Synthesis Report on the Viability of Micro-Generation Systems in Different Operational Contexts

Energy in Buildings and Communities Programme

October 2014

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

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On behalf of IEA EBC Annex 54

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Maurizio Sasso (Subtask B Leader), Evgueniy Entchev, Peter Tzscheutschler (Operating Agents)

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1 Introduction

The aim of Annex 54 “Integration of Micro-Generation and Related Energy Technologies in Buildings” of the International Energy Agency is the analysis of the micro-generation performance in buildings. Within this context, ‘micro-generation’ refers to different low-carbon technologies providing power, heating, and/or cooling to buildings and/or district heating and cooling networks. These technologies include combustion engines and fuel cell-based cogeneration and polygeneration systems, as well as renewable-energy technologies. Micro-generation technologies can be deployed individually or in combination (so-called hybrid systems).

Subtask B of Annex 54 mainly focused on the applications and performance assessment of microgeneration in individual residences, multi-residences, and small commercial buildings. The scope of the work was also expanded to encompass mobile energy systems such as plug-in hybrid electric vehicles (PHEV) and more conventional EVs, as they can provide important flexibility through demand-side management.

In the framework of Subtask B, contributing groups developed (mainly by simulation) a library of country-specific simulations, experimental, and field-test studies, covering several technology types and combinations, climatic conditions, and end-users. These studies evaluated the performance of different microgeneration configurations (hybrid, poly-generation, etc.) within different operational contexts: systems that are dimensioned/optimised and controlled using algorithms and optimisation approaches developed within Subtask A of Annex 54 resulting in country-specific performance-related data.

The aim of this report is therefore to highlight the main results of the microgeneration system-performance assessments carried out in the country-specific studies, as well as in other analyses developed by Annex 54 participating countries and presented at the Microgen III conference[1].

This report is therefore divided in two main parts: in the first part (chapter 2), a review of the country-specific simulations, experimental, and field test studies is performed, with the aim to identify generic factors and performance trends (i.e., not country-specific) affecting the viability of microgeneration systems. This review required the establishment of common reference points for the comparison of performances, requiring agreement on common performance assessment methodology and metrics, as defined in [1]. This report [1] provided a possible methodology, but different valid and clearly defined approaches and criteria in the individual studies were chosen, as well.

In the second part (chapter 3) are described the studies performed by Annex 54 participating organisations and presented at the Microgen III conference. Finally, in chapter 4, some “common rules of thumb” for the appropriate deployment of microgeneration technologies in buildings and

[1]Microgen III, the 3rd International Conference on Microgeneration and Related Technologies, 15–17 April 2013, Naples, Italy.

communities are identified, as derived in chapters 2 and 3. Other issues of microgeneration, such as the impact on existing electrical systems and the optimal utilisation of microgeneration—encompassing approaches to control, related technologies such as energy storage (including hybrid vehicles), and demand-side control—are widely explored in [2].

2 Review of Country-specific Simulations, Experimental, and Field Test Studies

2.1 Overview

Six performance-assessment studies were developed by the following Annex 54 participating groups:

Japan
Korea/Canada
Italy – Second University of Naples
Italy – Università eCampus, Università Politecnica delle Marche
Italy – Università del Sannio
Canada

In Tab. 1 an overview of the devices, applications, criteria, and tools analysed within the country-specific performance-assessment studies is reported. The most analysed microcogeneration device is the internal combustion engine, followed by the different types of fuel cells (SOFC, PEFC, and PEMFC). Only one study deals with the Stirling engine. Therefore, in all studies, natural gas is considered as fuel. In terms of control of the cogeneration system, thermal following operation mode is analysed in all reports, except in the study from Politecnica delle Marche that focuses on economic and environmental criteria. The Second University of Naples investigated in addition the electric following approach.

As regards other energy-conversion devices involved in the microgeneration system, almost all studies introduce a thermal storage tank, in most cases a combined storage for domestic hot water preparation and space heating. The auxiliary heater is a gas burner in all country-specific studies; furthermore, the microgeneration system is connected to the electric grid to draw the shortage or to sell the surplus, except in Japan where surplus electricity generated by cogeneration cannot be sold to electricity utilities. For this reason, the electricity surplus is used for electric water heating in the Japanese study.

A renewable energy technology is considered in three of the received contributions, namely solar energy: solar collectors (NRC/CANMET), PV (Politecnicodelle Marche/e-Campus), and photovoltaic-thermal (KIER). A cooling/heating device is considered in four studies, mainly an electric heat pump. Thermally activated cooling systems are also considered: an absorption heat pump and a desiccant wheel, investigated by Politecnico delle Marche/e-Campus and Università degli Studi del Sannio, respectively. Mobile energy systems (plug-in hybrid electric vehicles) are investigated only by Second University of Naples.

Tab. 1: Overview of country-specific performance assessment studies

ST B Country specific performance assessment studies			NRC/CANMET	2nd University of Naples	Università degli Studi del Sannio	Osaka University	KIER	Politecnico delle Marche/e-Campus
Cogensystem	Cogeneration devices	SOFC				■		
		PEFC				■		
		PEMFC					■	
		Stirling	■					
		ICE		■	■	■		■
		Other					■	
	Fuel	Natural gas	■	■	■	■	■	■
		Other				■		
	Energy management, Control	Electric following		■				
		thermal following	■	■	■	■	■	
		Economic criteria following						■
		environmental criteria following						■
Other energy conversion systems	Storage	domestic hot water (DHW) storage				■	■	
		Space heat storage						■
		Combined storage DHW - space heat	■	■	■		■	
		Other					■	
	Auxiliary heater and electricity	Gas burner	■	■	■	■	■	■
		Electric heating				■		
		Grid connected	■	■	■	■	■	■
	Renewable Energy Technology	Solar collectors	■					
		PV						■
		Other					■ -	
	Cooling-Heating device	Absorption Heat Pump						■
		Electric Heat Pump				■	■	■
		Desiccant Wheel			■			
		Ground Source Heat Pump					■	
	Mobile energy systems	Plug-in Hybrid Electric Vehicles		■				

Tab. 2: Overview of country-specific performance assessment studies (continued)

ST B Country specific performance assessment studies			NRC/CANMET	2nd University of Naples	Università degli Studi del Sannio	Osaka University	KIER	Politecnico delle Marche/e-Campus
Building	Type	SFH	■			■	■	
		MFH		■		■		
		Small office building			■		■	■
		Other			■			■
	Energy level	Average	■		■		■	
		Low energy		■				
		Other				■		
	Heat (cold) distribution	Air heating/cooling	■	■	■		■	
Boundary conditions	Climate	Climatic Zones	■	■			■	
	Electricity generation mix	Power Plant mix		■	■	■		■
		Best Available Technology	■		■			
	Energy price	Electricity		■	■	■		■
		Fossil fuel		■	■	■		■
Criteria		Energy	■	■	■	■	■	■
		Environmental	■	■	■	■		■
		Economic		■	■	■		■
Tools	Simulation	TRNSYS	■	■	■		■	
		Matlab/Simulink						■
		Other				■	■	

Different types of buildings have been considered in the country-specific studies, almost equally distributed between single-family homes (SFH), multi-family homes (MFH), and office buildings. Average is the most diffused energy level, in terms of energy consumption of the building, with an air heat/cold distribution system (namely fan coils and air handling units).

The effect of climatic conditions on the investigated microgeneration system has been evaluated in three country-specific studies, considering the installation of the system in different climatic zones. A fixed location has instead been assumed in the other reports.

As regards the reference system based on separate production used for comparison purposes with the performance of the microgeneration system, in most cases the "national power plant mix" approach has been used. In two studies the best available technology is also used. In all studies an energy performance of the system is performed, while the environmental and economic analysis is missing in one and two reports, respectively. Finally, the most used simulation software is TRNSYS.

2.2 Japan

2.2.1 Summary

A performance assessment study was performed for a number of micro combined heat and power (MCHP) generation systems in residential buildings in Japan [3]. The authors developed a residential energy end-use simulation model in which the entire household stock is classified into several categories according to a number of criteria that directly affect energy consumption. This model can be used to estimate all of the demand profiles, including hot water and electricity, for each household category, at five-minute intervals. Furthermore, household types are divided into detailed categories in order to account for the variation among households. These features allow the evaluation of the potential contribution of MCHP systems to energy conservation and global-warming mitigation.

The strong focus on demand profiles is due to two considerable differences in the utilisation of cogeneration between Japan and other countries, such as European countries:

- surplus electricity generated by cogeneration can be sold to electricity utilities in Europe, while this is not allowed in Japan;
- the heat recovered from cogeneration can be utilised for both space heating and water heating in Europe, but recovered heat can only be utilised for water heating in Japan. This is because a central heating system is not usually employed in Japanese households.

These two restrictions on the utilisation of cogeneration in Japan need a careful attention to the demand profile of households in the investigation of the performance of cogeneration; the energy, economic, and environmental performance of cogeneration varies significantly with the demand profile for electricity and heat.

The performance in terms of primary energy consumption, CO_2 emission, and cost was analysed for different cogeneration technologies already commercialised in Japan, namely natural gas-fuelled internal combustion engines (MGE), polymer electrolyte membrane fuel cells (PEFC), and solid oxide fuel cells (SOFC). Conventional systems and condensing water heaters (LHB) were also evaluated as references.

These systems were examined for 19 household categories (that differ in number of household members, family composition, and number of employed household occupants), 12 building types (6 categories for detached houses and 6 categories for apartment houses, according to floor area), and four different thermal insulation levels. It is concluded that the performance of the cogeneration system strongly depends on household type (number of household members). The difference in the primary energy saving among household categories for the PEFC and SOFC systems is large compared to LHB and MGE systems. In particular, the energy-saving effect of PEFC strongly depends on household type since the operation time is affected by the amount of hot water consumption.

SOFC generates about two-thirds of the total electricity consumption and shows the highest energy reduction rate and CO_2 reduction rate from the baseline, which is 14–20% in primary energy and 19–23% in CO_2 emission reduction rate for families with more than two members. PEFC generates electricity smaller than SOFC and the energy saving ratio is affected by household types strongly.

2.2.2 Performance criteria used

The following indicators were used to evaluate the performance of the different MCHP systems.

Primary energy consumption

Electricity consumption is converted to primary energy consumption by considering the power generation efficiency using a factor of 9,760 kJ/kWh. The HHV of natural gas and kerosene is directly used to assess primary energy consumption.

CO_2 emissions

CO_2 emissions induced by energy consumption are calculated using the following emission factors provided by the Japanese Ministry of Environment: 0.559 $kgCO_2$/kWh for electricity, 50.8 $kgCO_2$/GJ for natural gas, 68.0 $kgCO_2$/GJ for kerosene.

Cost

The economic performance of the MCHP system is evaluated as the net present value (NPV) considering the initial cost of the cogenerator, the annual running cost reduction from baseline case, and the discount rate (3%).

2.2.3 Description and characteristics of system components

Simulation models for conventional and cogeneration systems are developed. In these models, the efficiency of each system is defined based on the manufacturer's design value. Kuroki et al. [4] also used design values and both values are compared.

Conventional water heaters

As a baseline for the study, conventional instant gas water heaters are used. The efficiency of a conventional instant gas water heater is set at 78% as higher heating value (HHV). This reference value is based on the approach of the national technological mix, as it represents the average efficiency of conventional water heaters installed in Japan. If the baseline value changes — for example, it may increase because of a technological improvement of the installed units — the calculation of the savings, in terms of primary energy consumption, CO_2 emissions, and costs, achieved by MCHP systems and the related overall conclusions should be updated.

Condensing gas water heater (LHB)

This unit employs a secondary heat exchanger to recover latent heat from the exhaust gas. The thermal efficiency of such a system is 95%, based on HHV.

Micro gas engine cogeneration system (MGE)

The MGE consists of a micro gas engine power-generation unit, a waste heat-recovering water-heating unit, an electricity resistance water heater, an auxiliary gas water heater, and a hot-water storage tank. The MGE produces electric power and hot water using natural gas. The rated power generation efficiency is assumed to be 23.7% and the waste-heat recovery efficiency is 59.3% ([4], based on HHV). Since the generation efficiency of an MGE system decreases during part-load operation, the MGE is generally operated at the rated capacity. When the electric power generated by an MGE system is larger than the electricity demand of the house, the residual is used by the electric resistance heater to generate hot water. The operation of an MGE system depends on the hot water demand; when the hot water demand exceeds the production capacity of the MGE, an auxiliary gas water heater makes up for the shortage. The model used for the MGE employs the same conditions used for the systems described above. The power generation capacity is assumed to be 1 kW in the model.

Obviously, electric and thermal efficiencies of a MGE depend on the unit and its size; for example, there are other MCHP devices based on natural gas-fired internal-combustion engines that have electric efficiencies up to about 30%. Therefore, the results and the overall conclusion on the feasibility of MCHP systems strongly depend on the investigated unit and its performance.

Polymer electrolyte fuel cell cogeneration system (PEFC)

A PEFC system consists of a reformer that transforms natural gas into hydrogen, a fuel cell that generates electric power from hydrogen using a proton exchange membran, a water heating unit that transfers the heat recovered from the fuel cell to the water, an electrical-resistance water heater, an auxiliary gas water heater, and a hot-water storage tank. The rated power generation efficiency is assumed to be 35.2%, while waste heat recovery efficiency is 50.6% (HHV). Kuroki et al. [4] uses 33% and 45%, respectively. To extend the reformer lifetime, the PEFC is usually operated in a daily start-and-stop mode at one of four output levels (25, 50, 75, and 100%) of the rated capacity. The output level is determined by electric power demand. Similar to the MGE system, when the electricity generated exceeds the electricity demand, the residual power is utilised by the resistance water heater. When the amount of hot water produced is less than the hot water demand, the auxiliary gas water heater makes up for the shortage. The model used for the PEFC follows the operating conditions described for the systems above. The power generation capacity is 750 W. The PEFC system is operated when the electricity demand exceeds 25% of the rated capacity of the PEFC.

Solid oxide fuel cell cogeneration system (SOFC)

A SOFC system consists of a reformer, a fuel cell using an solid oxide or ceramic electrolyte, a waste heat recovery unit, an auxiliary gas water heater, and hot-water storage tank. The SOFC is assumed to have a power generation efficiency of 42%, which is higher than a PEFC, and a waste-heat recovery efficiency of 39.2% (HHV). Kuroki et al. [4] used 41% and 36%, respectively. The SOFC is usually operated in response to the demand for electricity due to a low heat-to-power ratio. The rated power generation capacity is 700 W. Fig. 1 shows an example of the simulated daily operation of the SOFC. The electricity generation follows the electricity demand and, because of the low hot-water demand during the morning and afternoon, thermal energy accumulation increases until the very high hot-water demand at about 20:00 when the storage tank is fully exploited.

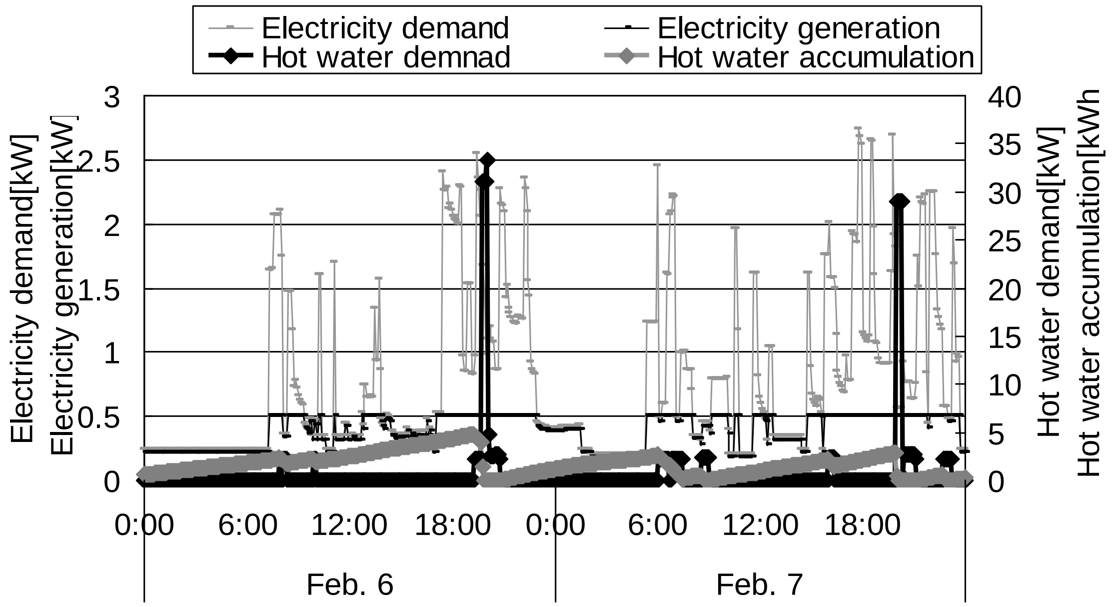

Fig. 1: Example simulation of daily SOFC system operation.

2.2.4 Description of systems

In Japan, hot water generated by micro-cogeneration and other water heaters is used for hot water supply and also used for floor heating in many cases. However, only hot water supply is considered as heat demand of micro-cogeneration and water heaters in this study. All electricity from microcogeneration is assumed to be consumed in the residence. The heat loss ratio of all hot water storage tanks used in this study is assumed to be 16% and that of the house supply pipes is assumed to be 7%.

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

2.2.5 Results

As an example of the obtained results, in Fig. 2 the total annual primary energy consumption for a four-member family is shown.

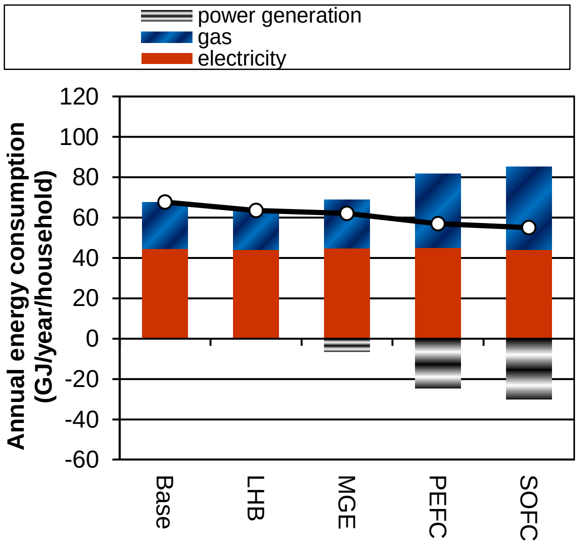

Fig. 2: Total annual primary energy consumption for a four members family.

Negative value means power generation by micro-generation. Total energy consumption is shown as a bold line. The SOFC generates about two-thirds of the total electricity consumption. It also shows the highest energy reduction rate from the baseline, which is 15–20%. PEFC and MGE generate less electricity than SOFC.

Fig. 3 shows the baseline total CO_2 emissions for the residential sector of Osaka City. In addition, data for the cases in which all of the households in Osaka City install LHB, MGE, PEFC, and SOFC systems is also shown. Replacement of all of the water heaters with LHB systems reduces the total CO_2 emissions by 4.4%. The CO_2 reduction effects of cogeneration systems are 8.5% (MGE) to 17.3% (SOFC).

2.2.6 Conclusions

From the Japanese country-specific performance assessment study, the following “rules of thumb” can be derived:

- The energy-saving effects of cogeneration differs with household type;
- Optimal water heating systems exist for each household category, determining differences in terms of primary energy, CO_2 emission, and cost reduction;
- SOFC systems have the highest energy and CO_2 reduction potential. Large-scale introduction of SOFC systems to Osaka city would markedly reduce the primary energy consumption (12.3%) and CO_2 emissions (17.3%);
- To improve the feasibility of small-scale cogeneration systems, they need to be sized according to the electric base load of the user; thus, the electricity is consumed on-site and is

not exported to the grid. Furthermore, the electric and thermal energy demand and supply profiles should adequately match (for example, as in Fig. 1) in order to minimise heat dissipation from the storage tank and thermal integration from the auxiliary heater.

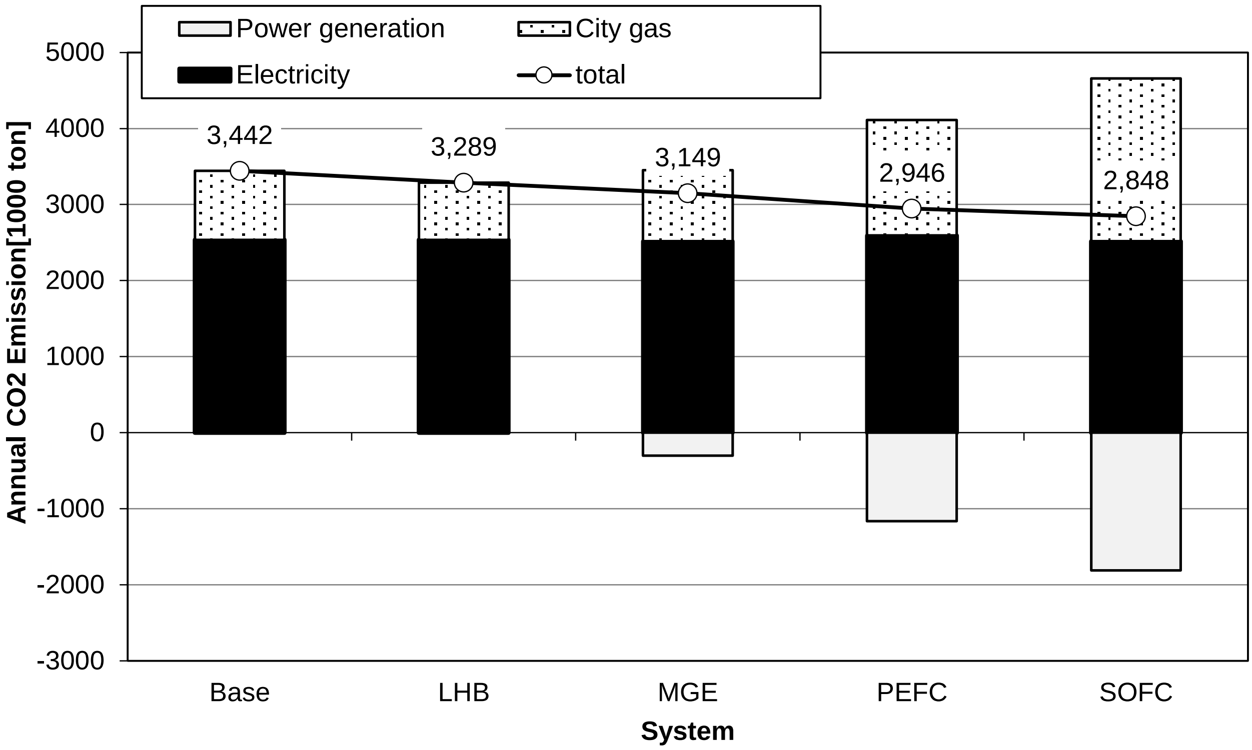

Fig. 3: Annual CO_2 emission of the residential sector of Osaka City using the various cogenerations systems and water heaters.

2.3 Korea/Canada

2.3.1 Summary

This work was developed in the framework of a joint project involving CanmetENERGY Research Centre and Korea Institute for Energy Research (KIER) in which were analysed seven systems with conventional, microgeneration, and renewable energy technologies for applications in residential and commercial buildings [5]:

Case 1: a conventional setup — boiler and chiller to meet heating and cooling demands of a single detached house (200 m^2 floor area).
Case 2: the same conventional set up as Case 1 — boiler and chiller to meet heating and cooling demands of an office building that has the same layout and floor area as the house in Case 1.
Case 3: a simple summation of Case 1 and Case 2 systems and loads.
Case 4: a load-sharing setup featuring a common boiler and chiller used to meet the combined loads of both the house and office.
Case 5: a load-sharing case utilising a ground source heat pump (GSHP) to meet the combined loads.

Case 6: a load-sharing case where a hybrid PEM fuel cell (FC)/ground source heat pump (GSHP) system is used to meet the combined loads.
Case 7: a load-sharing case where a photovoltaic-thermal (PVT)/ground source heat pump (GSHP) system is used to meet the combined loads.

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

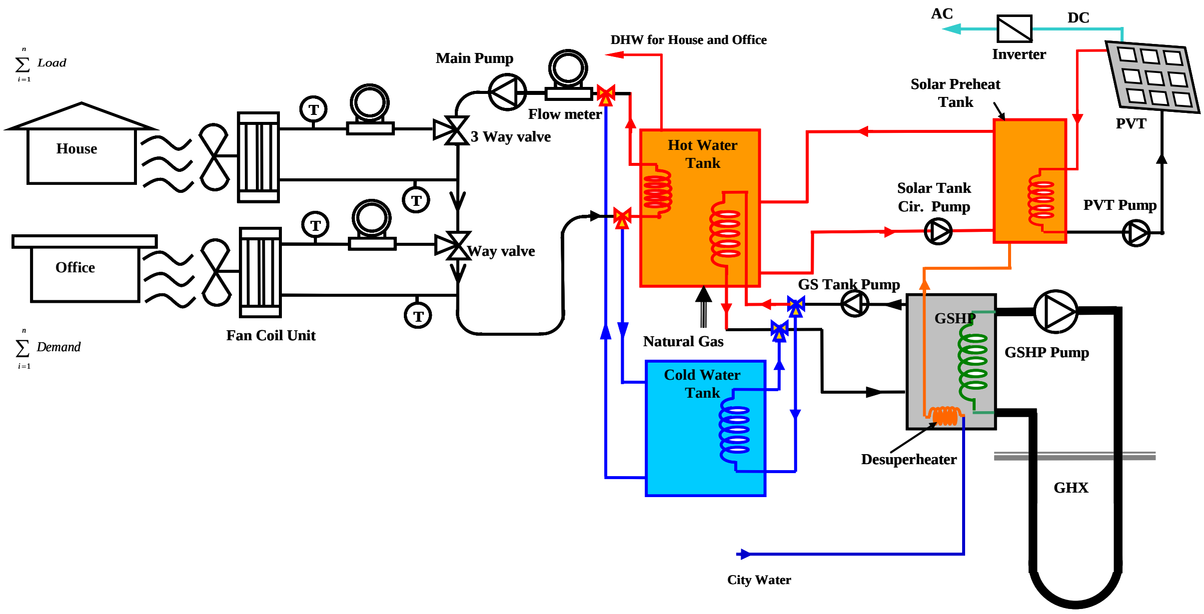

Fig. 4: Layout of case 7.

Detailed simulation models were developed to better understand the performance of different system designs and layouts under various weather conditions and occupants' behaviour by means of the "TRaNsient Systems" (TRNSYS-17) software platform. Component models were selected from the TRNSYS libraries and enhanced with latest manufacturer's system-performance data. Additional models were developed for those components that are not present in the TRNSYS libraries, such as PEMFC (Proton Exchange Membrane Fuel Cell), GSHP (Ground Source Heat Pump) desuperheater, etc. The models were run with Ottawa (Canada) and Incheon (Korea) weather data over a year to simulate and analyse the energy systems' performance while satisfying the buildings heating and cooling demands. Besides that, "Energy Plus" was also used as another commercial software to model and analyse these cases.

2.3.2 Thermal and Non-HVAC Electrical Loads of Studied Buildings

Both thermal and non-HVAC electric loads of the two buildings (residential and office) were analysed through appropriate time-series methodology. The house and office were assumed to be separated from each other with no thermal interaction between them. Both buildings have identical geometries with floor area of 200 m^2 and are assumed as a single interior zone for the simulations. Detailed building models were developed using typical Canadian house/office heating and cooling loads. The domestic hot-water consumption for the house and office were based on ASHRAE-124 recommendations for residential and office building. Non-HVAC electrical load profiles in 15-min intervals for weekdays and weekends were generated for both the house and office based on the "average" consumption of a detached house used for a residential or office purpose in Canada.

2.3.3 Performance of Load Sharing Systems

While the thermal loads occur in the evening through the early morning in residential houses, the thermal loads in offices happen during the daytime. The two thermal loads have opposite profiles. In general, the separated systems are operated at very low partial-load conditions during the day for houses and during the evening for offices. By combining the two opposite loads, the peak thermal demand could be reduced and, as a result, the initial capital cost could be reduced considerably. Moreover, the load sharing system could be operated at higher part load ratios. However whether the load sharing system could result in energy use reduction compared to the separated systems depends on the performance characteristics of the HVAC equipment. Simulations and analyses were carried out to investigate the benefits of the load sharing, as well as the impact of equipment performance characteristics on system energy uses and savings.

2.3.4 Results

The energy-consumption analysis results for the seven case studies are summarised in Tab. 3. The following are summaries drawn from the energy analysis and comparisons between the three load-sharing systems, the hybrid renewable energy systems, and the Reference System.

The consumption of the load-sharing system with separate "production" (Case 4, natural gas boiler + electricity grid) is 173 kWh/m^2 less than that consumed by the Reference Case 3 (178 kWh/m^2); that is a 3% operational energy savings, which mainly resulted from higher equipment efficiency, better partial load performance, as well as less pump and fan energy consumption.
The simulation results for the load-sharing system with GSHP able to meet both thermal and cooling loads (Case 5) showed a total energy consumption reduced to 106 kWh/m^2 and an overall energy savings of 40.6% due to the introduction of a significant renewable component. The net energy consumption is reduced to 132 kWh/m^2 for the hybrid GSHP-PEMFC system (Case 6), with an overall energy savings of 25.8%. The net energy consumption was further reduced to 77 kWh/m^2, the lowest among all the case studies, for the GSHP-PV/T system (Case 7). Compared to the conventional system (Case 3), this indicates an overall energy saving of 56.6% due to the contribution of both geothermal and solar renewable energy.

Further analysis revealed that even higher operational energy savings (15–20%) can be achieved for the load-sharing application with optimal system sizing and appropriate implementation of control strategies. Significant capital cost savings (20–25%) are also apparent; these are due to the reduced equipment size and the optimal distribution and utilisation of system layout. The study on the effect of buildings' U-values and climate on building thermal loads showed that, for the same building specification, the heating and cooling loads under Incheon (Korea) weather conditions are about 0.53 and 1.3 times, respectively, in comparison to Ottawa (Canada) weather conditions.

Tab. 3: Annual Energy Consumption, Production and Savings in kWh for Cases 1–7

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

2.3.5 Conclusions

The first aim of the project was to model and simulate seven systems with conventional and renewable energy technology for single residential and commercial buildings. The aim was to gain a better understanding of the performance of different system designs and layouts under various weather conditions and occupants' behaviour.

The systems were modelled and simulated with Ottawa, Canada weather data for one year using "TRNSYS" software platform for individual and load-sharing case studies. The first and second cases, for the house and office, respectively, use a boiler and a chiller to meet heating and cooling load demands. Case 3 is a simple sum of case 1 and 2 for thermal load and energy consumption. Case 4 used a single-unit boiler and chiller to satisfy the combined thermal demands of the house and office. Case 5 investigated the integration of GSHP system with load sharing. In case 6, a hybrid microgeneration system (GSHP–FC) is studied in a load-sharing application. Finally, case 7 is a load-sharing case where a photovoltaic-thermal (PVT)/ground source heat pump (GSHP) system is used to meet the combined loads.

Besides the results listed in the previous section, the following main conclusions can also be derived from this study:

- In a simple summation of the different loads of the building, aimed at characterising its overall energy consumption and the different contributions, not taking into account any conversion method (such as exergy-based evaluations), space-heating load accounted for the largest share of the total building loads with more than 50% for the house and combined (house + office) and close to 50% for the office. The non-HVAC electrical load was the second, followed by the cooling load, and then the DHW load for the house, office, and the combined house and office.

- The total thermal load for residential and commercial buildings is 154 and 126.4 kWh/m^2, respectively, and 139 kWh/m^2 for load sharing.
- Compared to the Reference Case (Case 3), the load-sharing Case 4 reduced the boiler and chiller capacities by 18% and 25%, respectively. Hence, the initial capital cost could be reduced significantly because of both equipment quantity and capacity reduction.
- The "Energy Plus" simulation results showed a peak heating load reduction of 21% and a peak cooling load reduction of 19% compared to the simple sum of Case 1 and Case 2 (i.e., Case 3). The annual heating and cooling energy savings were 15.9% and 14.6%, respectively.
- Spreadsheet modelling showed that the most efficient microgeneration configuration is PVT-GSHP which consumes only 37.8 kWh/(m^2·y).

2.4 Italy – Second University of Naples

2.4.1 Summary

This work examines the performance of a residential building-integrated microcogeneration system (alternative system) during the heating season by means of building simulation software (TRNSYS), considering the transient nature of building- and occupant-driven loads as well as the partial-load characteristics of the cogeneration unit [6].

The alternative system was based on a natural gas-fuelled reciprocating internal combustion engine-based cogeneration unit (MCHP) with 6.0 kW as rated nominal electric output and 11.7 kW as rated nominal thermal output. Auxiliary thermal energy was supplied by a natural gas-fired boiler; the heat provided by both the MCHP device and the boiler was accumulated within a storage tank. The cogeneration system supplied thermal and electric energy to a multi-family house composed of three floors, compliant with the transmittance values of both walls and windows suggested by Italian Law.

In order to evaluate the influence of the climatic conditions, the analyses were performed by considering the multi-family house located in four different Italian cities (Palermo, Napoli, Roma, and Milano), representative of the different Italian climatic conditions. In addition, a parametric analysis was performed to evaluate the effect of the tank size on the system performance: three different hot-water storage volumes were investigated.

As the economic viability of the cogeneration unit strongly depends also on the economic value of the cogenerated electricity, the system operation was also evaluated by considering two different electric demand profiles: first, the operation of lighting systems and other domestic appliances was considered, while in the second the electric consumption associated with the overnight charging of an electric vehicle was further added.

The energy, environmental, and economic sensitivity analysis were performed with both electric and thermal load-following control strategies of the MCHP. The simulated performance of the MCHP was compared with the performance of a conventional system consisting of a natural gas-fired boiler and to the national electric grid.

2.4.2 Components, building, load profiles and reference system models

Each component of the whole system was simulated using the software “TRNSYS”, where each piece of equipment is modelled with a component named “type.”

MCHP unit

The reciprocating internal combustion engine-based micro-cogeneration unit commercialised by the AISIN SEIKI company was investigated in this study. The main characteristics of this device are reported inTab. 4.

Tab. 4: Main characteristics of the investigated MCHP unit

Model	AISIN SEIKI unit GECC60A2 (NR-P)
Engine type	Reciprocating internal combustion engine, water cooled, 4 cycles, 3 cylinders
Displacement	952 cm^3
Speed revolution	1,600–1,800 rpm
Fuel	Natural gas, LPG
Generator type	Permanent-magnet type, synchronous generator 16 poles
Rated electric output	0.3–6 kW
Heat recovery rate	11.7 kW
Operating sound at 1.0 m distance and 1.5 m height	54 dB
Electric efficiency at maximum load	28.8 %
Thermal efficiency at maximum load	56.2 %

The cogeneration unit was simulated by using the detailed dynamic model developed within Annex 42 of the International Energy Agency [7],[8]. This model is designed to predict primary power consumption, electric power generation, thermal output, coolant outlet temperature, etc., during both steady-state and transient operation. It was calibrated and validated on the basis of laboratory tests performed by the authors at the Built Environment Control Laboratory of the SecondaUniversitàdegliStudi di Napoli (Italy).

Hot water storage

The combined tank for both heating purposes and domestic hot-water production was modelled in this study by means of the "type60f." The tank is divided into N fully-mixed equal sub-volumes; for each sub-volume, mass and energy balances are considered in a transient state, allowing one to be used to calculate thermal stratification in the component. In this study, ten nodes were used in the tank; a uniform tank loss coefficient per unit area equal to 3.0 kJ/(h·m^2·K) was assumed.

A vertical cylindrical hot water storage unit with one flow inlet (from the building) and one flow outlet (towards the fan-coils) was considered. The tank is equipped with three internal heat exchangers: the lower one is connected to the MCHP, the upper one is connected to the natural gas-fired, the third one is used for domestic hot-water production.

Taking into consideration that the selection of the tank volume is very important to optimise the plant performance, its optimal value was determined by carrying out a sensitivity analysis; the whole-system operation with three different commercially available hot-water storages characterised by different sizes were considered: TANK1=0.855 m^3; TANK2=0.738 m^3; TANK3=0.503 m^3.

Boiler

A 20.0-kW$_{th}$ natural gas-fired boiler was considered in this study. The boiler was modelled in TRNSYS by using the "type6" included in TRNSYS library. It is activated only if the water temperature within the tank is lower than 55°C, or when the domestic hot water temperature is lower than 45°C.

The boiler efficiency is evaluated by means of a linear interpolation of the manufacturer data (0.927 at rated output, 0.924 for a part load ratio equal to 30%).

Building

The layout of the building is a multiplication of a single-family house type building geometry. The main geometrical characteristics of each floor and the building orientation are shown in Fig. 5. All three floors have the same useable floor area (96.0 m^2), while the net height of each floor is 3.0 m.

The threshold values of transmittance for both walls and windows of renovated buildings were assumed depending on the climatic zone and the wall type. Italian Law specifies the duration of the heating season depending on the climatic zone; according to this, the system was simulated with a 1-min time step for the heating period corresponding to each city. Fan coils are installed into the building in order to balance the space-heating sensible load. Heat coming from occupants, personal computers and lighting systems was assumed to contribute to the internal gains of the building.

The "type56a" was used for modelling the building envelope, indoor air set-point temperature, infiltration, and internal gains. "Type15-6" was used for reading the external "Energy Plus" weather data files of the four above-mentioned cities.

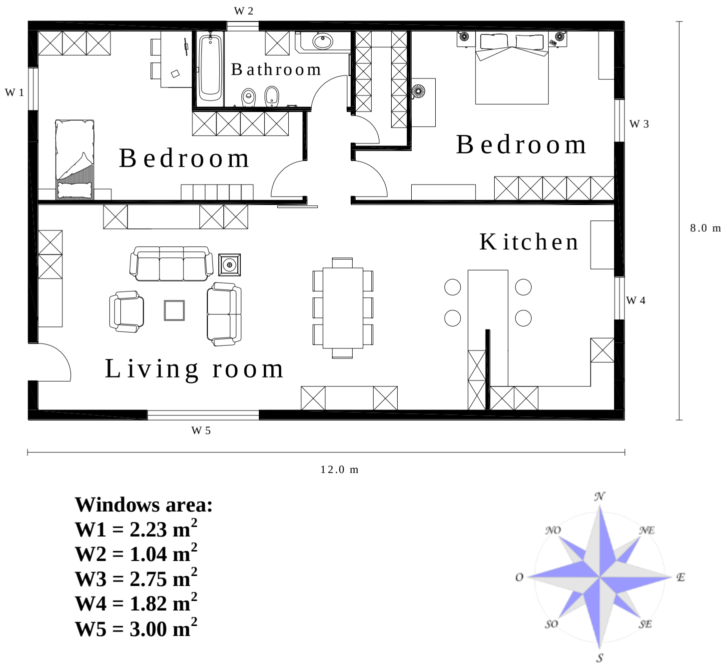

Fig. 5: Main geometrical characteristics of a single flat of the whole multi-family house.

Domestic hot water and electricity demand profiles

The domestic hot-water demand profile with an average basic load of 200 l/day in the time scale of 1 minute was used for estimating the demand of each single flat, according to the load profiles defined within IEA-SHC Task 26.

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

Reference system

A 32.0 kW_{th} natural gas-fired boiler was considered for the thermal energy production within the reference system. The boiler efficiency is evaluated by means of a linear interpolation of the manufacturer data (0.937 at rated output, 0.911 for a part load ratio equal to 30%). Concerning the efficiency of the centralised power plants connected to the national electric grid, a figure of 0.461 was assumed that represents the power-plant average efficiency in Italy, including transmission losses.

2.4.3 Case studies

Tab. 5 shows the 32 simulated case studies.

Tab. 5: Simulated case studies

Case number	Electric demand profile	City	MCHP control strategy	Tank volume [l] (liters)
Case 1	without overnight charging of an electric vehicle	Palermo	Electric load-following	855
Case 2				738
Case 3				503
Case 4			thermal load-following	855
Case 5				738
Case 6				503
Case 7		Napoli	Electric load-following	855
Case 8				738
Case 9				503
Case 10			thermal load-following	855
Case 11				738
Case 12				503
Case 13		Roma	Electric load-following	855
Case 14				738
Case 15				503
Case 16			thermal load-following	855
Case 17				738
Case 18				503
Case 19		Milano	Electric load-following	855
Case 20				738
Case 21				503
Case 22			thermal load-following	855
Case 23				738
Case 24				503
Case 25	with overnight charging of an electric vehicle	Palermo	Electric load-	855
Case 26			thermal load-	
Case 27		Napoli	Electric load-	
Case 28			thermal load-	
Case 29		Roma	Electric load-	
Case 30			thermal load-	
Case 31		Milano	Electric load-	
Case 32			thermal load-	

2.4.4 Results

As an example of the obtained results, the values of FESR (Fuel Energy Saving Ratio) as a function of the city, the MCHP control logic, and the electric demand profile are shown in Fig. 6.

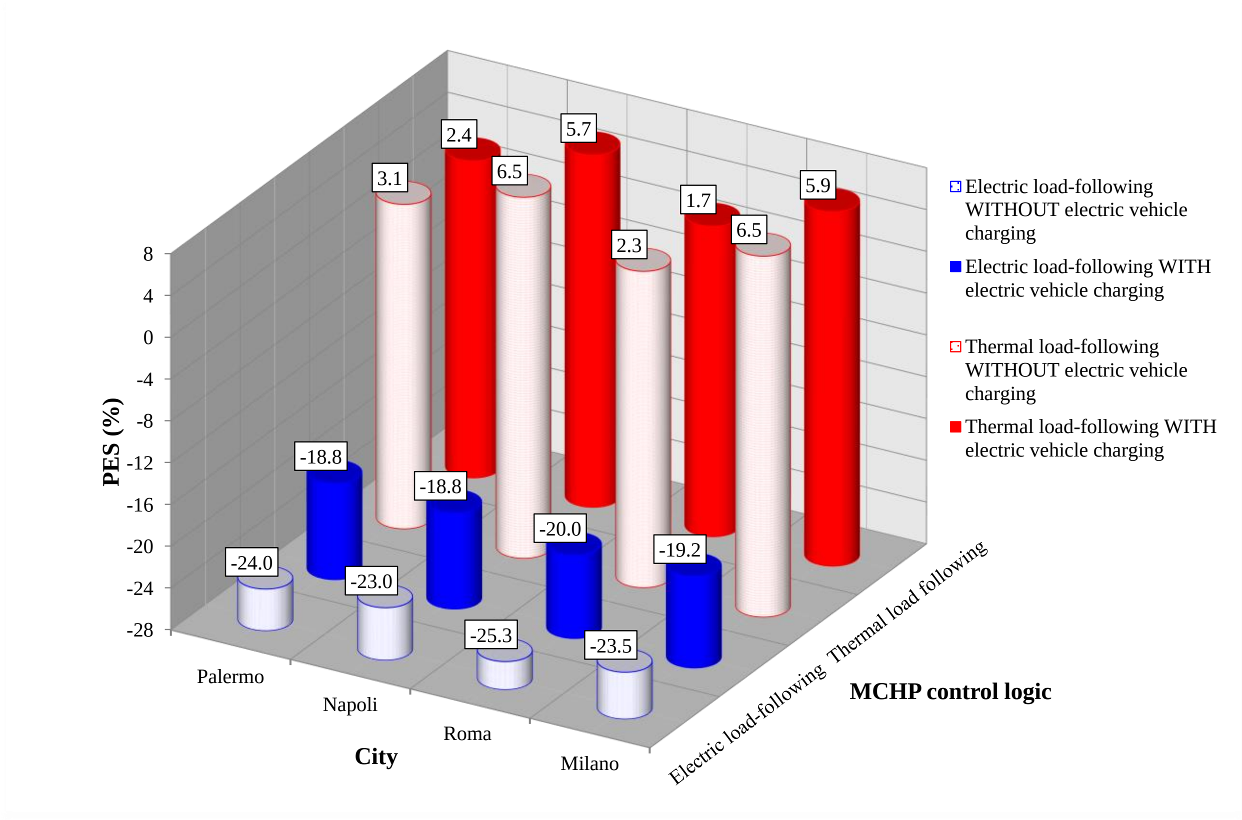

Fig. 6: Values of FESR as a function of city, MCHP control logic, and electric demand profile.

It is noted that:

the values of FESR are always negative in the case of electric load-following logic and positive in the case of thermal load-following logic;

the overnight electric-vehicle charging allows for significant increase of the values of FESR in the case of electric load-following operation, while it reduces the values of FESR in the case of the thermal load-following operation;

for the best condition (thermal load-following operation without the electric-vehicle charging), the maximum value of FESR is obtained when the building is located in Napoli or Milano;

for thermal load-following operation with the electric-vehicle charging, the maximum value of FESR is obtained when the building is located in Milano;

In Fig. 7, the CO_2 equivalent emissions of the alternative system during the whole heating season, as a function of the tank volume (TANK1, TANK2, TANK3), the city, and the MCHP control logic are reported; the electric demand profile without the overnight charging of the electric vehicle was considered.

The tank with the largest volume (TANK1) allows for minimising the CO_2 equivalent emissions of the alternative system, while the tank with the intermediate volume (TANK2) provides the maximum pollutant emissions. In the case of electric load-following operation, the operation with TANK1 allows the system to achieve a percentage reduction ranging from 3.6% (Palermo) up to 4.7% (Milano) if compared with TANK2. In the case of thermal load-following operation, the operation with TANK1 allows the system to achieve a percentage reduction of emissions ranging from 9.1% (Napoli) up to

15.7% (Milano) if compared with TANK2. The thermal load-following logic gives lower values of carbon dioxide equivalent emissions in comparison to the electric load-following control strategy.

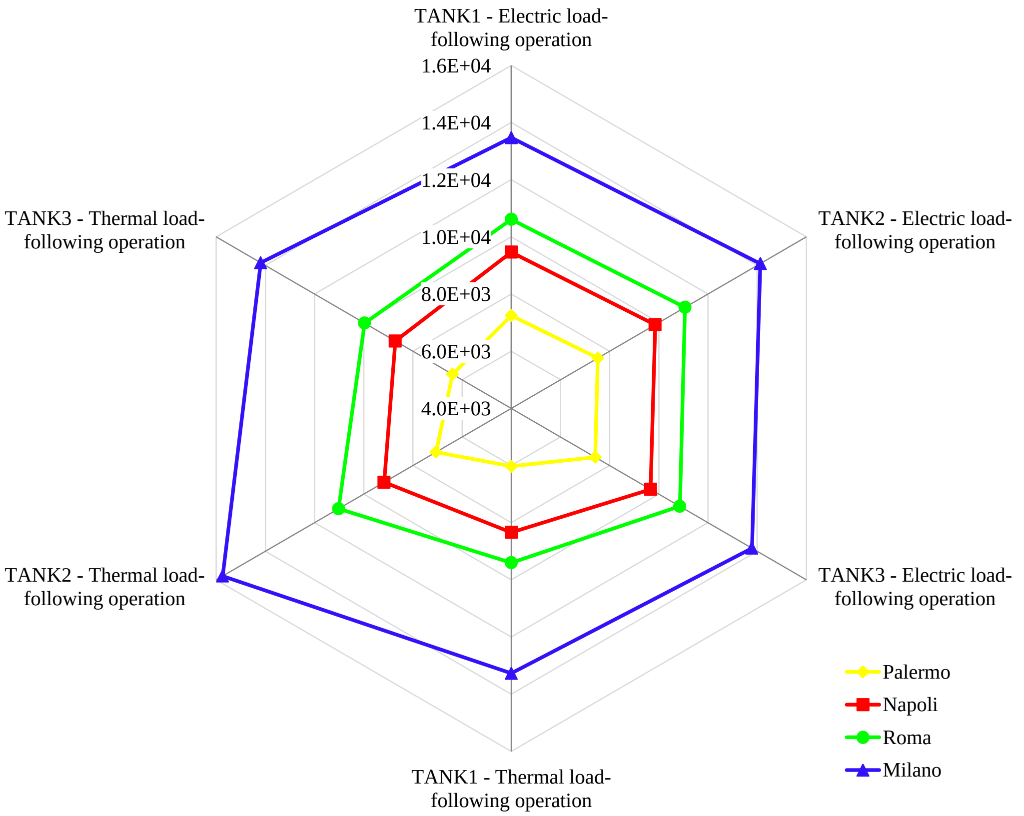

Fig. 7: Values of CO_2 equivalent emissions as a function of tank volume, city, and MCHP control logic.

A similar analysis is also performed in terms of economic performance, considering the operating costs due to both natural gas and electric energy consumption, the tax rebate on natural gas purchased for high-efficiency MCHP systems, as well as the revenue from selling the electric energy surplus.

2.4.5 Conclusions

From this Italian country-specific performance assessment study, the following "rules of thumb" can be derived:

- the hot water tank with the largest volume allows the cogeneration unit to operate more continuously, reducing the inefficiencies related to the occurrence of transient behaviour during start-up and shutdown. Therefore, the total primary energy consumption, the equivalent carbon dioxide emissions, and the operating costs of the alternative system are minimised;
- the microcogeneration system allows for both an energy saving and a reduction of carbon dioxide equivalent emissions in comparison to the reference system only in the case of thermal load-following logic;

- the microcogeneration system is more convenient than the conventional system from an economic point of view (operating costs);
- the electric demand profile including the overnight charging of the electric vehicle provides better results of the MCHP in terms of energy, environmental, and economic performance in comparison to the electric demand profile without the overnight charging of the electric vehicle only when the MCHP unit is operated under electric load-following logic;
- under thermal load-following logic, the best results are obtained when the building is located in the coldest city (Milano), regardless of the electric demand profile.

2.5 Italy – Università e-Campus, Università Politecnica delle Marche

2.5.1 Summary

This work dealt with the performance assessment of a hybrid micro combined cooling heat and power (MCCHP) system, consisting of a variable speed ICE cogenerator and a high concentrator photovoltaic (HCPV) system [9]. This solution provides advantages in terms of operating costs, carbon dioxide emissions, and primary energy consumption if compared to separate production and, in specific working conditions, also compared to the single usage of MCCHP and solar-power systems.

The hybrid system was applied to representative public buildings of a small urban area in Central Italy: Corinaldo. Three building typologies have been considered in the analysis: office buildings, school buildings, sport facilities.

Since several factors influence the performance of hybrid micro-CCHP applications, such as weather condition, fuel, and electricity prices; an optimisation approach for the management of the entire system has been followed, with the aim to maximise energy, environmental, and economic savings.

In detail, the performance analysis has involved the following steps:

1) building dynamic simulation analysis to assess hourly thermal and cooling profiles;
2) hourly assessment of building electrical loads on the basis of electricity bill and typical load profiles defined in the literature;
3) assessment of hybrid system-operation parameters following a multi-objective optimisation approach that pursues the minimisation of three items: i) operating costs, ii) carbon dioxide emission, and iii) primary energy consumption, on the basis of weighting factors defined 'a priori';
4) post-processing of operation parameters to calculate the indexes required by the 3-E performance analysis — Energy, Economic and Environmental, ([1], section IV.1);
5) fulfilment of a sensitivity analysis to assess the influence of the main design parameters on the results.

2.5.2 Buildings, load and external factors

Numerical simulations were performed in a dynamic state with the “Energy Plus” software of the US Department of Energy. A virtual model was developed for each building under analysis in order to determine heating and cooling loads. A typical load profile on was determined an hourly basis for each month by simulating one full representative day in terms of climatic conditions and building operation schedule.

Input data included climatic data records of the location on an hourly basis, the geometry of the building, characteristics of the building envelope, and HVAC systems and operation schedules. Output hourly profiles of net heating and cooling demand were compared with measured monthly consumption data for each building in order to check the reliability of the simulation tool.

2.5.3 Description and characteristic of system components

In order to assess the hybrid system, both HCPV and ICE have been modelled in the “Matlab/Simulink” environment by describing all the subsystems which compose the ICE (such as the engine and the heat exchangers) and the HPVC (the triple junction photovoltaic cell, the optics, and the tracking mechanism).

2.5.4 Description of systems

Fig. 8 shows the conceptual layout of the hybrid MCCHP system that was analysed. It has been designed with the aim to maximise the plant flexibility. The system comprises a MCHP based on an ICE, a HCPV unit, a thermal energy storage (TES), an additional heating boiler, an absorption chiller (ABHP), and a vapour compression chiller (EHP). Both micro-CHP and HCPV systems are connected in parallel to the grid and to the end user. The thermal demand can be satisfied either by the additional heating boiler, or by the thermal power recovered from the ICE, or by the thermal power stored in the TES. The cooling demand can be satisfied either by the vapour compression chiller or by the absorption chiller.

Since energy, economic, and environmental performance of hybrid systems depend on several parameters such as fuel tariffs, purchasing and selling price of electricity, ambient conditions, and energy loads, an optimisation approach is needed to correctly assess the potential of the introduction of hybrid systems. The algorithm developed follows a multi-objective approach, aiming at minimising operating costs, primary energy usage, and carbon dioxide emissions.

For the calculation, all three objectives have been expressed on a cost basis and weighting factors have been defined ‘a priori.’ Finally a sensitivity analysis has been conducted to understand the influence of the defined weighting factors. The objective function is given by the yearly weighted sum of operating costs, primary energy consumption cost, and CO_2 emissions cost.

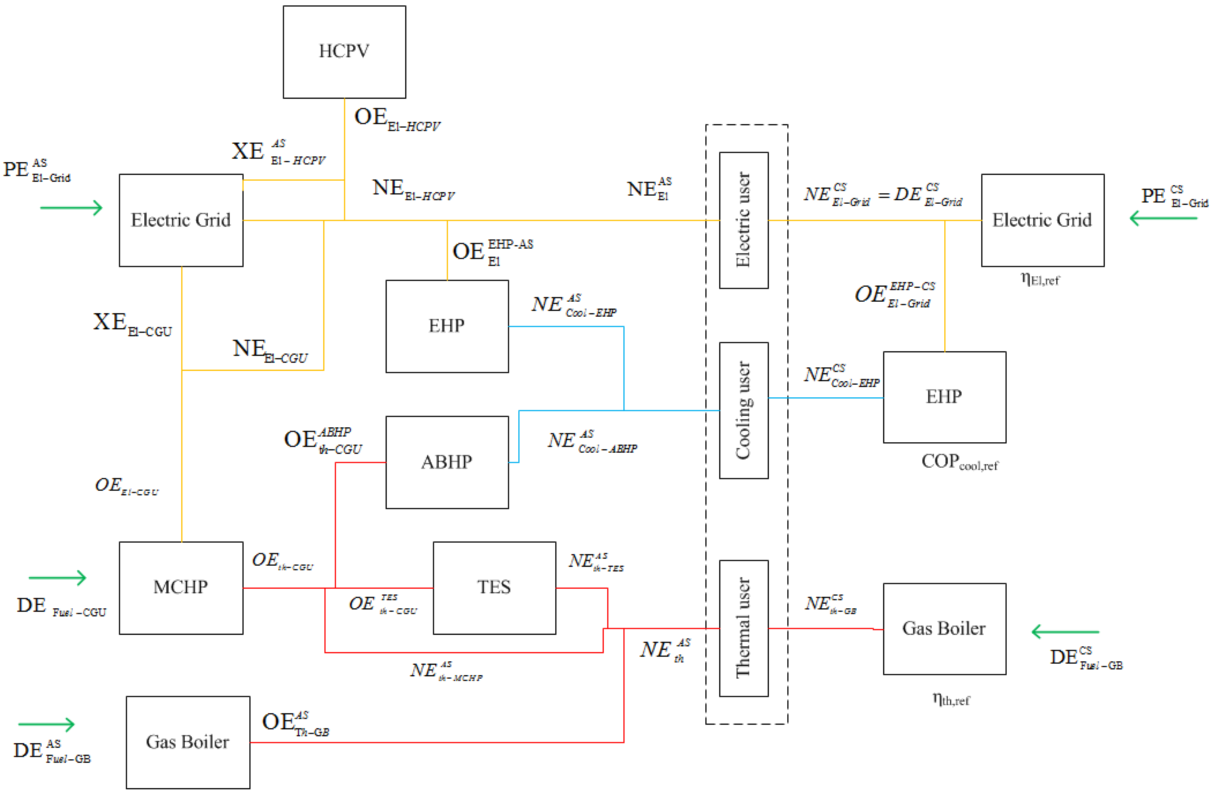

Fig. 8: Diagram of the system analysed in this study.

2.5.5 Performance criteria

In order to assess the hybrid MCCHP system (defined as the alternative system, AS) from an energy point of view, the primary energy saved with respect to the conventional system (CS: electric grid, gas boiler, space cooling) is calculated by means of the fuel energy saving ratio [1]. For the case under analysis, Fig. 8, it can be written as:

$$FESR = 1 - \frac{DE^{AS}_{Fuel-CGU} + DE^{AS}_{Fuel-GB} + PE^{AS}_{El-Grid}}{DE^{CS}_{Fuel-GB} + PE^{CS}_{El-Grid}}$$

The index used to assess the hybrid system from an environmental point of view is the global CO_2 emission reduction. It is a comparison of the CO_2 emissions of the hybrid system with emissions of the conventional system.

The index used to assess the hybrid MCCHP system from an economic point of view is the simple pay-back period. For the case under analysis the extra investment cost of the alternative system is given by the cost of the combined heat and power unit, the high concentrator photovoltaic system, and the absorption chiller.

The operational cost of the AS is given by the sum of fuel cost of running MCHP unit, electricity bought from the grid, fuel cost of feeding the gas boiler to satisfy the thermal demand when not covered by the MCHP, and operating and maintenance cost of the MCHP system. It is necessary to subtract from the operational costs the revenues coming from selling the electricity produced by the power unit and not used by the user.

2.5.6 System cases and configurations

In order to assess the system performances and advantages derived from hybrid applications, instead of comparing the hybrid system to a conventional system (baseline case), two other configurations have been analysed: the single cogeneration unit and the solar power unit. Fig. 9 shows a sum of all the studied configurations, considering both the alternatives (A, B, C) and conventional (D) ones.

2.5.7 Results and conclusions

The main outline of the work is:

- hybrid system configurations provide energy and environmental benefits of about 40% compared to conventional systems;
- hybrid system energy performance is better than the single use of MCHP and HCPV; the advantage increases when the number of MCHP operating hours increases;
- assuming the same weight to energy ratio and environmental and economic criteria, the ICE works in thermal priority in order to maximise the primary energy savings, and thus reduce CO_2 emissions;
- the economic performance of the system deeply depends on the specific ratio between thermal and electric load, rather than energy prices. A limited thermal load reduces the number of operating hours of the ICE, which penalises the return on investment. In this case, the combination of two low-carbon systems with respect to a single system is not justified;
- as regard the HCPV, the high investment cost could be better recovered in regions characterised by a higher value of the direct component of the solar radiation;
- the introduction of the hybrid system strongly cuts the operating cost from a minimum of 35% up to 60%. The advantages are particularly meaningful when there is a higher thermal demand throughout the year, which increases the operating hours of the MCHP unit;
- the main problem in the adoption of this type of technology is the high capital investment cost, which can be recovered only in some cases;
- in none of the case studied does the optimal algorithm recommend the absorption chiller. The electric energy produced by the HCPV system, which is strongly correlated to the end-user demand, can be used more efficiently to feed a vapour compression chiller that has a higher COP than the absorption systems;
- the adoption of hybrid MCCHP by Public Administrations provides a reduction of public expenditure and an exemplary action to promote carbon dioxide emission reduction. At the same time, specific financing mechanisms should be promoted in order to overcome the

problem related to high investment costs such as third-party financing and a favoured access to national and international government funding.

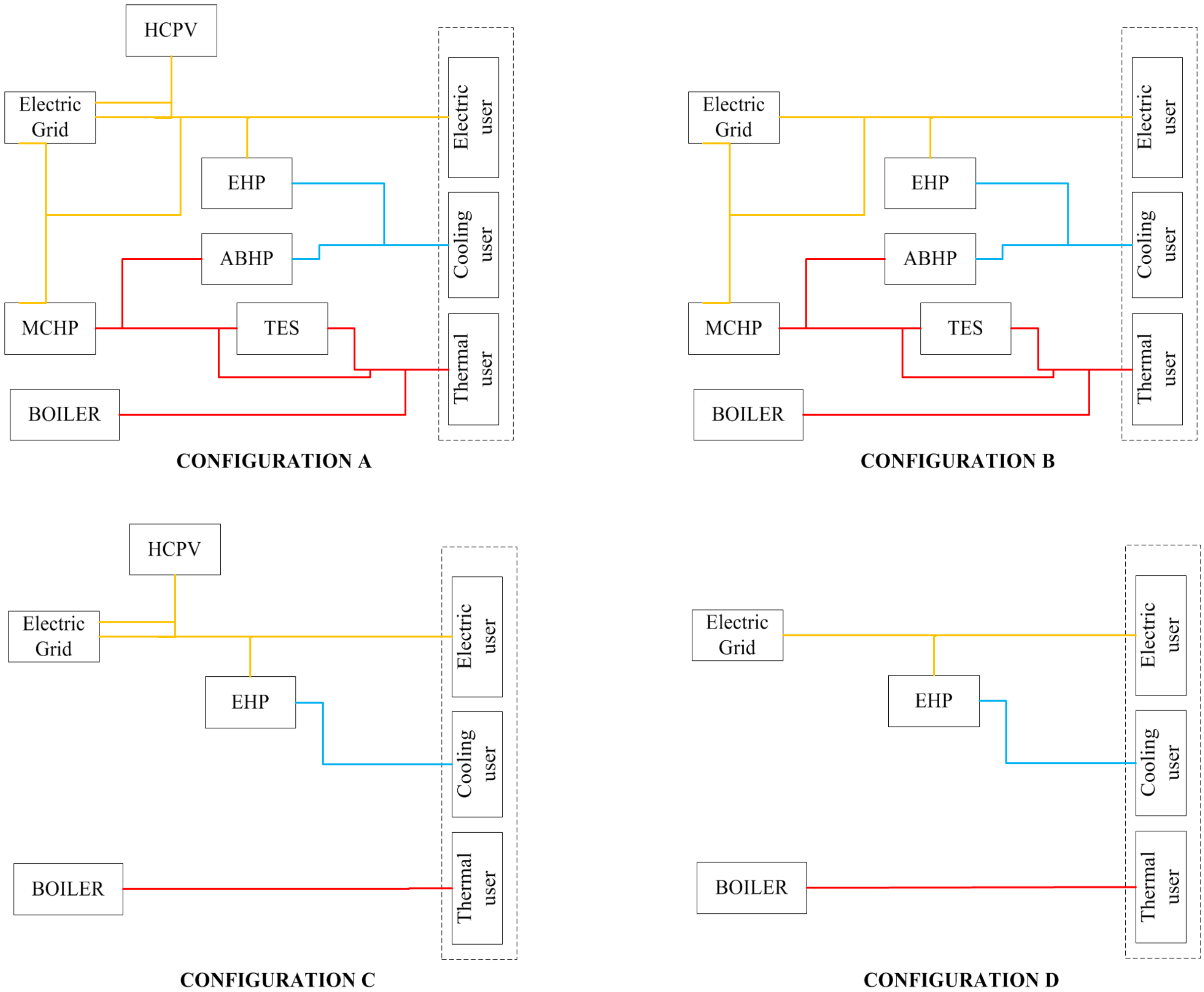

Fig. 9: Diagrams of the configurations analysed in this section.

2.6 Italy – Università del Sannio

2.6.1 Summary

A system (alternative system, AS) is analysed consisting of a small-scale trigeneration system in which a heat-led microcogenerator interacts with a desiccant-based air handling unit (AHU), equipped with a silica-gel desiccant wheel (DW). The system provides the air-conditioning service to a lecture room during summer and winter periods.

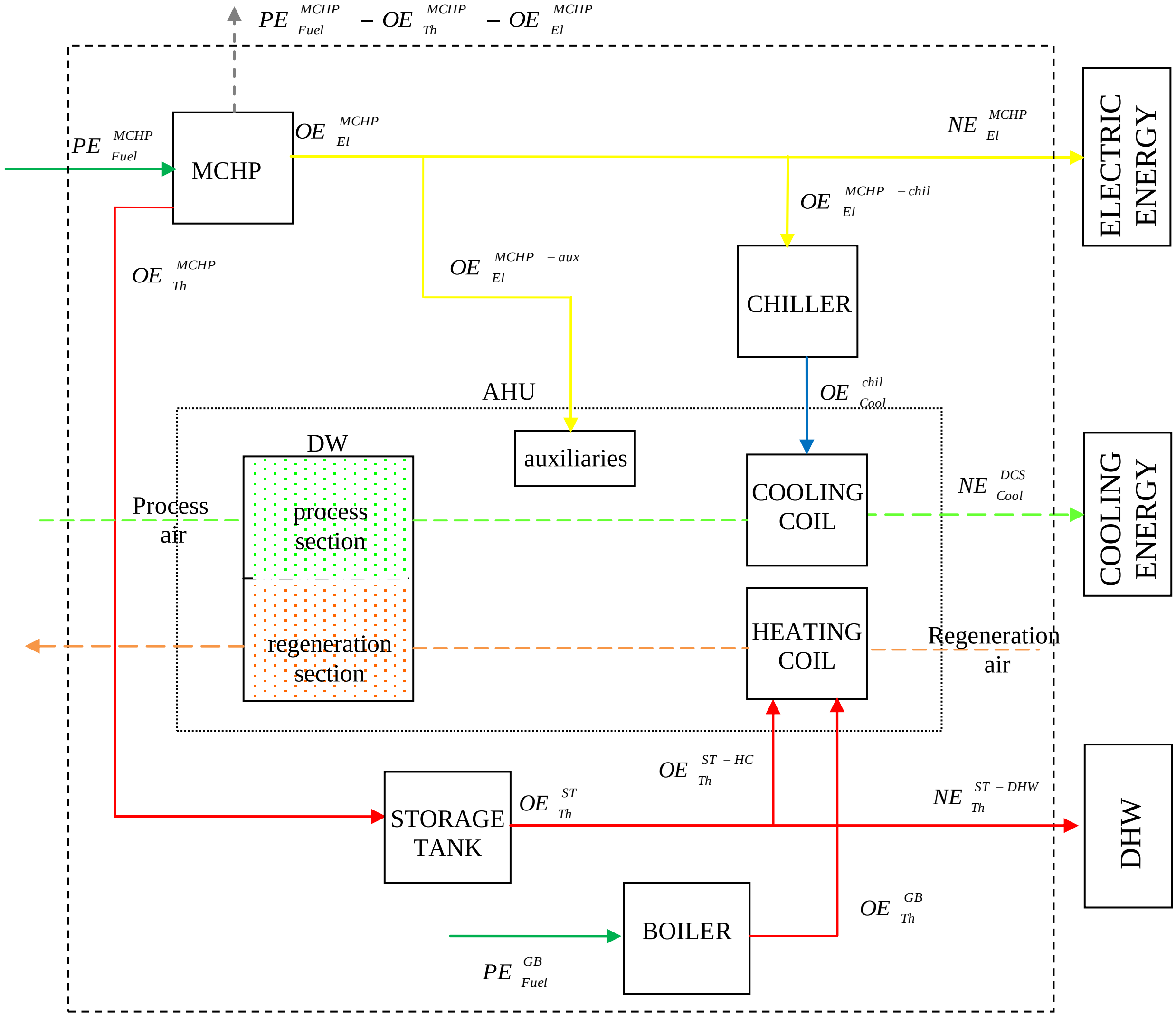

Fig. 10: Main energy flows of the trigeneration system during summer operation.

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

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

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

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

2.6.2 Performance assessment procedure

The following analyses were applied within this Subtask B study: energy analysis, CO_2 emission analysis, economic analysis ([1], section IV.1):

The energy, environmental, and economic analysis involved the following steps: A building simulation produced values for energy demand and, by simulation of the building integrated generation systems, the demand for delivered energy to the building. Primary energy consumption was also derived by simulation of generation systems. From these energy values, further figures such as overall efficiencies, primary energy ratio, emissions, and operating costs were derived. Post-processing was performed to calculate comparative indicators (*FESR*, $\Delta CO_{2,eq}$, *SPB*, etc.).

The following systems are used as the reference energy system:

- condensing gas boiler, providing heat for space heating and for loading a DHW storage tank;
- electric compression chiller, providing cold for space cooling;
- electricity supply from the electric grid.

In terms of economic performance, the effect of three policy instruments on the feasibility of the system is analysed: a subsidy on gas price, a CHP generation bonus, and an investment subsidy.

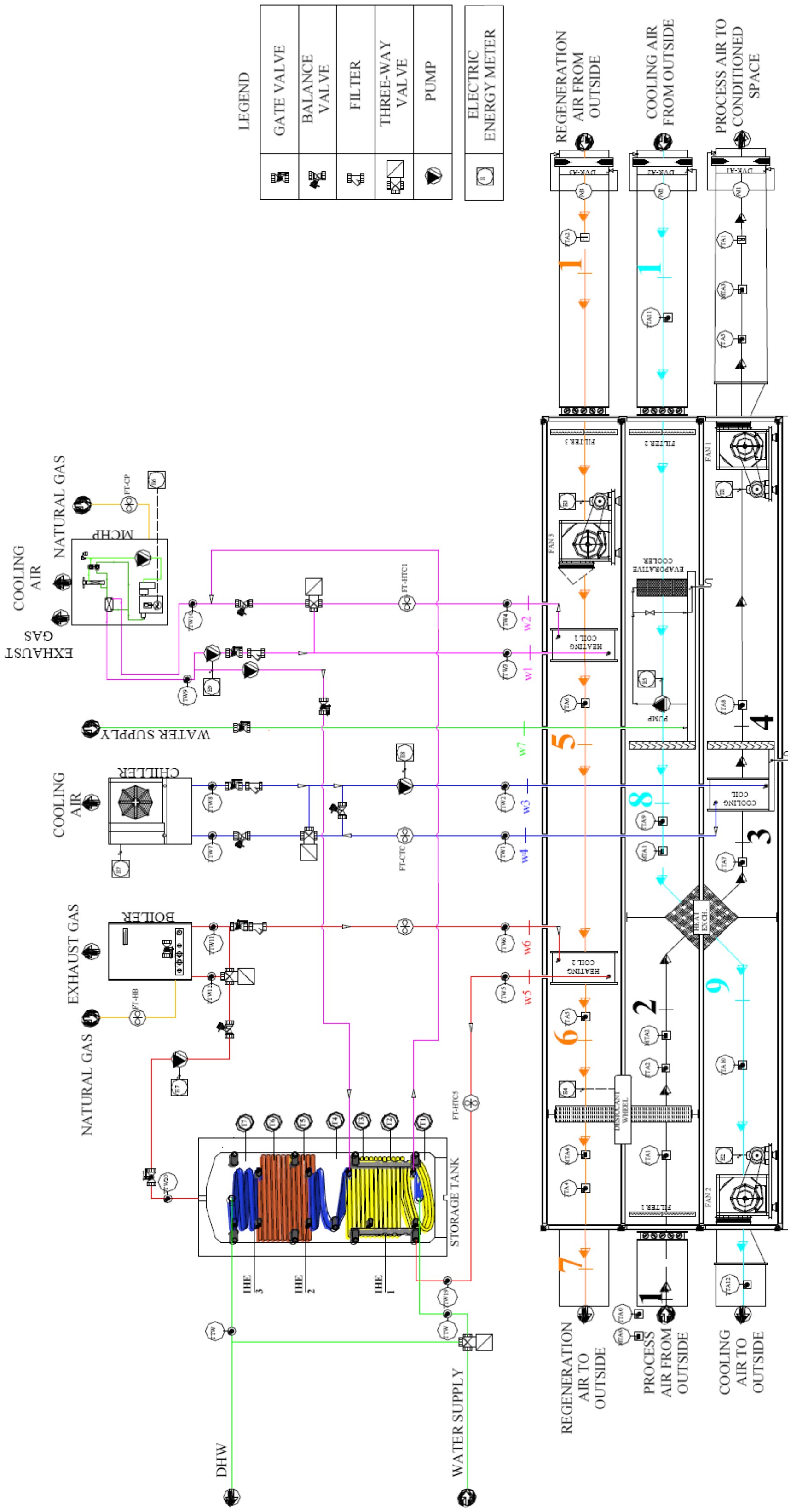

Fig. 11: The test facility.

2.6.2 Building, loads, and external factors

The system is installed in Benevento (mean annual temperature 13.8 °C), for which the corresponding “Meteonorm” climatic file was used. Benevento belongs to climatic zone C for Italy, with 1,316 heating degree days and a heating period from November 15th to March 31th (for a maximum of 10 hours/day). The length of the cooling period was assumed from June 1st to September 15th. Finally, the intermediate season is from September 16th to November 14th and from April 1st to May 31th.

The small-scale trigeneration system, based on the desiccant-based cooling system, provides the air-conditioning service to a lecture room (63.5 m^2 floor area, activation schedule from Monday to Saturday from 9:00 to 19:00) during summer and winter periods. The summer and winter set-point temperatures are 26 °C and 20 °C, respectively.

The occupancy schedule, the rates of heat gain from occupants, the heat gain from artificial lighting, the dimensions and thermal insulation characteristics of the opaque and transparent components of the building envelope, as well as the infiltration rate were set using the interface "TRNBuild" of “TRNSYS” and its "type 56" to simulate the cooling and heating loads. A typical value of electric energy consumption in office applications was assumed.

The classroom has no DHW demands; therefore, it is assumed that such DHW is provided to a nearby building (i.e. a gym) as explained in next section. A tool to generate realistic domestic hot water load profiles was developed in the framework of “IEA/SHC Task 26.” Throughout the year, the MCHP provides thermal energy, by means of the storage tank, for DHW preparation with a requirement of 1,200 litres per day.

2.6.3 Description and characteristics of main system components

MCHP

A simplified MCHP model, suited for whole-building simulation software, has been developed, calibrated, and validated by means of the available experimental data on a AISIN Toyota MCHP.

To simulate the micro-cogenerator operation, the “TRNSYS” RIC (reciprocating internal combustion) engine model has been used: “type 907.” It uses a table of performance data to determine the outputs of the engine, given a set of input conditions. The model relies on an external data file which contains efficiency (both mechanical and electrical), air flow rate (fraction of rated flow rate), and heat transfer data (fraction of total thermal power recovered from the generator, the oil cooler, the exhaust gas heat exchanger, the engine jacket, and the fraction dissipated to the environment) as a function of the intake temperature and the part-load ratio (actual power over rated power).

A plate heat exchanger, used to transfer the recovered thermal power to a secondary fluid (i.e. water), a three-way valve that mixes the part of solution flow rate that passes through the plate heat exchanger and the one that is bypassed toward the engine, and the control system that manages the thermal recovery circuit of the micro-cogenerator were also modelled.

Thermal storage tank

In the test facility of University of Sannio, a thermal storage system was installed and experimentally tested. It has three heat exchangers: two of them, placed in the lower and upper part of the storage, are carbon steel heat exchangers that can interact with an external energy-conversion device; the third one, that extends along the entire height of the storage, is a stainless steel corrugated coil heat exchanger for domestic hot water "production." A third energy-conversion device can directly interact in open circuit with the fluid stored in the tank.

The model used to simulate the described storage tank is "type 60," which represents the most detailed model available in TRNSYS to simulate stratified thermal storage. The thermal performance of a water-filled sensible energy storage tank, subject to thermal stratification, is modelled by assuming that the tank consists of N fully-mixed equal-volume segments; for each of them a uniform temperature is considered. The degree of stratification is determined by the value of N. If N=1, the storage tank is modelled as a fully-mixed tank and no stratification effects are possible. By means of experimental tests conducted in the test facility of University of Sannio, the model was experimentally calibrated and validated.

The desiccant wheel

The desiccant wheel is a rotor filled with desiccant material and used to dehumidify the process air, exploiting the difference in water vapour pressure between the incoming humid air and the surface of the desiccant material. In order to ensure a continuous operation of the system, the DW has to be regenerated by means of a regeneration air flow, heated up to a suitable temperature (from 60 °C up to 140 °C, depending on the adsorbent material and the desired humidity ratio reduction).

The simplified approach of Maclaine-Cross and Banks has been used to model the DW [11]. This approach models the dehumidification process, a combined heat- and mass-transfer process, in analogy with a simple heat-transfer process. Equations for coupled heat and mass transfer are reduced to two uncoupled differential equations of two independent variables (characteristic potentials). Then, actual outlet conditions are estimated using two effectiveness indices of the wheel, calculated in analogy to the efficiency of a heat exchanger. Intense laboratory activities provided over 200 hours of experimental data necessary to calibrate and validate the model.

2.6.4 Results

The performance of the AS and CS strongly depend on several operating conditions. First is the electric demand profile that influences the share of self-use of electricity. The best case is achieved when the maximum value of the share of self-use electricity is assumed; for the analysed case, the maximum value of this ratio means that no electricity is drawn from the grid for electric appliances and auxiliaries, and about 10% of the cogenerated electricity is exported to the grid.

The analysed system is favourable with respect to the conventional one in terms of energy and environmental performance, achieving a primary energy saving of about 7% and a CO_2 emissions saving of about 15%. However, to guarantee the economic feasibility of the system, it is necessary that it can access the support mechanisms introduced by Italian legislation for small-scale gas-fuelled trigeneration systems: a lower taxation on gas price, the white certificates, an investment subsidy (up to 40% of the investment cost), and the net metering scheme. In fact, if the analysed system can contemporary benefit from all these mechanisms, a quite acceptable simple payback period of about 9 years can be obtained.

2.6.5 Conclusions

From this performance assessment study, the following “rules of thumb” related to a micro-trigeneration system with a desiccant-based air handling unit can be derived:

- the performances of desiccant cooling systems are strongly influenced by outdoor thermal-hygrometric conditions;
- desiccant cooling is a very interesting technology, in particular for high latent load applications;
- in Mediterranean climates, the desiccant dehumidification technology can guarantee a reduction of both energy consumption and GHG emissions;
- in regions characterised by quite low thermal energy needs for space heating of buildings, it is crucial to utilise thermal energy available from the MCHP also for DHW requirements and to supply thermally-activated cooling systems, in order to increase the operating hours of the system;
- a key parameter is the size of the storage interacting with the MCHP unit, as a correct dimensioning of the tank, as well as an optimal control of the cogenerator/storage system, can reduce the number of starts and stops of the device, increasing its durability;
- the investment costs for this system are still quite high; therefore, it is necessary that it can access all the support mechanisms introduced by Italian legislation for small-scale gas-fuelled trigeneration systems.

2.7 Canada

In [12], a study is described to analyse the hybridisation of Stirling engine-based residential cogeneration systems with solar thermal systems in order to meet the space- and water-heating loads of a typical Canadian family house. Simulation results of four hybrid system configurations applied in various locations in Canada are presented and compared to a base case system without solar input. Additional optimisation cases are discussed.

Adding solar collectors to a residential cogeneration system has a clear potential to reduce natural gas consumption and GHG emissions. The simulated cases showed a 10–15% decrease in the consumption of natural gas, which corresponds to a GHG emission reduction of approximately 700–1200 kg per house per year (depending on configuration and location).

Hybrid systems are complex and highly integrated systems. A full system optimisation was therefore not possible in this study. Recommendations are given for further optimisation of these type of systems.

2.7.1 Method

The hybrid systems were simulated in the whole-building simulation program TRNSYS and annual simulations were run for various locations in Canada using standard Canadian weather for energy calculation (CWEC) data. Performance of the hybrid systems was compared to that of a reference system without renewable energy input. The aim was to maximise the usage of solar energy by varying system configuration, collector area, heat storage capacity, and hybrid system control strategy. The modelling approach was to use measured data from non-optimised prototypes or early-generation systems, including real-life efficiency losses (internal power consumption, reduced performance from cyclic operation, etc.).

2.7.2 System description

Base case

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

Hybrid renewable – microgeneration energy systems

Solar heat is used in four variants of a hybrid renewable–microgeneration energy system to replace fossil energy for space heating and DHW production. In Cases 1 and 2, solar heat is only used to heat DHW; in Cases 3 and 4 the output of the solar collectors is used for both DHW and space heating. Cases 2 and 4 (Fig. 12) differ from Cases 1 and 3 in that they have a preheat tank interacting with the solar circuit, aimed at enhancing the solar yield.

Microcogeneration system

The model is based on the Annex 42 combustion cogeneration model, [7],[8]. The parameters of the model are based on a calibration resulting from experimental testing of a modern Stirling engine. The model takes differences in cooling water temperatures into account when calculating thermal and electrical efficiencies. The SE is operated in on/off mode and produces approximately 7 kW of heat.

Solar collectors

TRNSYS “type 539” was used to model the thermal performance of flat-plate solar collectors. In this component model, the collector efficiency curve is modelled by a first-order equation, and correction for off-normal solar incidence is applied by a second-order incidence angle modifier (IAM).

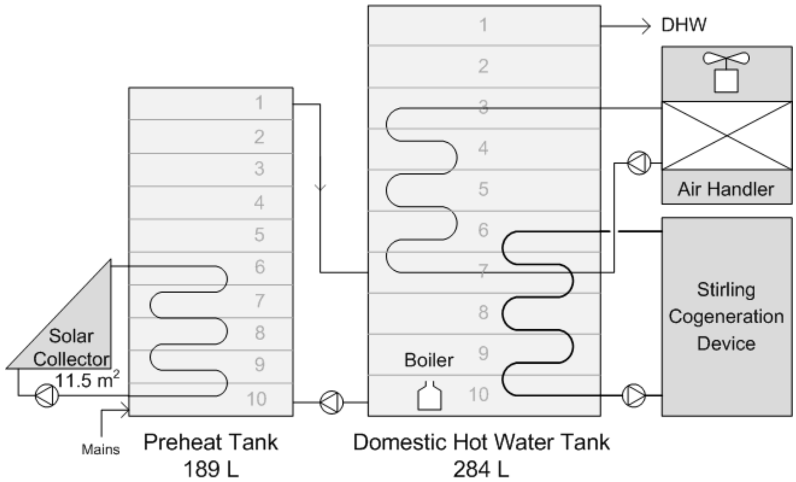

Fig. 12: Configuration for Case 4.

The solar collector model was calibrated on the basis of manufacturer specifications. The solar collectors were assumed to be installed at the optimum angle for the investigated locations.

Furnaces and boilers

The furnaces and gas-fired boilers were modelled as on/off devices with a capacity of 29.3 kW, with efficiencies of 92% and 85%, respectively, based on HHV.

Heat storages

Heat storage tanks were modelled as vertical storage tanks with immersed coiled tube heat exchangers and with flow streams passing in and out (TRNSYS "type 534"). Each storage tank was divided into ten isothermal temperature nodes in order to model stratification in the tank. Heat losses to the environment were also considered in the model.

Balance of Plant

A commercially available air handler was used to calibrate the air handler model in "TRNSYS" ("type 753a"). Power consumed and flow rates for the pumps were also set for the simulations.

Control strategies

Two separate temperature nodes in the DHW tank are used to control when the SE and auxiliary back-up heaters are turned on and off. The solar pump turns on when the difference between the panel outlet temperature and the bottom of the preheat tank (or the DHW tank when only one tank is used) is greater than 10ºC; it turns off when this difference is less than 3ºC. The tank recirculation pump turns on when the difference between the top of the preheat tank and the bottom of the DHW tank is greater than 7ºC; it turns off when this difference is less than 2ºC. The house thermostat controls the circulation fan, the air handler, and, if needed, the furnace to 21ºC ± 0.5ºC. When the SE serves the DHW and air handler coil in parallel, the SE comes on when there is either a demand for space heating or to heat the DHW storage. Priority is given to heating DHW.

House model

The house model is based upon the twin research houses of the Canadian Centre for Housing Technology in Ottawa. The model was first calibrated against the measured space-heating demand of one of the houses. Subsequently, the insulation thickness and air tightness in the model were decreased to the level at which the model would represent a house situated in Ottawa with a heat load equal to the space heating demand of the average Canadian single detached house. A daily schedule was applied of 6 DHW draws, totalling 200 litres of hot water per day.

2.7.3 Basis for results comparison

The performance index for comparing hybrid systems to the reference system is the potential to reduce natural gas consumption and associated GHG emissions. The net electricity consumed is considered as being supplied by a 51% (HHV) efficient natural gas-fired combined-cycle power plant. An 8% loss for transmission and distribution of grid electricity was taken into account.

Natural gas for heating and power production was assumed to have an emission intensity of 59.4 kg GHGeq/GJ.

2.7.4 Results

Main results for the simulated cases are presented in Tab. 6 and Fig. 13.

The base case system has been simulated for four cities in Canada: Vancouver, Calgary, Ottawa, and Halifax. These cities represent different geographical areas and climates, which results in a range of space-heating loads. The operational characteristics of the base case system are very similar for all locations. The SE supplies close to 90% of the total heat demand for SH and DHW, with the back-up heater providing the remainder.

Cases 1 and 2 use solar heat for DHW production. A series configuration of two solar collector panels with a total surface area of 5.748 m^2 produce 7% and 10% of the total annual heat demand for Ottawa Cases 1 and 2, respectively. The solar heat primarily replaces the output of the back-up heater. The reductions in natural gas consumption and GHG emissions compared with the base case were 9.9% for Case 1 and 12.2% for Case 2.

Solar heat is used in Cases 3 and 4 for both space heating and DHW. The systems are equipped with four solar collector panels in series (11.496 m^2 total area). The solar heat replaces output from both the SE and the back-up heater. The reduction in natural gas consumption and GHG emissions is 11.2% for Case 3 and 10.4% for Case 4, for location in Ottawa. For both Cases 2 and 3, the operation and performance of the hybrid systems are very similar over the range of heating conditions for the analysed cities.

Parameter variation cases were run in order to investigate the effect of doubling the solar collector area, doubling the volume of the heat storage tanks, and removing the low-flow pump between the two heat storages. Doubling the area of the solar panels results in a 49% increase in solar yield for Case 2 and 28% more solar heat collected for Case 3, but with a marginal improvement, as the additional solar heat captured mainly replaces thermal output from the SE. The reduction in natural gas consumption and in GHG emission increases to 14.0% for Case 2 and 14.1% for Case 3.

Tab. 6: Main results for all simulated cases

Configuration	Heat into system				Heat out of system			Electricity			Performance				NG savings and GHG reduction £
	SE heat output	Back-up burner	Furnace	Solar heat output	SH load *	DHW load	Tank heat loss	SE net power out	Fan power	Other HVAC elec ‡	SE net η_{th} (cycle) †	SE net η_{el} (cycle) †	Avg SE cycle time	Solar η	
	MWh				MWh			MWh			%	%	min	%	%
Base															
Vancouver	17.5	2.4	0.0	0.0	15.2	5.0	0.5	1.2	0.8	0.1	70.4	4.9	104	N/A	(Base)
Halifax	22.3	2.7	0.0	0.0	20.5	5.0	0.5	1.7	1.0	0.2	70.5	5.4	126	N/A	
Ottawa	25.2	3.1	0.0	0.0	24.0	4.9	0.5	2.1	1.1	0.2	70.5	5.8	168	N/A	
Calgary	25.7	3.5	0.0	0.0	25.0	4.8	0.5	2.1	1.1	0.3	70.5	5.9	169	N/A	
Case 1															
Ottawa	25.2	0.0	1.4	2.0	24.6	5.0	0.4	1.9	1.2	0.1	74.8	5.7	123	22.2	9.9
Case 2															
Vancouver	17.4	0.0	0.0	2.7	15.5	5.1	0.7	1.0	1.0	0.1	74.7	4.2	78	33.0	12.8
Halifax	22.6	0.0	0.1	2.6	20.9	5.1	0.7	1.6	1.2	0.1	74.8	5.2	101	31.0	11.4
Ottawa	25.0	0.0	0.7	2.8	24.4	5.0	0.7	1.9	1.3	0.1	74.8	5.8	141	31.2	12.2
Calgary	25.5	0.0	1.2	3.2	25.5	5.2	0.7	2.0	1.3	0.1	74.8	5.8	136	30.8	11.8
Case 3															
Vancouver	15.7	0.8	0.0	3.9	15.4	5.3	0.6	1.0	0.8	0.2	70.3	4.6	97	24.2	13.6
Halifax	20.8	0.8	0.0	3.8	20.8	5.1	0.6	1.6	1.0	0.3	70.4	5.3	122	22.8	11.0
Ottawa	23.4	1.0	0.0	4.2	24.2	5.0	0.6	1.9	1.1	0.4	70.5	5.8	171	23.2	11.2
Calgary	23.9	1.1	0.0	4.7	25.2	5.1	0.6	2.0	1.2	0.4	70.5	5.8	171	22.7	11.8
Case 4															
Ottawa	23.6	1.1	0.0	4.3	24.2	5.2	0.7	1.9	1.1	0.4	70.5	5.8	172	23.7	10.4
2xVol$_{tank}$ (Ottawa)															
Base	27.0	1.5	0.0	0.0	24.0	4.9	0.7	2.4	1.1	0.2	70.5	6.8	321	N/A	0.0
Case 2	25.0	0.0	0.6	3.0	24.4	4.7	1.0	1.9	1.3	0.1	74.8	5.8	144	33.2	12.6
Case 3	23.9	0.4	0.0	4.5	24.2	4.9	0.9	2.0	1.1	0.3	70.4	6.0	282	24.6	12.0
2xA$_{panel}$ (Ottawa)															
Case 2	24.6	0.0	0.6	4.2	24.4	5.7	0.8	1.9	1.3	0.1	74.8	5.8	131	23.2	14.0
Case 3	22.7	0.9	0.0	5.4	24.2	5.3	0.6	1.8	1.1	0.3	70.5	5.7	176	14.9	14.1
Low-flow pump off (Ottawa)															
Case 2	25.1	0.0	0.7	2.8	24.4	5.0	0.7	1.9	1.3	0.1	74.7	5.8	140	30.5	12.1
Optimized cases (Ottawa)															
Case 3-50°	23.3	1.0	0.0	4.2	24.2	5.0	0.6	1.9	1.1	0.4	70.5	5.8	128	23.5	11.5
Case 1-Opt.	24.7	0.0	0.6	3.7	24.4	5.5	0.6	1.9	1.3	0.1	74.8	5.8	85	20.3	13.7
Case 3-LTH	19.8	4.2	0.0	4.5	24.5	4.8	0.5	1.5	1.2	0.4	73.6	5.5	128	25.0	15.0

* Space heating load consists of heat output of air handler and furnace and the electrical load of the fan.

‡ This is the power consumed by the air handler pump, the solar pump, and the low-flow pump.

† Presented SE efficiencies are *cycle* efficiencies, which are lower than full load efficiencies due to losses from warm-up, cool-down, and stand-by periods.

The base case with double tank volume has a 14% higher SE power production thanks to increased use of the SE and a higher electrical efficiency due to a near doubling of the average cycle time. This improvement, however, is totally consumed by a higher demand for natural gas to overcome higher heat losses from the storage tank and efficiency differences between the SE and the back-up heater. Overall, the base case with a double tank size has the same natural gas use and GHG emissions as the original base case.

Case 2 with double heat storage volumes shows a small increase in solar yield. The operation of the hybrid system is almost identical to that of the regular Case 2 and natural gas consumption and emissions decrease by 0.4%. As regards Case 3, owing to a 6% higher solar input, a net reduction in natural gas consumption and GHG emissions of 0.8% is achieved in comparison with the standard Case 3 for Ottawa. Turning off the low-flow-pump in Case 2 has a net effect of –0.1% in natural gas saving and GHG emission reduction.

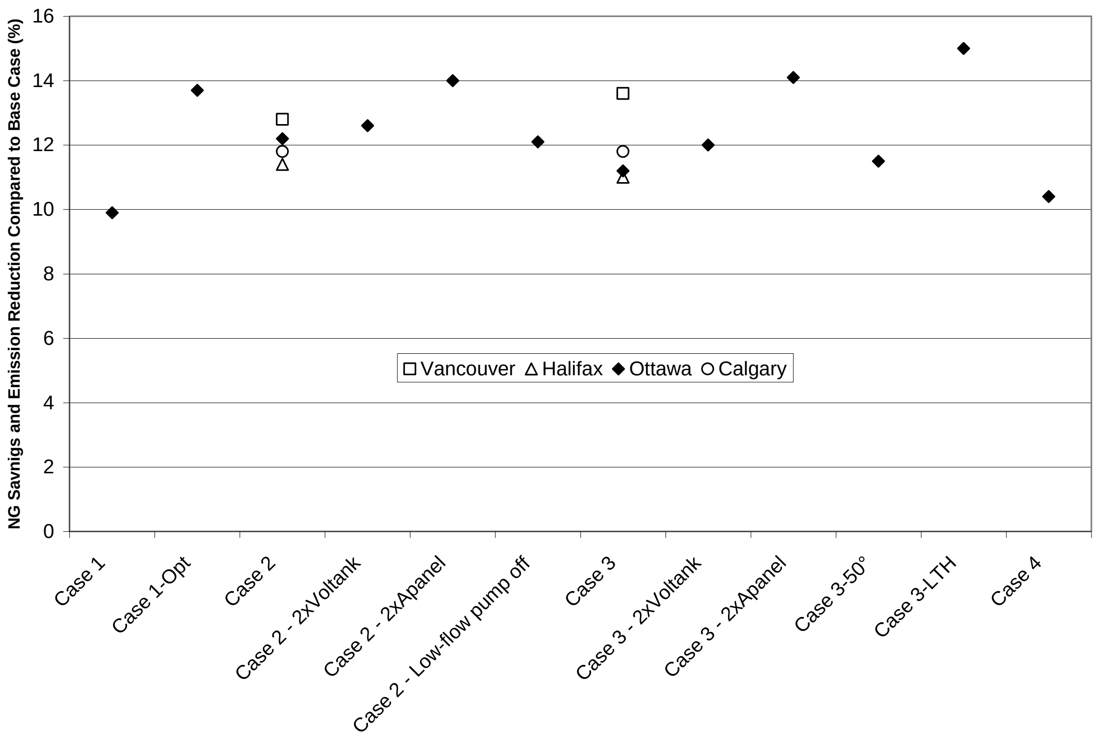

Fig. 13: NG savings and GHG emission reduction for simulated cases compared to the base case for the same location.

In all cases described above, the solar collector panels were assumed to be installed at the optimum angle for total annual solar heat production (37°). A number of simulations were run for Case 3 (Ottawa) with a variation of solar panel angle. A slightly higher angle (50°) than the 37° used in the first round of simulations is favourable towards optimum overall efficiency. With the solar panel at the optimum angle of 50°, two routes for further optimisation were investigated. The first route aimed at maximising the use and performance of the Stirling engine, while also trying to capture the greatest amount of solar heat. Because of its similarities to Case 1, this case was called 'Case 1_Optimized'. The results show an almost exclusive use of the Stirling engine in providing heat for space heating and DHW. With a 13.7% reduction in natural gas use and associated emissions, this configuration has a better performance than both the original Case 1 and Case 3 with a solar panel angle of 50°.

The second route for optimisation was the application of the hybrid system with a low-temperature heating (LTH) system, i.e. a floor heating system. Using a Case 3-type configuration, the results for Case 3_LTH clearly show the positive effect of lower heat storage temperatures on the performances of the Stirling engine and the solar panels. The thermal efficiency of the Stirling engine increased to 73.6% compared to 70.5% for Case 3 with solar panels at an angle of 50°. The heat production by the solar panels increased by 6% from 4.2 to 4.5 MWh. Case 3_LTH has the highest percentage of reduction in natural gas use and associated GHG emissions of all evaluated cases: 15.0%.

2.7.5 Conclusions

In this report, a study is presented into the hybridisation of residential cogeneration systems and solar thermal technology for providing space heating and domestic hot water to a residence with an average heating load. Hybrid systems displaying various configurations and parameter settings were simulated in TRNSYS and their results compared to a base case without solar input. From this study, it can be concluded that:

- adding solar collectors to a residential cogeneration system has a clear potential to reduce natural gas consumptions and GHG emissions. Simulated cases showed a reduction in annual natural gas consumption of 10–15%, which corresponds to a reduction of approximately 700–1200 kg GHG per house per year;
- providing low heat-exchange temperatures for both the Stirling engine and the solar thermal system is crucial for high system efficiencies;
- it is important to provide sufficient storage capacity for the collected solar heat;
- system performance increases with solar collector area, but with a rapid decrease in marginal improvement;
- the solar-panel angle has a limited impact on the overall system performance;
- the hybrid systems show similar operation and performance when applied in four cities across Canada with a broad range of heat demands.

3 Review of Other Country-specific Results Deriving from the Microgen III Conference

3.1 Germany

To calculate the potential of small-scale cogeneration in Germany, technical data of MCHP systems and performance data from field tests and laboratory experiments have been taken into account in [13]. The business areas were selected according to a significant yearly heat demand: a butcher shop, a small hotel, and a fitness centre. To derive the economic potential, cost data of the systems and tariffs for electricity and natural gas have been included, as well as the current regulatory framework.

The investment for the MCHP system has to be recovered by cost reductions during the life time compared to a conventional heating system and electricity purchase from the grid. Fig. 14 shows a sensitivity analysis of such a system. In addition, the base values for the different parameters are included into the legend. The parameters are varied from 20% below to 20% above the base value and the impact on the annual total profit is shown. A MCHP system with a maximum electrical output of 50 kW and thermal output of 120 kW that achieves 5,000 full load operating hours annually is considered for the analysis.

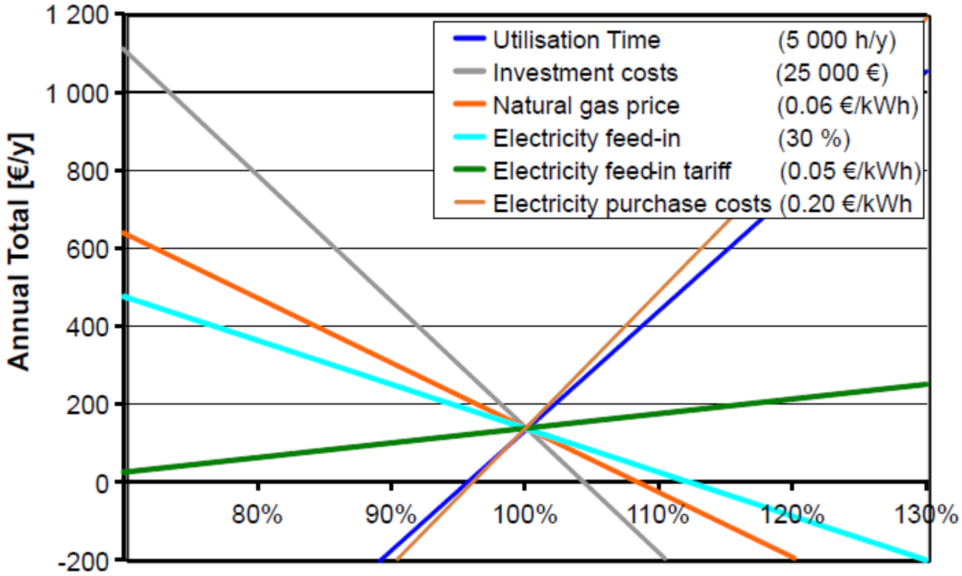

Fig. 14: Influencing factors on annual total profit of MCHP.

The profit is very sensitive on the utilisation time, the electricity purchase costs, and the investment costs. With progressing market entry, lower investment costs and better profitability can be expected. The crucial parameter is the utilisation time; a decrease of only 5% would lead to an economic deficit of the CHP system.

The potential of MCHP in the small business sector in Germany has been projected from statistical data. The higher heat demand during the summer is an advantage of non-residential applications and increases the profitability of MCHP systems. However, the potential for MCHP systems in the sectors trade, commerce, and services is limited. Also, by including CHP systems with higher capacity, a total of about 40% of the heat and about 25% of the electricity demand of the sector TCS could be supplied.

In [14], the need to develop typical profiles of heat load, DHW tapping, and electricity demand for real-time experiments of CHP (combined heat and power) systems is analysed. These load profiles are needed for three typical days, representing the climatic periods summer, winter, and transition time.

For the selection of these so called "Type Days," a method is implemented. First, each day of a field measurement campaign is classified as Summer, Winter, or Transition Day, depending on its mean ambient temperature. Second, for each group, mean profiles of heat load, DHW tapping, and electricity demand are calculated. Subsequently, Type Days are selected using a least-squares approach. Depending on these Type Days, load profiles with a resolution of one minute are calculated and used as input data for the test bed at the Institute for Energy Economy and Application Technology (IfE), where it is possible to apply different hydraulic schemes with dynamic heat loads and DHW tapping profiles for MCHP testing. Results show very good consistency of test-bed data with the data measured during the field test in terms of electricity generation, heat supply, and system efficiency of the MCHP.

The results confirm that using MCHP units in the sector of trade and services can be ecological and economical, especially in business sectors with a high heating base load. In particular, an optimised hydraulic system gives (Fig.15) a potential of up to 6% of primary energy saving.

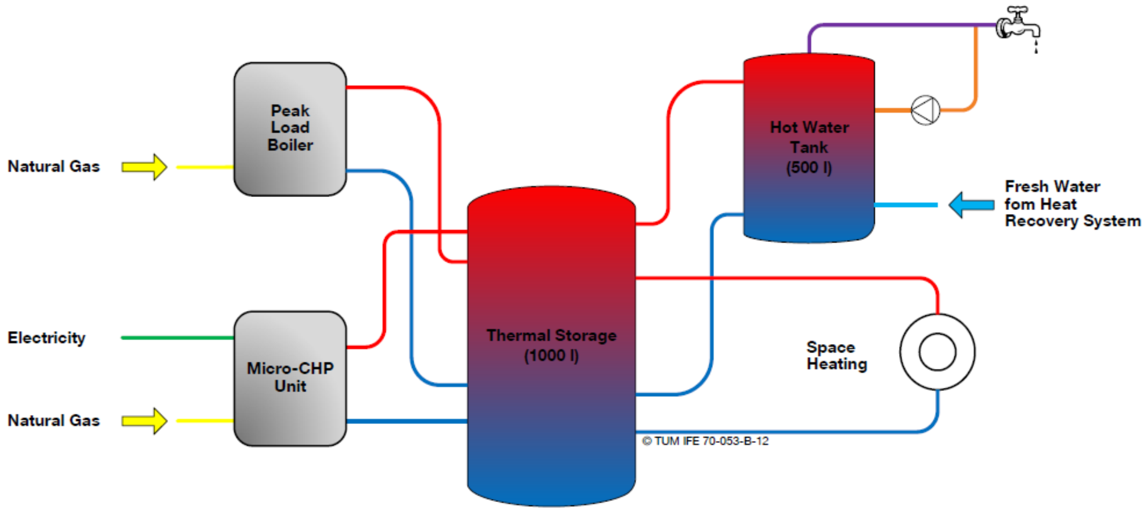

Fig.15: Optimized hydraulic system.

3.2 United Kingdom

In the UK, heat pumps are often promoted as the means to provide low-carbon space heating and hot water for future dwellings as the electricity supply decarbonises. However, a major issue with growing heat-pump use is the additional load that this could place on the electrical network. A means to alleviate potential demand problems is to stagger the operating times of heat pumps by integrating them with thermal buffering. However, focusing on the domestic sector, substantial volumes of thermal storage would be required, and this poses a particular problem in the UK where the floor areas of urban dwellings are small. Thermal storage featuring phase change material (PCM) offers the potential of more volumetrically efficient heat buffering, which may be more suitable for integration into domestic heating systems.

In [15], the potential to shift the operating time of heat pumps integrated with PCM-enhanced thermal storage is assessed and compared to conventional hot-water storage, where the limits of flexible operation are determined by the comfort and hot water needs of the end-user. In particular, an integrated "ESP-r" model of a conventional UK detached dwelling (usable floor area of 136 m^2 spread over an upper and ground floor), featuring an 11-kW nominal thermal output air source heat pump (ASHP) heating system (Fig. 16), was used to investigate the potential for PCM thermal storage and to provide practical and more efficient thermal buffering for the load shifting of heat pumps.

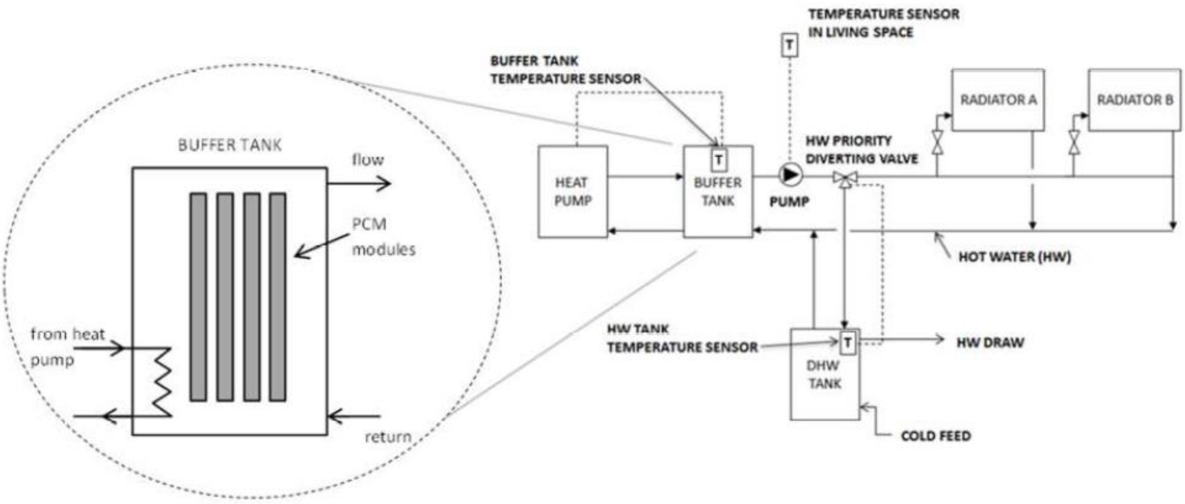

Fig. 16: The modelled heating system supplied by the ASHP with PCM-enhanced buffer tank.

The operating times of the heat pump were set to off-peak periods (when the house was unoccupied or when the occupants were asleep), whilst the volume of the thermal buffer was varied from 200–1200 L and the percentage of PCM in the thermal buffer (by volume) was varied from 0% up to 70%.

The performance of both the buffered system (with and without PCM) was compared to the case with no load shifting, where the heat pump was connected directly to the heating circuit and the DHW tank (reference case). In the unbuffered case, the hours of heating operation were set to the periods of active occupancy within the dwelling.

The simulations were undertaken for winter, spring, and summer weeks for a warm (Southern England) and cool (North East Scotland) climate. In total, 186 simulations were undertaken, with a 1-min time resolution. For each simulation, the heat pump performance data was post-processed to determine the energy costs for the end user and the carbon emissions associated with the use of the heat pump.

The results indicate that in all cases the PCM-enhanced buffer offers improvements in terms of the size of storage required to achieve effective load shifting: the size of the buffer tank could be reduced by between 2–3 times compared to hot-water buffering. For example, without PCM, a tank size of 1200 l was required to load shift over the winter weeks for both the warm and cold climates—this would be a very large tank to accommodate within a dwelling. With PCM added, a 500 l tank is required for the winter week for both the UK climate sets.

However, thermal buffering with load shifting can increase heat pump energy demand and (at present) in the UK results in increased emissions and cost penalties for the end user. These results may change in future as the energy mix of the UK electricity system changes and if tariff structures are revised to encourage load shifting.

For example, Fig. 17 shows that, for the case of the warm-climate winter week, increasing the buffer size and the addition of PCM to the buffer tank increased the electrical energy consumption of the heat pump. In the worst case, the PCM-enhanced buffer results in a 38% energy penalty compared to the reference case.

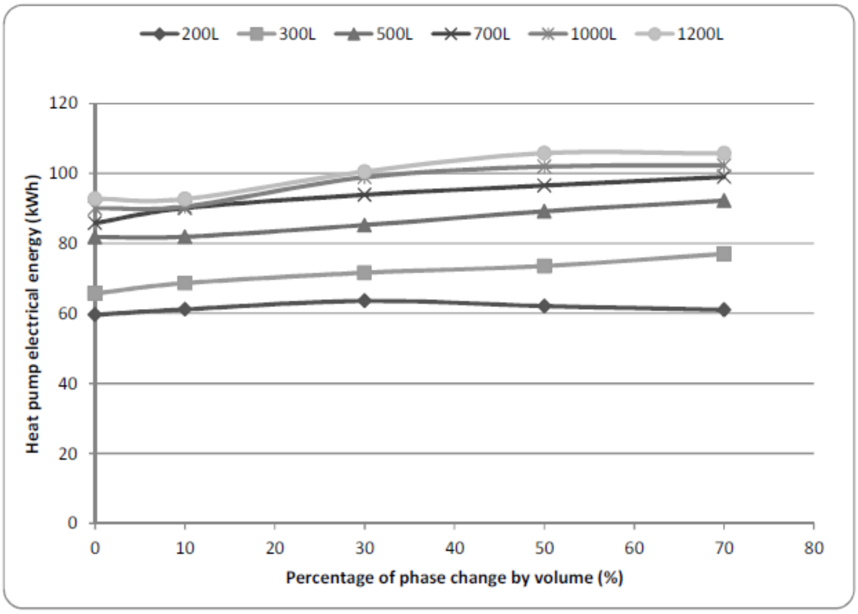

Fig. 17: Electrical energy consumption of heat pump for operation shifted to off-peak against % of PCM in buffer tank for different buffer tank volumes; warm UK climate, winter week.

The increased heat pump electrical energy use is attributable to two main causes. Firstly, the addition of the buffering tank introduces extra standing system losses. Second, the COP of the heat pump is reduced by up to 15% because of the addition of a heat exchanger in the buffer (it is necessary to supply water to the buffer at a higher temperature) and because the heat pump operates at off-peak times when ambient temperatures are lower.

Furthermore, the addition of sensible-only buffering is beneficial with respect to the cycling of the heat pump. The large sensible store reduces heat pump cycling by up to 35%. This could have a beneficial effect on both maintenance requirements and the heat pump lifespan. However, with the PCM-enhanced thermal buffer, there is no clear reduction in thermal cycling.

4 Conclusions

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

In terms of economic performance, significant capital cost savings (about 20–30%) can be obtained, but very often the initial installation cost is still considerably high, especially for very complex small-scale trigeneration systems, determining quite long pay back periods, even assuming that all the support mechanisms introduced by national legislations are effectively achieved. Therefore, specific financing mechanisms should be promoted in order to overcome the problems related to high investment costs such as, for instance, third-party financing and favoured access to national and international government funding. Moreover, there is the need to further improve the performance of microgeneration systems, to increase the cost savings with respect to conventional systems based on separate “production;” a reduction of the installation costs performed by manufacturers and distributors of high-efficiency energy conversion devices would be also highly desirable.

As a conclusion, it should be highlighted that the aforementioned energy, environmental, and cost benefits can be achieved if the following main "rules of thumb" are observed, both in the design and the operation phases of small-scale cogeneration and trigeneration plants:

- the energy-saving effects differ with household-type, therefore an optimal solution exists for each household category;
- the best energy, environmental, and economic performance are obtained with thermal load-following logic of the MCHP, rather than electric-load following logic;
- under thermal load-following logic, the best results are obtained in more colder climates;
- the benefits increase when the utilisation time of the microgeneration system increases, as it represents the most crucial parameter;
- the performance of the system deeply depends on the ratio between thermal and electric load;
- the correct sizing of the storage tank is a crucial issue, as it allows the minimisation of the total primary energy consumption, the equivalent carbon dioxide emissions, and the operating costs of the microgeneration system;
- the thermal recovery circuit should be properly designed, i.e. achieving enough low return temperature to maximise the performance of combustion-based devices and solar thermal systems;
- the performance of microgeneration systems strongly increases with the share of own-use electricity;
- the electric demand profile including the overnight charging of the electric vehicle provides better results of the MCHP, in comparison to the electric demand profile without the

overnight charging of the electric vehicle, only when the MCHP unit is operated under electric load-following logic;

- higher operational energy savings can be achieved with the load-sharing approach, with optimal system sizing and appropriate control strategy implementations;
- an electrically driven cooling device based on vapour compression systems should be at the moment preferred to a thermally activated one (absorption chiller or desiccant cooling system) in small-scale trigeneration systems, as the former allows the achievement of higher overall efficiency;
- the economic feasibility of microgeneration systems is very sensitive on the electricity purchase costs and the investment costs;
- with progressing market entry of microgeneration technologies, lower investment costs and better profitability can be expected.

Terminology and Abbreviations

ABHP	Absorption Heat Pump
AHU	Air Handling Unit
AS	Alternative System
ASHP	Air Source Heat Pump
ASHRAE	America Society of Heating Refrigeration and Air Conditioning Engineers
CHP	Combined Heat and Power
CO_2	Equivalent CO_2 emissions
COP	Coefficient Of Performance
CS	Conventional System
DCS	Desiccant Cooling System
DHW	Domestic Hot Water
DW	Desiccant Wheel
EHP	Electric Heat Pump
EV	Electric Vehicle
FESR	Fuel Energy Saving Ratio
GHG	Green House Gas
GSHP	Ground Source Heat Pump
HCPV	High Concentrator PhotoVoltaic
HHV	Higher Heating Value
HVAC	Heating, Ventilation and Air-Conditioning
IAM	Incidence Angle Modifier
ICE	Internal Combustion Engine
LHB	condensing water heater
LTH	Low Temperature Heating
MCCHP	Micro Combined Cool Heat and Power
MCHP	Micro Combined Heat and Power
MGE	Micro Gas Engine
NE	Net Energy
NG	Natural Gas
NPV	Net Present Value
OE	Output Energy
PCM	Phase Change Material
PE	Primary Energy
PEFC	Polymer Electrolyte Membrane Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PHEV	Plug-in Hybrid Electric Vehicles
PV	PhotoVoltaic
PV/T	PhotoVoltaic-Thermal
RIC	Reciprocating Internal Combustion

SOFC	Solid Oxide Fuel Cell
SE	Stirling Engine
SH	Space Heating
SPB	Simple Pay Back period
TES	Thermal Energy Storage
TRNSYS	TRaNsientSYStems

Subscripts

Cool	cooling
El	electric
Fuel	fuel primary energy
Th	thermal

Superscripts

aux	auxiliaries
chil	chiller
DCS	Desiccant Cooling System
DHW	Domestic Hot Water
GB	Gas Boiler
HC	Heating Coil
MCHP	Micro Combined Heat and Power
ST	Storage Tank

References

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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 & CO_2 Emissions Optimisation in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO_2 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 other associated energy technologies.

Scope of activities

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

Outcomes

- An update on occupant-related DHW and electric load profiles.
- Component models and their implementation in building simulation tools.
- Review of best practices in the operation and control of integrated micro-generation systems.
- Predictive control algorithms to maximise 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 commercialisation/ regulatory approaches for micro-generation.
- Compilation of case studies of the introduction of microgeneration technologies.

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

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

Subtask A - Technical Development

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

Subtask B - Performance Assessment

This 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

This subtask contains work related to the interaction between technical performance, economic instruments, and commercialisation strategies and provisions 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)