual heat is supplied (OE_{Th-QHO}^{MCHP}). This portion may be eligible for benefits.

Step 1:

It is necessary to calculate the new heat efficiency needed to reach a QI of 100. For these prime movers, the electrical efficiency is fixed regardless of heat recovery; consequently, the calculation uses the basic definition for the QI:

$$100 = X \cdot \eta_{El}^{MCHP} + Y \cdot \eta_{Th(QI=100)}^{MCHP} \tag{136}$$

This equation can be rearranged to give:

$$\eta_{Th(QI=100)}^{MCHP} = \left[100 - \left(X \cdot \eta_{El}^{MCHP}\right)\right] / Y \tag{137}$$

Step 2:

It is necessary to calculate the equivalent heat-to-power ratio for the scheme as if it had achieved this new level of heat utilization and, consequently, a QI of 100. This is expressed as:

$$(Heat-to-power\ ratio\ at\ QI=100) = \eta_{Th(QI=100)}^{MCHP} / \eta_{El}^{MCHP} \tag{138}$$

Step 3

OE_{El-QPO}^{MCHP} is calculated as follows:

$$OE_{El-QPO}^{MCHP} = OE_{Th-QHO}^{MCHP} / (Heat-to-power\ ratio\ at\ QI=100) \tag{139}$$

(ii) Annual electrical energy supplied in excess of the OE^{MCHP}_{El-QPO} . This portion of the energy does not qualify as an output from a "good quality" CHP.

CHP Qualifying Power Capacity

For schemes that meet the threshold QI criterion, the qualifying power capacity is the same as the total power capacity, $P^{MCHP}_{El-QPC} = P^{MCHP}_{El-TPC}$. For schemes that do not qualify as a "good quality" CHP for the whole of their output, the CHP qualifying power capacity (P^{MCHP}_{El-QPC}) should be calculated. P^{MCHP}_{El-QPC} is that portion of the power generating capacity that would provide a QI value of 100 for existing schemes and 105 for new schemes; it is assumed that this occurs under the conditions of maximum heat output in normal operating conditions. Normally, for an existing CHP scheme that is based on gas turbines or reciprocating engines:

$$P^{MCHP}_{El-QPC} = MaxHeat \Big/ \left(Heat-to-power\ \ ratio\ \ at\ \ QI_{MaxHeat}=100\right) \tag{140}$$

where MaxHeat = the maximum heat output under normal operating conditions,

$$\left(Heat-to-power\ \ ratio\ \ at\ \ QI_{MaxHeat}=100\right) = \eta^{MCHP}_{Th\,(QI_{MaxHeat}=100)} \Big/ \eta^{MCHP}_{El} \tag{141}$$

$$\eta^{MCHP}_{Th\,(QI_{MaxHat}=100)} = \left[100-\left(X\cdot\eta^{MCHP}_{El}\right)\right] \Big/ Y \tag{142}$$

4.7 Method to evaluate the annual energy performance of micro-cogeneration heating systems in dwellings

This is a method for determining the annual energy performance of micro-cogeneration systems for space heating and hot water provision (or space heating alone) in single dwellings in the UK. It makes specific assumptions about the size of the micro-cogeneration system and the way it is used, but not about the design or particular technology adopted [58]. This method requires the input of data obtained from suitable laboratory tests performed under carefully controlled conditions that are specified by PAS 67, which was developed by the Energy Saving Trust in collaboration with the British Standards Institution [14].

The purpose of PAS 67 is to determine, by measurement under a variety of load conditions, the data needed to calculate the energy performance of a MCHP. Its application is restricted to packages whose function is the production of thermal and electric energy and whose method of control is by heat demand. The results obtained from testing with the requirements of PAS 67 are not intended for use as a direct comparative assessment of MCHPs. However, these results can be fed forward into procedures for calculating one or more indices of performance for the purpose of comparative assessments. The PAS results can used to calculate annual energy performance, as is the case with the "Method to evaluate the annual energy performance of micro-cogeneration heating systems in dwellings". This method enables estimations of the annual energy performance to be made, allowing the derivation of a single index of performance for product comparison.

This PAS specifies a comprehensive set of test conditions for determining the heating and electrical performance of heat-led MCHP packages that are primarily intended for use in dwellings. It is suitable for testing units with a thermal output of up to 70 kW.

The method is only valid under the following main conditions:

1) Laboratory tests have been carried out under the conditions prescribed by PAS 67.

   The tests must have been carried out while the package was operating in synchronous mode (not island mode);

2) The micro-cogenerator package is the primary heating system for a typical UK dwelling and is heat-led. Heat is never wasted;

3) The electricity generated is a useful by-product and is never wasted. The full amount of electricity generated receives carbon emission credits because it displaces an equivalent amount of carbon that would otherwise be generated by the public electricity supply;

4) The micro-cogenerator package is matched to the building using a suitable plant-size ratio (PSR). A limited degree of over or under sizing is considered acceptable. If the package is under sized, the shortfall of thermal energy is assumed to be met by electrical heating, and if it is over sized, the load profile is adjusted accordingly;

5) The MCHP is used to provide either both space heating and DHW, or space heating alone. If DHW is not included it is provided by an electrical immersion heater.

The known limitations of the method are:

I. The heating and summer seasons are assumed to have fixed lengths;

II. The space heating and DHW loads are treated as being indistinguishable;

III. The PSR must not be less than 0.5 or greater than 4.

The method comprises the following parts.

4.7.1 Input data

Most of the input data are results from PAS 67, which provide information on the performance under various part-load operating conditions. Part load means the system is operating over the heating period of a day in which the generated heat for space heating is a specified fraction of the full heat output. In short, the part load is expressed as the percentage of the daily heat output from the micro-cogenerator, which is assumed to be running at nominal rated heat output (i.e., 100% is 24 hours multiplied by the nominal rated heat output).

Regimes

Some micro-cogenerator packages may have their performance optimised by heating the dwelling for 24 hours/day or 16 hours/day, rather than for the standard assessment procedure (SAP) heating time of 77 hours per week (11 hours/day on average). To allow for these variations, this method assesses the operation of the micro-cogenerator package under any of the four regimes specified in the PAS 67 procedure:

Regime 1 – 24 hours/day – Continuous 100, 30, and 10% part-load;

Regime 2 – 16 hours/day – Continuous 100% operation, plus uni-modal operation (07:00–23:00) at 30 and 10% part-load;

Regime 3 – 11 hours/day – Continuous 100% operation, plus bi-modal operation (06:00–9:00 and 15:00–23:00) at 30 and 10% part-load;

Regime 4 – Mixed option – Continuous 100% operation, plus uni-modal operation at 30% part-load, plus bi-modal operation at 10% part-load.

If the package is assessed under extended hours of heating operation with respect to the SAP (77 hours/week), additional heat will be needed to keep the house warm outside of the hours assumed by the SAP. This increase is represented in the seasonal performance index, through the introduction of an extended heating factor (X).

Plant Size Ratio

The *PSR* is defined as the nominal heat output of the heating plant divided by the design heat loss (the average heat loss of the building on a cold day with a temperature differential of 20°C). The annual results are required for four values of PSR, 0.5, 1, 1.5, and 4. For a particular dwelling where the design heat loss is known, the annual results are then interpolated using the results for the above values of PSR.

The PSR must not be lower than 0.5, or supplementary heating of more than half the heat demand would be required, and the micro-cogenerator package cannot be regarded as the primary heating system of the dwelling.

Fuel input and power output under part-load conditions

The daily electricity generated, heat generated, and fuel consumed are measured for a limited number of part-loads. Laboratory tests should be performed at 0 (standby), 10, 30, and 100% of the full 24-hour maximum load, as a minimum. To reduce interpolation errors, tests at the supplementary part-load conditions 20, 40, 60, 70, 80, or 90% may also be performed.

Annual fuel consumption and electricity generated

Part-load conditions for dwellings in the UK are represented by a heat-load profile, which is the number of days per heating season at 13 part-load bands, each approximately 10% in range; this is plotted on a graph presented in Fig. 34. By way of example, one range is the number of days when the package is expected to operate between 5 and 15% of the full load. Heat-load profiles are derived from meteorological data and vary with PSR and the heating regime.

To estimate the annual fuel input and net electricity generated, the profile is multiplied by the interpolated part-load performance results.

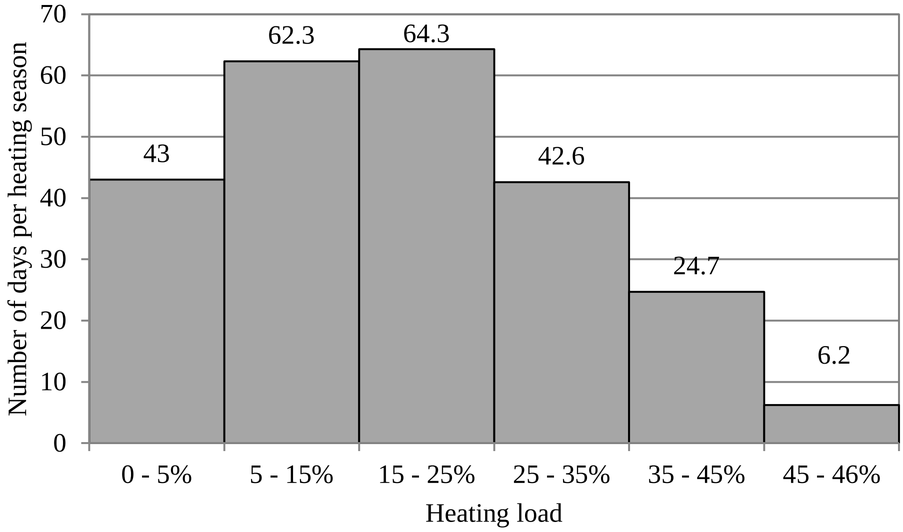

Fig. 34: Load profile for the space heating and hot water for regime three (*PSR* = 1.5) [58]

Seasonal Performance Index: the Heating Plant Emission Rate (HPER)

The purpose of a seasonal performance index is to assist in making comparisons between different products using a single number. The index is called the heating plant emission rate (*HPER*), and represents the carbon dioxide emissions from fuel and the power required to provide space heating and hot water service in a building. It is defined as the carbon dioxide emissions from the fuel and power consumed by the heating plant. These emissions are offset by the emissions saved as a result of the central electricity production that is avoided (full credit is given for all electricity generated; it is assumed that any not used within the building is exported to the grid); this is then divided by the heat output over the whole year (kg_{CO2}/kWh).

It is important to remember that the *HPER* includes any auxiliary space and water heating that may be necessary. This means that it represents the performance of the whole heating plant that is required in order to provide space and water heating services to the building.

4.7.2 Procedure

The required data for this calculation are presented in Tab. 14.

Item 1: P_{nom} – The nominal heat output in kW declared by the manufacturer.

For items 3 and 4, the classifications RegPK, CombiPK, and HeatPK, which are defined in section 2.9, are needed.

item 5: The test regime number.

Items 6, 7, and 8: F_{x1}, F_{x2}, and F_{100} – The fuel input, measured by the gross calorific value, in kWh/day, under the part-load conditions 10, 30, and 100%. The same is true for E_{x1}, E_{x2}, and E_{100}, where E is the net electrical energy generated, and also for Q_{x1}, Q_{x2}, and Q_{100}, where Q is the heat output to space heating.

Item 9: Q_{Wa}, F_W, and E_W – The heat content of the hot water drawn, the fuel input, and the net electrical power during the DHW test, as outlined in PAS 67. These results are only required if the value produced by item 3 is "YES", i.e. the micro-cogeneration system provides the DHW service.

Item 10: E_0 and F_0 – The net electrical energy generated and the fuel input, in kWh/day, during standby operation over a nominal test period that is scaled to an equivalent 24-hour value. Electrical quantities may be negative, indicating that the package has consumed more electrical power than it generated.

Items 13 and 14 are required for regular packages only and are estimated from temperature measurements of the cylinder during the DHW test specified by PAS 67.

Tab. 14: Data required for the methodology [58]

Table 1: Input data from laboratory tests and manufacturer's declaration					
Item	PAS 67 Results table	Description	Value		
1	1	Nominal rated heat output	P_{nom}: .....kW		
2	1	Fuel	Natural gas / LPG / oil / solid fuel		
3	2	DHW service	YES (package type RegPK or CombiPK) / NO (package type HeatPK)		
4	2	Direct DHW supply	YES (package type CombiPK) / NO (package type RegPK or HeatPK)		
5	2	Test regime number	Regime 1, 2, 3 or 4		
6	2	100% thermal output ("Full output")	Fuel input (gross) kWh/24h F_{100} =	Electrical output kWh/24h E_{100} =	Heat output kWh/24h Q_{100} =
7	2	30% thermal output	Fuel input (gross) kWh/24h F_{x2} =	Electrical output kWh/24h E_{x2} =	Heat output kWh/24h Q_{x2} =
8	2	10% thermal output	Fuel input (gross) kWh/24h F_{x1} =	Electrical output kWh/24h E_{x1} =	Heat output kWh/24h Q_{x1} =
9	2	DHW performance	Fuel input (gross) kWh/24h F_W =	Electrical output kWh/24h E_W =	Heat output kWh/24h Q_{Wa} =
10	2, 4	Standby performance	Fuel input (gross) kWh/24h F_0 =	Electrical output kWh/24h E_0 =	Heat output kWh/24h $Q_0 = 0$
11	2	Supplementary tests at part load s_i and condition j: where j=c for continuous, j=u for unimodal or j=b for bimodal.	Fuel input (gross) kWh/24h $F_{s_1,j}....F_{s_n,j}$	Electrical output kWh/24h $E_{s_1,j}....E_{s_n,j}$	Heat output kWh/24h $Q_{s_1,j}....Q_{s_n,j}$
12	2	Method of electricity connection	Island or grid (connected to the public mains supply)		
13	3	Heat required to keep the cylinder and primary pipes warm during the DHW test	Q_{hwstby} (kWh/day)		
14	3	Change in the energy of the water in the cylinder during the DHW test	Q_{hwres} (kWh/day)		

Fuel input and power generated under part-load conditions

- *Regime 1*

For each row in Tab 15, fuel input (*F3*) and net electrical output (*E3*) can be calculated by:

1. Determining the next and nearest part load below and part load above; this can be achieved using the data at the precise loads of 0, 10, 30, and 100%, or any supplementary part load used.
2. Entering the part-load below and above ×% in columns B and C; the corresponding fuel used and net electricity generated can be entered into columns E1 – E2 and F1 – F2, respectively.
3. Columns E3 and F3 can be calculated using:

$$Col\ \ F3 = \{(Col\ \ D - 1) \times Col\ \ F1\} + Col\ \ D \times F2 \tag{143}$$

$$Col\ \ E3 = \{(Col\ \ D - 1) \times Col\ \ E1\} + Col\ \ D \times E2 \tag{144}$$

Tab. 15: Fuel input and power output 24 hours/day heating worksheet

Part load (%)				Net electrical power output (kWh/day)			Gross fuel input (kWh/day)		
A	B	C	D	E1	E2	E3	F1	F2	F3
x	Nearest value above x x_U	below x x_L	$\frac{(x - x_L)}{(x_U - x_L)}$	at x_U	at x_L	at x	at x_U	at x_L	at x
2.5%	x1	0		E_0	E_{x1}		F_0	F_{x1}	
10.0%									
20.0%									
30.0%									
40.0%									
45.5%									
51.0%									
61.0%									
66.5%									
72.5%									
83.0%									
94.0%									
100%	n/n	n/n	n/n	n/n	n/n	E_{100}	n/n	n/n	F_{100}

n/n – not necesessary

- Regime 2

  It is possible to estimate the fuel input and net electricity generated when running at full output for 16 hours:

$$F_{66.5\%} = 16/24 \times F_{100} + 8/24 \times F_0 \qquad E_{66.5\%} = 16/24 \times E_{100} + 8/24 \times E_0 \tag{145}$$

  Following this, the procedure to complete the corresponding table is identical to that used in regime 1. Loads above 66.5% of the maximum daily output are assigned a value of zero because they are considered impossible under 16-hour operation, requiring more hours.

- Regime 3

It is possible to estimate the fuel input and net electricity generated when running at full output for 11 hours:

$$F_{45.5\%} = 11/24 \times F_{100} + 13/24 \times F_0 \qquad E_{45.5\%} = 11/24 \times E_{100} + 13/24 \times E_0 \tag{146}$$

Following this, the procedure to complete the corresponding table is the same as was utilized in regime 1. Loads above 45.5% of the maximum daily output are assigned a value of zero because they are considered impossible under 11-hour operation, requiring more hours.

- Regime 4

  The fuel input and net electricity generated at the maximum load of the unimodal and bi-modal operation can be estimated as follows:

$$F_{45.5\%} = 11/24 \times F_{100} + 13/24 \times F_0 \qquad E_{45.5\%} = 11/24 \times E_{100} + 13/24 \times E_0 \tag{147}$$

$$F_{66.5\%} = 16/24 \times F_{100} + 8/24 \times F_0 \qquad E_{66.5\%} = 16/24 \times E_{100} + 8/24 \times E_0 \tag{148}$$

  Following this, the procedure to complete the corresponding table is identical to that used in regime 1.

Fuel consumed and electricity generated summation

The worksheet presented in Tab. 16 can be completed by copying the values for the fuel input and electrical output, both of which are calculated in columns F3 and E3 of Tab. 15 for the table of the selected regime. Through selecting table A1, A2, A3, or A4 in appendix A of [58], chosen according to the specified test regime, the number of days at part-load for each value of *PSR* can be found. A separate table is required for each of the four values of *PSR*.

Tab. 16: Worksheet for fuel used and electricity generated due to space heating

Column A	Column B	Column C	Column D	= B x D	= C x D
Part-load	Fuel input (gross) (kWh/day)	Net electrical output (kWh/day)	Number of days at part load	Total fuel used (gross) (kWh)	Total net electricity generated (kWh)
2.5%					
10.0%					
20.0%					
30.0%					
40.0%					
45.5%					
51.0%					
61.0%					
66.5%					
72.5%					
83.0%					
94.0%					
100.0%					
TOTALS:			243	F_T =	E_T =

Auxiliary requirements

For space heating auxiliary requirements, the number of load hours, N_{h1} and N_{h2}, can be located from one of the tables (A1–A4), according to specific test regime. N_{h2} is the number of hours each year during which the MCHP operates at full load, including hours during which the maximum capacity is exceeded. N_{h1} is the number of hours during which the MCHP operates at full load without thermal integration. Consequently, the auxiliary thermal energy for space heating can be expressed as:

$$Heat_{aux} = (N_{h2} - N_{h1}) \times Q_{100} / 24 \quad (149)$$

With regards to the auxiliary water heating requirement for the hot water service, HW_{aux}, it can be considered equal to 0 if the package provides DHW for the whole year, or equal to 2961 kWh if the package does not provide hot water service.

It is assumed that direct-acting electric heaters are used to supply any auxiliary heating that is required.

Concerning auxiliary electricity, $Elec_{aux}$ refers to the consumption by components within the heating system other than the MCHP package. It is equal to 0 if the electricity generated is offset by an internal water circulator, or is considered equal to 130 kWh/year if the electricity generated is not off-set by an internal circulator, or no internal circulator is present.

Fuel and electricity during the summer season

If the package provides DHW service for the whole year:

$$Fuel_{sum} = 113 \times F_W \quad Elec_{sum} = 113 \times E_W \quad Heat_{sum} = 113 \times Q_{Wa} \tag{150}$$

where F_W, E_W, and Q_{Wa} are fuel input, electrical output, and thermal output during the DHW test, respectively; 113 is the product of the number of days in summer (122) and a scaling factor (0.927).

If the package does not provide hot water service, the above three quantities are assumed to be zero.

Fuel and electricity in the heating season

The fuel consumption and net electricity generated in the heating season are:

$$Fuel_{hs} = F_T \times \left(1 + \frac{Heat_{hs,hw} + 0.67 \times Heat_{hwstbylab}}{(Q_{100} / 24) \times N_{h1}}\right) \tag{151}$$

$$Elec_{hs} = E_T \times \left(1 + \frac{Heat_{hs,hw} + 0.67 \times Heat_{hwstbylab}}{(Q_{100} / 24) \times N_{h1}}\right) \tag{152}$$

$Heat_{hs,hw}$ is the energy content of the hot water drawn during the heating season; it is equal to 225xQ_{Wa} for regular and combination packages, and is equal to 0 if DHW is not provided.

$Heat_{hwstbylab}$ is the daily heat generated in the laboratory featuring an external indirect cylinder (117 liter) multiplied by 365 days/year for regular packages. It is equal 0 for combination packages and if DHW is not provided. F_T and E_T are the total fuel used and the total net electricity generated; both are expressed in kWh.

Seasonal Performance Index (HPER)

The *HPER* is defined as:

$$HPER = \frac{CO_{2,Fuel} + CO_{2,El}}{Heat_{gen,HP}} \tag{153}$$

where $CO_{2,Fuel}$ is the product of the annual fuel consumed per carbon intensity factor of the fuel. $CO_{2,El}$ is the product of the annual net electricity consumed per carbon intensity factor for electricity (it is negative if the electricity generated is higher than that consumed by the package). $Heat_{gen,HP}$ is the annual heat generated for heating and hot water (if any). It excludes heat loss from an external hot water store but includes any heat losses resulting from secondary heating or hot water heating.

$$Heat_{gen,HP} = \frac{Q_{100}}{24} N_{h1} + Heat_{hs,hw} + Heat_{sum} + HW_{aux} + Heat_{aux} \tag{154}$$

The *HPER* can be calculated in kg_{CO2}/kWh as follows:

$$HPER = \frac{(Fuel_{sum} + Fuel_{hs}) \times CIF_{Fuel} + Elec_{conHP} \times CIF_{El}}{Heat_{gen,HP} / X} \tag{155}$$

where the carbon intensity factor (CIF_{Fuel}) is provided in Tab. 17.

Tab. 15: Carbon intensity factors [58]

Energy Carier	**Carbon Intensity Factor [kg/khW]**
Gas	0.194
LPG	0.234
Fuel Oil	0.265
Electricity (supplied by public grid)	0.422
Electricity (displaced from the public grid)	0.568

$Elec_{conHP}$ is given by

$$Elec_{conHP} = -Elec_{hs} - Elec_{sum} + HW_{aux} + Heat_{aux} + Elec_{aux} \quad (156)$$

If it is negative, it is appropriate to use the *CIF* for the electricity displaced from the public grid. If it is positive, the *CIF* for the electricity supplied by the public grid is appropriate.

Concerning the parameter *X*, calculating the *HPER* requires the heat output necessary to keep the building warm within the heating hours assumed by the SAP (77 hours/week, 11 hours/day on average). Some packages may operate outside these hours. This is catered for by an extended heating factor (*X*), which is outlined in Tab. 18..

Tab. 18: Extended heating factor, *X* [58]

24 hours/day heating	1.289
16 hours/day heating	1.109
11 hours/day heating	1
mixed eating	Table A4

The *HPER* must be calculated for each of the four values of *PSR*.

In summary, the method refers to the energy flows that can be observed in Fig. .

Lower values of *HPER* indicate lower emissions, and better overall thermal and electrical performance. Negative values are considered to be best. Some sample values are provided in Tab. 19.

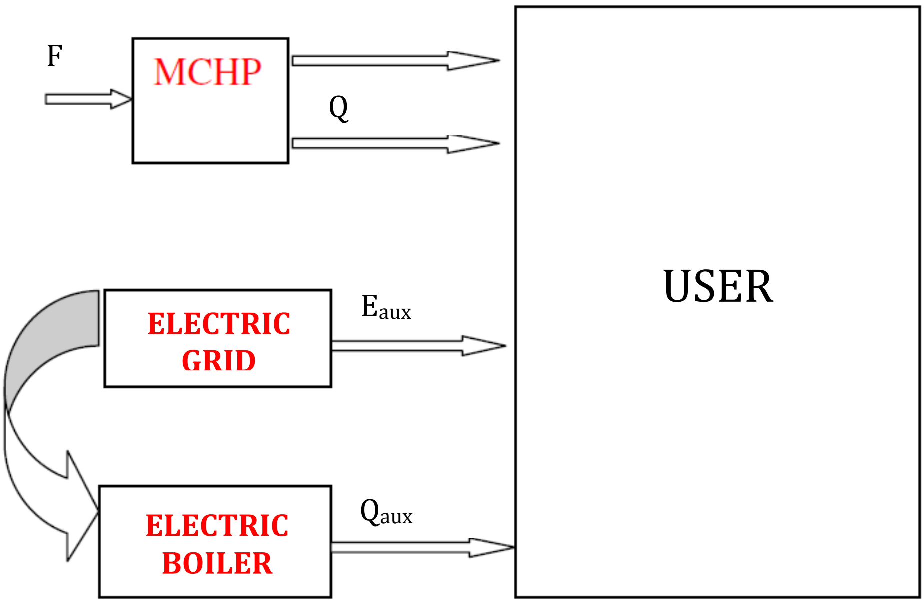

Fig. 35: Energy flows for the APM method

Tab. 19: Example values of HPER

Description (11 hours heating unless specified otherwise)	***HPER* [$kgCO_2/kWh$]**
Cogenerator with 70% thermal efficiency and 20% electrical efficiency	-1.018
Cogenerator with 50% thermal efficiency and 20% electrical efficiency	0.161
Boiler with an average thermal efficiency of 100%	0.194
Boiler with an average thermal efficiency of 90%	0.216
Boiler with an average thermal efficiency of 70%	0.307

5 Recommendations and conclusions

In this chapter, several existing national calculation methods for small-scale cogeneration and polygeneration systems have been described, with the aim of identifying a common approach that the Annex 54 participants could apply in their country-specific performance-assessment studies.

From the reviewed methodologies, it was concluded that the 3-E analysis is the most suitable for this purpose; this is because it is a comprehensive yet simplified approach facilitating the comparison of the energy, environmental, and economic performance of a micro-generation system with those of a reference system. In fact, the 3-E analysis has the following favourable characteristics in comparison with the other methodologies analysed in this chapter:

- it is based on a consolidated approach, based on a comparison with a benchmark case following the EU Directive 2004/8/EC and the Italian methodologies used to calculate white certificates for cogeneration systems;
- it uses a few, simple parameters that are very familiar to those already known and understood by the Annex 54 research groups;
- it is a very general methodology and is not strictly related to detached houses or district heating and cooling systems, unlike the Japanese methods; consequently, it can be used for any application (individual buildings, clusters of buildings connected via a local electric grid, district heating and cooling networks, etc.);
- it is not based on a single criteria, unlike the UK “Quality Assurance for Combined Heat and Power” and “Method to evaluate the annual energy performance of micro-cogeneration heating systems in dwellings” methods, which are only based on energy and environmental parameters, respectively;
- it introduces a simplified economic analysis.

Further work is still needed with regards to performance assessment in terms of the following issues:

- emission reductions are very often calculated considering standard emission factors, which are based on the carbon content of each fuel. These cover all the CO_2 emissions that occur owing to energy consumption, either directly through fuel combustion or indirectly via fuel combustion associated with electricity and thermal/cooling energy usage.

  However, many authors have addressed the evaluation of micro-generation systems through LCA tools, using emission factors that take the overall life cycle of the energy carrier into consideration (exploitation, refinery, transport, processing, and final combustion). This approach should be preferred for the environmental assessment of small-scale trigeneration systems that exploit renewable energy sources when certain LCA emission factors are available;
- the specific equivalent CO_2 emissions factor for electricity that is often used in calculations is the grid-average emissions rate, which is calculated by dividing the total CO_2 emissions from electricity generation by the amount of electricity produced (or consumed).

However, the change in the electricity-generation profile caused by some interventions (such as the installation of a natural gas cogenerator or a PV system) does not act upon all generators of the electricity system. Specific generators respond to these changes according to their dispatching priority, and it is the CO_2 intensity of these generators that dictates the actual CO_2 reduction achieved. The corresponding emission factor is called the marginal emissions factor; it is a function of the specific CO_2 intensity of the individual generators that respond to that change;

- local emissions of micro-generation systems (NO_x, CO, SO_x and PM) should also be taken into account;
- finally, more precise and accurate data regarding the costs of micro-generation systems are necessary in order to perform more realistic evaluations of their economic feasibility.

Nomenclature

a	discount rate,
A	collector area, m^2
C	carbon emission value, $kgCO_2$
CIF	Carbon Intensity Factor, $kgCO_2/kWh$
CO_2	CO_2 emissions, $kgCO_2$
COP	Coefficient Of Performance,
c_p	isobaric specific heat capacity, kWh/kg or kJ/kg
DE	Delivered Energy, MJ or kWh
E_0	net electrical energy generated during standby operation, kWh/day
EC	Extra Cost, € or $
EER	Energy Efficiency Ratio,
EI	Electric Index,
EIHR	Electrical Incremental Heat Rate,
$Elec_{aux}$	auxiliary electricity, kWh/year
$Elec_{conHP}$	annual electricity generated, kWh/day
Elec	electrical output, kWh/year
E_s	adjusting factor, GJ/y
ESEER	European Seasonal Energy Efficiency Ratio,
E_{x1},E_{x2},E_{100}	net electrical energy generated under part-load conditions 10, 30, and 100%, kWh/day
EW	net electrical power during the DHW test, kWh/day
F_0	fuel input during standby operation, kWh/day
f_T	conversion factor from MWh to tep, tep/MWh
FESR	Fuel Energy Saving Ratio,
F_k	yearly Cash Flow, € or $
Fuel	fuel consumption, kWh/year
F_{x1}, F_{x2}, F_{100}	fuel input, measured by gross calorific value, under part-load conditions 10, 30, and 100%, kWh/day
F_W	fuel input during the DHW test, kWh/day
G	solar radiation intensity, W/m2, or number of days in a month,
GWP	Global Warming Potential, $kgCO_2$,equivalent
h	enthalpy, kJ/kg, or hours, h
$Heat_{aux}$	auxiliary thermal energy for space heating, kWh/year
$Heat_{gen,HP}$	annual heat generated for heating and hot water, kWh/day
$Heat_{hs,hw}$	energy content of the hot water drawn in the heating season, kWh/year
$Heat_{hwstbylab}$	daily heat generated in the laboratory due to an external indirect cylinder. kWh/day
$Heat_{sum}$	thermal output during the summer season, kWh/year
HPER	Heating Plant Emission Rate, kgCO2/kWh
HR	Heat Rate,
HW_{aux}	auxiliary water heating requirement for the hot water service, kWh/year
IRE_{mod}	modified version of an Italian energy saving index,
IRR	Internal Rate of Return,

k	parameter that takes into account the efficiency reduction of a CHP during start-up and cool-down period,
K	generic energy quantity for emissions calculation, kWh, or correction factor for white certificate calculation,
LHV	Lower Heating Value, kWh/kg or kWh/Sm3
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
n	number of years,
N	number of load hours per year, h/year
NE	Net Energy, MJ or kWh
NPV	Net Present Value, € or $
NS	Net Saving, toe
OC	Operating Costs, € or $
OE	Output Energy, MJ or kWh
p	correction coefficient of daily excursion temperature, -
P	Power, kW
PE	Primary Energy, MJ or kWh
PEF	Primary Energy Factor,
PER	Primary Energy Ratio,
PES	rimary Energy Saving,
PHR	Power to Heat Ratio,
PI	Profitability Index,
PLR	Partial Load Ratio,
PSR	Plant Size Ratio,
Q	thermal energy, MJ
QI	Quality Index,
Q_{x1},Q_{x2},Q_{100}	eat output to space heating under part-load conditions 10, 30, and 100%, kWh/day
Q_{Wa}	heat content of the hot water drawn during the DHW test, kWh/day
R	ratio of electric appliance in total electricity consumption,
RE	Renewable Energy generated on the building premises, MJ or kWh
r_e	share of MCHP electric energy output used in electrically driven cooling equipment
r_t	share of MCHP thermal energy output used in thermally driven cooling equipment
SCOP	Solar Coefficient Of Performance,
SCR	Solar Cooling Ratio,
SEER	Seasonal Energy Efficiency Ratio,
SHF	Solar Heat Fraction,
SPB	Simple Pay Back period, years
SS	Spark Spread,
t	time, s
T	temperature, °C
TIHR	Thermal Incremental Heat Rate,
TSS	Total Supply Spread,
UP	Unitary Price, €/kWh, €/kg, €/Sm3, $/kWh, $/kg, or $/Sm3
X	extended heating factor or coefficient related to alternative power supply options in "The UK Quality Assurance for Combined Heat and Power" methodology, or fraction of thermal energy provided by the CHP,

XE	exported energy, MJ or kWh
Y	coefficient for heat generation related to alternative heat supply options in “The UK Quality Assurance for Combined Heat and Power” methodology (see section 4.6),

Acronyms

ADHP	Adsorption Heat Pump
AHP	Absorption Heat Pump
AS	Alternative System
BAT	Best Available Technology
CCHP	Combined Cooling Heat and Power system
CHP	Combined Heat and Power system
CHPQA	K Quality Assurance for Combined Heat and Power
CS	Conventional System
DCS	Desiccant Cooling System
DHC	District Heating and Cooling
DHW	Domestic Hot Water
DW	Desiccant Wheel
EC	Evaporative Cooler
EHP	Electric Heat Pump
GHG	Green House Gas
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor-Air Quality
LCA	Life Cycle Analysis
LHV	Lower Heating Value
MCHP	Micro Combined Heating and Power system
TCS	Thermally activated Cooling System
THP	Thermally driven Heat Pump
WC	White Certificates

Greek symbols

α	fuel-to-thermal energy ratio for a conventional boiler, GJ/GJ, or index of adequacy of the storage tank,
β	fuel-to-electric energy ratio for electric grid, GJ/GJ
δ, Υ	coefficients used by UNI/TS 11300-4 to define normalized performance curves,
Δ	difference
$\Delta CO_{2,eq}$	avoided equivalent CO_2 emissions,
ξ	selling price, €/kWh or $/kWh, or allocation factor,
η	efficiency,
θ_p	conversion coefficient of electricity, GJ/GJ
λ	cogeneration Ratio,
μ	specific emission factor, kg_{CO2}/kWh
ψ	surplus factor,

Subscripts

a	artificial
AS	Alternative System
avg	average

bal	balance
conv	conventional
Cool	cooling
CO2	carbon dioxide
CO2,eq	equivalent carbon dioxide
CS	Conventional System
cw	cooling water
day	daily basis
DE	Delivered Energy
DHW	Domestic Hot Water
El	electric
eq	equivalent
Fuel	fuel primary energy
GC	Green Certificates
glo	global
h	generic hour of day
hs	heating season
hw	hot water
in	electricity in
loc	local
max	maximum
min	minimum
mon	monthly basis
NG	Natural Gas
nom	nominal
out	electricity out
PE	Primary Energy
peak	peak thermal power
proc	process
QFI	Qualifying Fuel Input
QHC	Qualifying Heat Capacity
QHO	Qualifying Heat Output
QI	Quality Index
QPC	Qualifying Power Capacity
QPO	Qualifying Power Output
R	return
ref	reference value
reg	regeneration
rh	room heating
S	supply
SH	Space Heating
sorpt	sorptive
sum	summer season
Sun	Sun
TFI	Total Fuel Input
Th	thermal

tot	total
TPC	Total Power Capacity
TPO	Total Power Output
VW	Value-Weighted
waste	waste heat
wh	water heater
year	annual basis
z	generic pollutant

Superscripts

AHP	Absorption Heat Pump
aux	auxiliaries
CCHP	Combined Cooling Heating and Power
chil	chiller
CHP	Combined Heat and Power
DCS	Desiccant Cooling System
DHC	District Heating and Cooling
DW	Desiccant Wheel
EHP	Electric Heat Pump
GB	Gas Boiler
Grid	electric grid
HVAC	Heating Ventilation and Air Conditioning
MCHP	Micro Combined Heat and Power
SC	Solar Collectors
ST	Storage Tank
THP	Thermally driven Heat Pump

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Background Information

International Energy Agency

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

The IEA Energy in Buildings and Communities Programme

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

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

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

The Executive Committee

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

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)

Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)

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

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

(*) – Completed

Annex 54

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

Scope of activities

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

Outcomes

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

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

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

Subtask A - Technical Development

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

Subtask B - Performance Assessment

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

Subtask C - Technically Robust Mechanisms for Diffusion

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

Research Partners of Annex 54

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