

ENERGETIC AND ENVIRONMENTAL PERFORMANCE EVALUATION OF MICRO-POLYGENERATION SYSTEMS FOR SMALL OFFICE BUILDINGS

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ABSTRACT

The performance of building integrated polygeneration in terms of energy savings and environmental impact reduction are evaluated for small, well insulated office buildings by means of a simulation based case study.

The micro-polygeneration system assumed comprises a natural gas driven micro-cogeneration (CGU) unit, a thermally driven cooling (TDC) unit and a back-up boiler. Cases with different combinations of capacities and efficiencies of CGU and TDC unit are analyzed, and compared to the reference system with gas boiler and grid electricity. The office building considered complies with advanced building standards. Cooling and heating is provided by thermo-active building systems (concrete core pipe systems). The building loads are determined as 1h-values with the whole-building simulation program TRNSYS, using standard occupancy and electric demand profiles specified by Swiss standards. Energy carriers are natural gas as fuel and grid electricity considering three different generation mixes: Swiss, European and combined cycle power plant.

The system performance is determined energetically in terms of non-renewable primary energy demand, and environmentally in terms of CO₂-equivalent reduction and the endpoint indicators according to Eco-Indicator 99 (resource depletion, ecosystem quality and human health). The calculations are based on the latest release of the internationally recognized LCA-inventory database *Ecoinvent*.

The current study focuses on simple performance assessment assuming average efficiencies based on measured performance data or on manufacturer's data. The aim of the study is to get indications on the potential of energy savings and environmental impact reduction. Future work has to focus on detailed modeling considering part load characteristics and control.

INTRODUCTION

For space conditioning, cooling often is the dominating factor in office buildings. Due to climate change and increased thermal comfort requirements, cooling becomes even more important [Frank 2005]. While passive methods have its limitations [Artmann 2007], mechanical cooling leads to increased electricity demand and respective peak load problems. Besides renewable energy technologies (solar cooling, PV), combined heat, cold and power (CHCP) or polygeneration is another option for cooling without increasing the electricity demand.

The aim of this study was to evaluate the potential of polygeneration systems for energy savings and environmental impact reduction in low energy office buildings.

METHODOLOGY

Modeling tool

In the frame of the European PolySMART [PolySMART] project, Empa developed an energy and environmental impact assessment tool for polygeneration systems. The CHCP system considered includes a cogeneration unit (CGU) and a thermally driven chiller (TDC), supplemented with a boiler and a mechanical chiller. The tool is mainly designed for office buildings; however, it could be used as well for other building types. It calculates the following impact key figures: primary energy savings, carbon dioxide equivalent savings and savings in terms of eco-indicator points. The latter consists of three midpoint indicators (ecosystem quality, human health, resource depletion). The weighting of these indicators can be specified by the user. In addition the tool delivers CHCP system related key figures such as CGU operation hours or ratio electricity export to grid vs. electricity demand. CHCP system related inputs taken into account are thermal and electric efficiencies, minimal and maximal thermal power of CGU, and parasitic electric demand of TDC. Building and occupants related inputs are floor

area and hourly demand profiles per square meter for heat (total of space heating and hot water), cold and non-HVAC electric power. The tool was implemented in Excel, with calculations based upon hourly heating/cooling and electric loads.

Performance assessment metrics

The energetic system performance is determined in terms of non-renewable primary energy (NRPE) demand, in comparison to the reference system, similar to the methodology outlined in [Dorer and Weber, 2007]. In addition the greenhouse warming potential was calculated applying the GWP(100a) methodology [IPCC 2001], and expressed in carbon dioxide equivalents emissions (CDE). The environmental performance was measured using the quantification systems “Eco-indicator 99” with the three endpoint indicators “resource depletion” (RD), “ecosystem quality” (EQ) and “human health” (HH). The environmental indicators were calculated on the basis of the NRPE demand. The relative savings were calculated in the same manner as the energy performance indicators i.e. the same reference systems were used. The aggregation of the endpoint indicators into a total environmental impact indicator (Eco-Total) was made using equal weighting factors. Some of the results are shown by the mixing triangle diagram developed by [Hofstetter 1998], allowing a system comparison for all weighting combinations. Inventory data used for all environmental performance indicators was the *Ecoinvent 2.0* database [Ecoinvent 2007].

However, customized inventory data was needed in this study as the *Ecoinvent* database contains for natural gas either datasets referring to heating value of the natural gas supplied or referring to the heat produced by the CGU. The former datasets do not include emissions due to natural gas combustion. The latter datasets are based on efficiencies of the CGU which were assumed in the process of building up the inventory data. As in this study varying values of CGU efficiencies were used, a dataset for natural gas including combustion was required; referring to the fuel’s heating value. This customized dataset was calculated by adding the fuel’s impact prior to combustion and the impact of the combustion emissions. Herein the combustion data was taken from a data set for a state of the art gas boiler. Thus, due to the cleaner combustion in boilers compared to combustion in most today available CHP systems the environmental performance results obtained represent a potential benchmark for future systems with improved combustion.

Unit impacts for fuel and electricity use

Three grid electricity generation mixes were considered: (i) Swiss mix (hydro 55 %, nuclear 45%, thermal & other 5%), (ii) European mix according to the Union for the Co-ordination of Transmission of Electricity (UCTE), as a an example for an existing quite fossil based grid, and (iii) a combined cycle power plant mix (CCPP) as the representative for an alternative marginal and innovative natural gas driven technology. No time dependency of generation mixes was considered. Unit impacts obtained from several *Ecoinvent* datasets as described in the methodology vary strongly on the electricity mix. This is valid in terms of non-renewable primary energy, carbon dioxide equivalents (table 1) as well as in terms of the endpoints and total according to the Eco-indicator 99 methodology (figure 1). However, the Eco-indicator total is similar for the two electricity mixes UTCE and CCPP. The high impact of natural gas, compared with the Swiss electricity mix, is due to the endpoint indicator “resource depletion” which encompasses depletion of fossil fuels and minerals.

Energy carrier	Factors Non-renewable primary energy [kWh/kWh]	Carbon dioxide equivalents [kg CDE/kWh]
Natural gas, including combustion (NG)	1.20	0.255
Electricity, Swiss mix (CH, Swiss)	2.50	0.133
Electricity, European mix (UTCE)	3.32	0.593
Electricity, combined cycle power plant (CCPP)	2.06	0.423

Table 1: Non-renewable primary energy factors and carbon dioxide equivalents emission factors, obtained from the Ecoinvent 2.0 database [Ecoinvent 2007]

Electricity delivered to the grid was credited using the same conversion factors. There, in order to take into account for electricity transmission to the final user the delivered electricity was discounted by 10%.

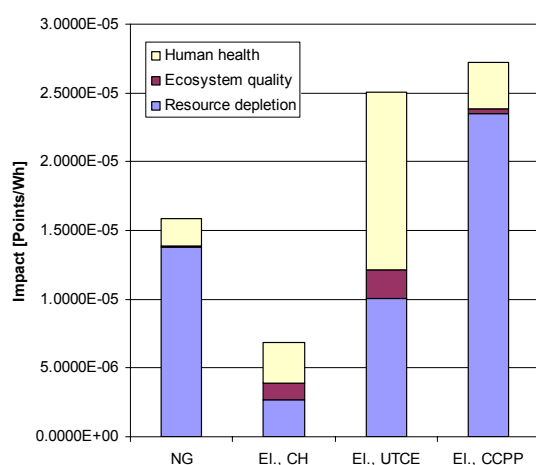


Figure 1: Endpoint indicators for natural gas and electricity mixes

CASES ANALYZED

Polygeneration systems

Natural gas driven CGUs with thermal capacities in the range of 1 to 30 kWth and efficiencies (LHV) of 60% thermal and 30% electric for the standard case were assumed. The capacity of the TDC was assumed to fully comply with heat power supplied from the CGU. The standard COP for the TDC was 0.63, with variations from 0.55 to 0.95. For the CGU and TDC analyzed, average efficiencies based on measured performance data or on manufacturer's data were used. Several operation modes for heat and cold demand driven operation and a modulation capacity within predefined power range were considered. For the gas boiler a thermal efficiency of 0.98, and for the mechanical chiller a COP of 3.0 were assumed. The locally generated electricity was either directly used or exported into the grid. The reference system for all cases comprises the gas boiler and the mechanical chiller, and grid electricity according to the selected mix.

Building

An office building complying with advanced building energy standards was used for the study (table 2). Space cooling and heating are provided by a thermo-active building system (concrete core pipe system) [Lehmann et al 2007]. Ventilation was assumed to be thermally neutral. The assumed pattern of internal heat gains during the day are specified incorporating the three components, lighting, occupants and equipment

using (i) standard full load values given in (SIA 2024), and (ii) realistic simultaneity or utilization factor patterns (no occupancy on week-end assumed).

Space heating and cooling loads were then determined as 1h-values for two types of room spaces (normal and corner rooms), using the whole building and plant simulation tool *TRNSYS* [TRNSYS 2005], and then aggregated for the whole building by defining the number of spaces and floors, assuming similar conditions in the adjacent rooms. For the building size given in table 2, the annual heating loads amount to 40MWh/a (16.6 kWh/m²/a), cooling load to 46 MWh/a (19.1 kWh/m²/a) and electric demand for office appliances and lighting to 44 MWh/a (18.4 kWh/m²/a). Monthly average values are shown in figure 2. In summer and winter, sun protection was activated for each façade separately, (i) upon direct solar incidence on the façade, or (ii) if the product global irradiation (on the façade) times the g-value of the glazing exceeds 90 W/m². Artificial lighting was from 25 to 100% according illumination.

Room	
Space	
length	3.33 m
width,	6.00 m
height,	3.00 m
floor area	20 m ²
Orientation	West (normal office) ; south and west (corner office)
Façade area/ glazed area	21/7.5 m ² (per façade side for corner office)
Solar heat gain coefficient (g)	
- glazing alone	0.41 -
- glazing with sun-shading	0.08 -
U-value of façade	0.65 W/(m ² K)
Internal heat gains	Standard values according (SIA 2024)
Building, number of	
Corner offices	4
Normal offices	8
Floors	10
Building	
Total floor area	2400 m ²

Table 2: Characteristics of considered office room types and building

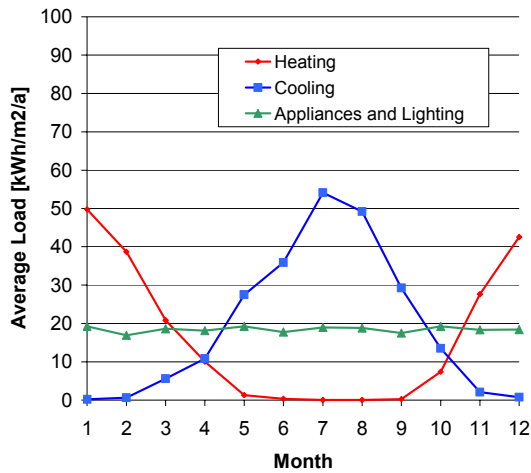


Figure 2: Simulated loads for the building analyzed

RESULTS

Sizing of CHCP

One main factor influencing operation parameters was the size of the CGU (figure 3).

When varying the CGU size (quantified as maximal thermal output) from 1 to 30 kW, the total annual CGU operation time decreased from 89 to 27%. Assisted operation decreased in the same power range from 86 to 10%. With the exception of small power sizes cooling required higher assistance than heating.

In roughly 10% of the year, the CGU operated in the ‘heating with CGU only’ mode within a broad range of CGU sizes, for cooling the time percentage was more proportional to the CGU size, this 10% relative time value was only attained at CGU sizes towards 30 kW.

Electricity export occurred for CGUs of at least 5 kW and reached its maximum closely to 30 kW. CGUs located at the lower or upper end of the power range analyzed might be inappropriately sized considering economic aspects (initial costs versus benefit) and might therefore play a minor role in market.

Operation without a TDC unit (cogeneration) resulted in substantially lower CGU operation time and electricity export (2nd diagram in figure 3).

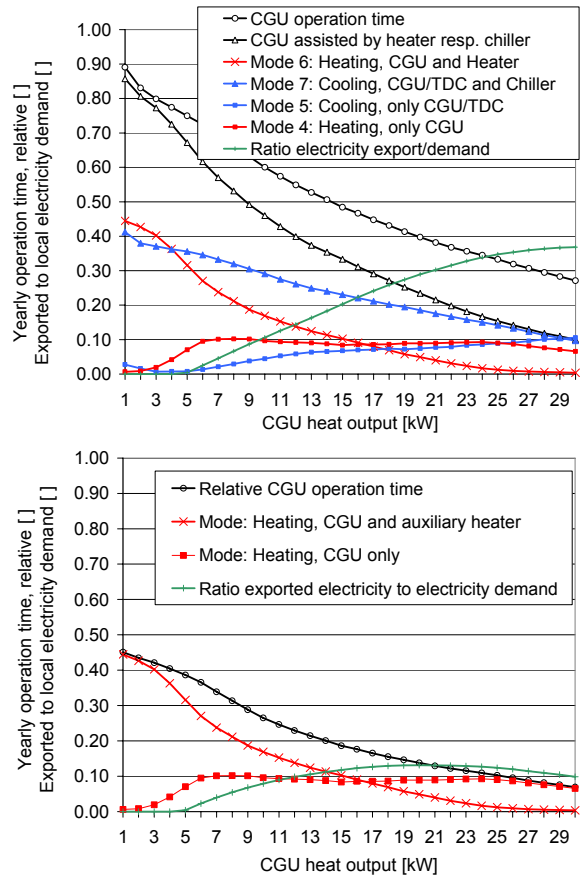


Figure 3: Operation indicators for polygeneration (1st diagram) and cogeneration (2nd diagram)

Performance of CHCP

The performance of the CHCP system was analyzed for different electricity mixes assuming a CGU size of 15 kW maximum heat output, and compared to the reference system (gas boiler and chiller only).

NRPE demand results were comparable to the reference for the Swiss mix, 12% lower for the UCTE mix and 12% higher for the CCP. P.

Emitted Greenhouse gas equivalents are substantially higher than for the reference with Swiss electricity mix.

Considering all environmental impacts, polygeneration showed a high total impact, up to the double compared to the reference in the Swiss mix case with equally weighted endpoint indicators. This high impact is mainly due to the endpoint indicators ‘ecosystem quality’ and ‘human health’ whereas the indicator ‘resource depletion’ has an attenuating effect. The performance of the cogeneration system shows a similar picture but with minor variations to the reference (2nd diagram in figure 4).

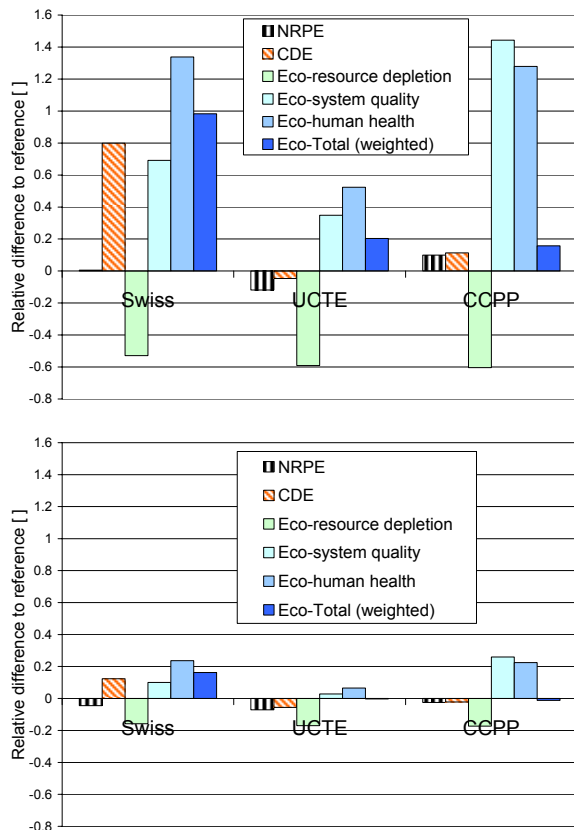


Figure 4: Performance results for different electricity mixes considering polygeneration (1st diagram) and cogeneration (2nd diagram)

The total environmental impact is based on weighting assumptions for the three endpoint indicators. Figure 5 shows for each possible weighting whether the reference system or the polygeneration system has a better total performance.

For the Swiss mix for most possible weightings the reference system performed better, for UCTE and CCPP the reference was also performing better for a wide range of weightings.

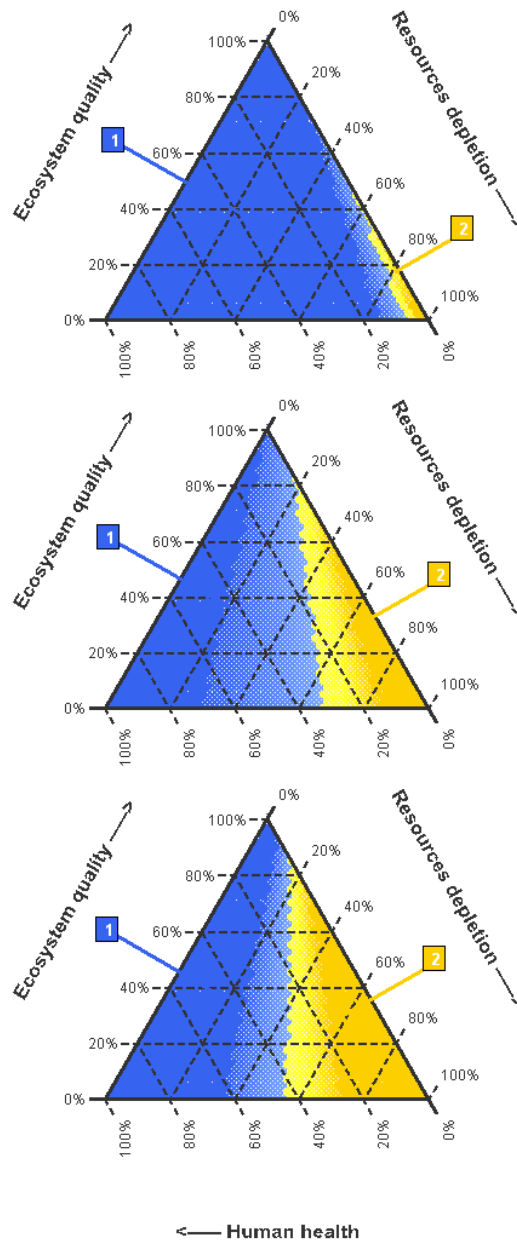


Figure 5: Total environmental performance for different electricity mixes (1st diagram: Swiss mix, 2nd diagram: UCTE mix, 3rd diagram: CCPP grid electricity). System 1 refers to the reference, system 2 to polygeneration. Fully colored area represents a performance of at least 35% better than the other system.

Sensitivity on sizing and efficiencies

Figure 6 to 10 show the system performance as a function of the CGU size and the system efficiencies, as relative difference values to the reference case. Positive relative differences indicate a higher impact value for the polygeneration or cogeneration system, compared to the reference system.

Figure 6 shows the system performance as a function of the CGU size. Within a broad power range the performance indicators NRPE, CDE and Eco-Total showed a rather flat curve. Thus the sizing of CHCP is not very critical in terms of these indicators. This is particularly valid for the case of cogeneration.

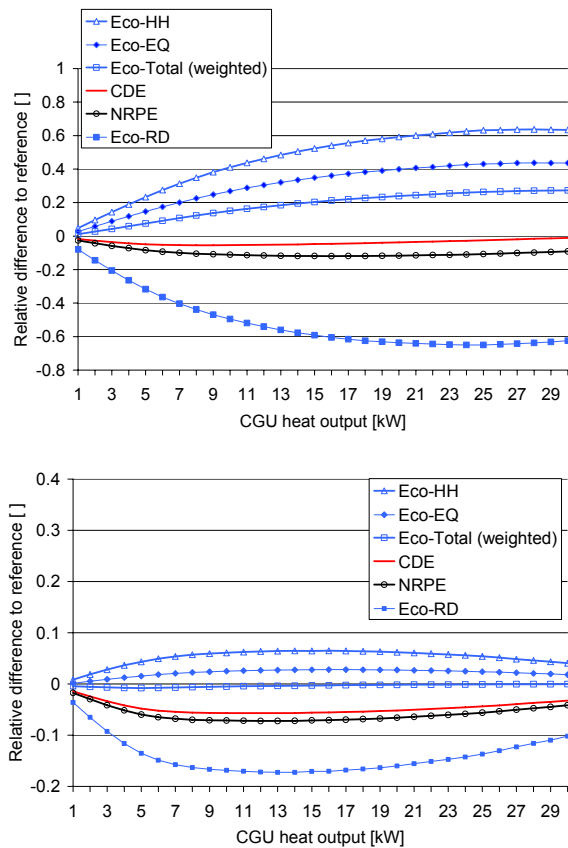


Figure 6: Performance results as a function of CGU size, UCTE electricity mix, for polygeneration (1st diagram) and cogeneration (2nd diagram)

Figure 7 shows polygeneration performance results as a function of the electrical efficiency of the CGU. NRPE performance increased with electrical efficiency for all electricity mixes. Advantageous results compared to the reference were obtained for efficiencies equal of higher than 31% for the Swiss mix, than 17% for the UCTE mix and than 46% for electricity generated by combined cycle power plants.

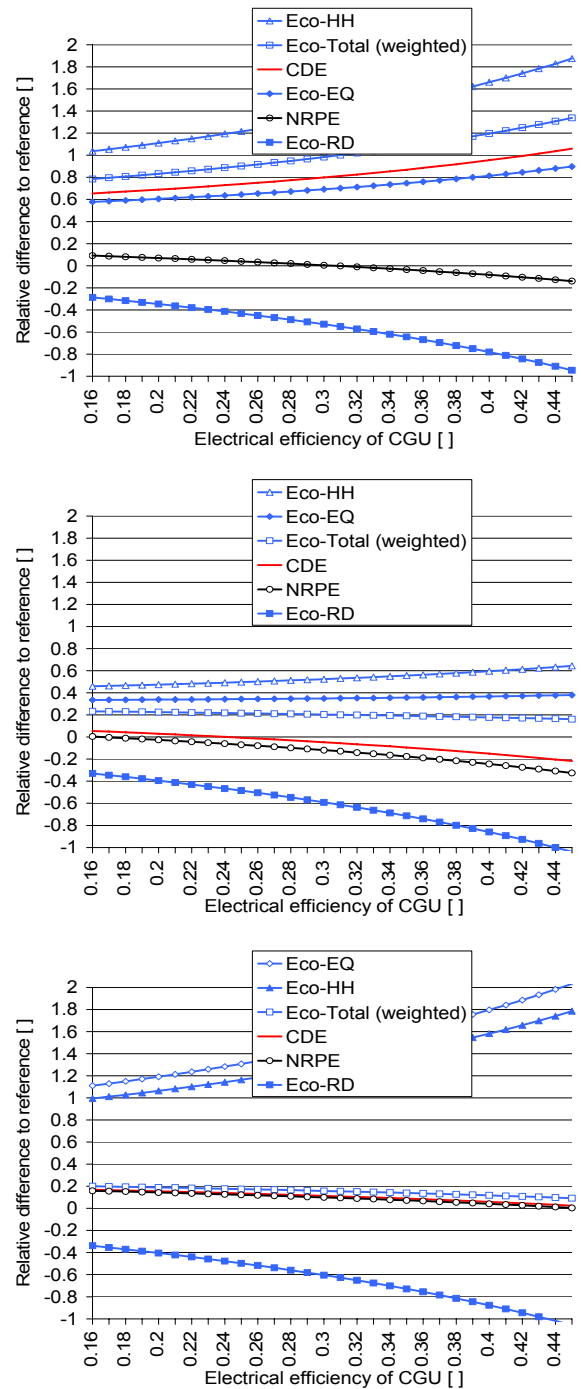


Figure 7: Polygeneration performance indicators relative to reference as a function of the electrical efficiency (LHV) of CGU for different electricity mixes (1st diagram: Swiss, 2nd diagram: UCTE, 3rd diagram: CCP). The results correspond to CGU size of 15 kW (heat output). The total CGU efficiency (LHV) was kept constant at 0.9.

The performance in terms of CDE decreased with electrical efficiency as well for the UCTE and CCPM mixes but increases for the Swiss mix. This also holds for the total environmental performance. However, total environmental performance was worse than the reference for all three electricity mixes and the whole investigated efficiency range. Further, it can be noticed that the relations between the performance in terms of NRPE, CDE and Eco-Total depend on the electrical efficiency of the CGU.

For a heat driven operation mode, as chosen in this study, the annual operation time is independent of the thermal electrical efficiency of the CGU. However, the TDC efficiency influenced the performance indicators as shown in figure 8. The variation was higher for the Eco-Total values than for the NRPE and CDE values. Even for high efficiency values the Eco-Total performance for polygeneration was significantly lower than for the reference.

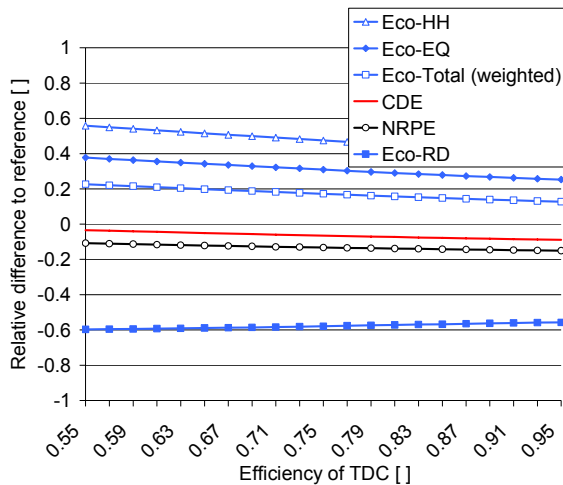


Figure 8: Polygeneration performance indicators relative to reference for UCTE electricity mix. The results correspond to CGU size of 15 kW (heat output)

When just considering the NRPE and CDE performance indicators, significant reductions can be observed for the UCTE mix, however. This is illustrated in figure 9. The electrical efficiency of the CGU had a much greater influence than the efficiency of the TDC unit (figure 10).

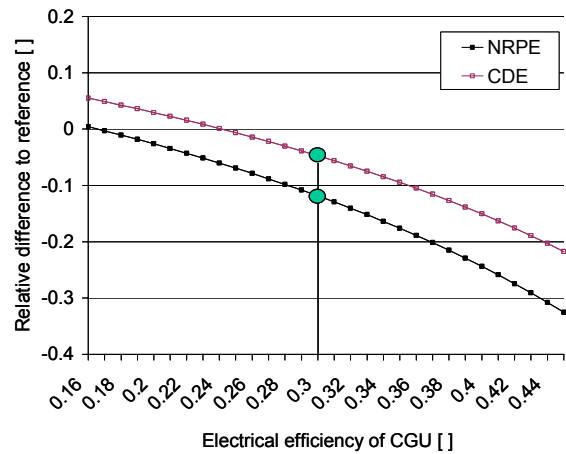


Figure 9: Polygeneration NRPE and CDE performance indicators relative to reference as a function of CGU electrical efficiency (LHV), for UCTE electricity mix. The results correspond to CGU size of 15 kW (heat output) and a TDC efficiency of 63% (see figure 10)

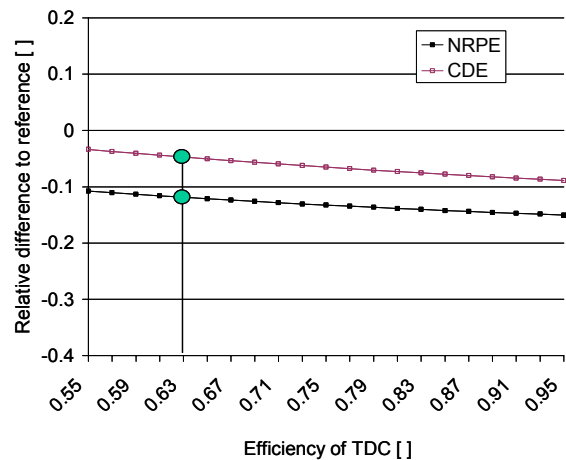


Figure 10: Polygeneration NRPE and CDE performance indicators relative to reference as a function of TDC electrical efficiency, for UCTE electricity mix. The results correspond to CGU size of 15 kW (heat output) with an electric efficiency of 30% (LHV) (see figure 9)

CONCLUSIONS

A simple performance assessment of polygeneration systems in an office building in terms of energetic and environmental indicators (in comparison to systems with gas boiler and mechanical cooling), and in terms of operational aspects was made.

The study shows that the operation time of the CGU unit can be significantly increased when coupled to a TDC unit.

In terms of non-renewable primary energy equivalents a reduction was found in all polygeneration cases with CGU electrical efficiencies (LHV) equal or higher than 17% for the UCTE mix, higher than 46% for electricity generated by combined cycle power plants, and higher than 31% for the Swiss mix.

NRPE reductions were much more influenced by the electric efficiency of the CGU than by the efficiency of the TDC unit.

Carbon dioxide emissions were only reduced by polygeneration in the cases of UCTE electricity mix, for CGU electrical efficiencies (LHV) equal or higher than 25%.

The findings for the environmental performance of polygeneration are based on equally weighted Eco-indicator 99 endpoint indicators. Values for the three endpoint indicators show a diverse picture. Thus, a different weighting for each of the endpoint indicators would lead to a contrary finding e.g. if only human health impacts would be considered.

With equally weighted endpoint indicators, the total environmental performance was below the reference for all three electricity mixes and for the whole efficiency range investigated, even though advantageous assumptions were made concerning combustion emissions.

Future work has to focus on detailed modeling considering part load characteristics, heat/cold storage capacity and control.

REFERENCES

- Artmann N., Manz H. and Heiselberg P. (2007), 'Climate potential for passive cooling of buildings by night-time ventilation in Europe', *Applied Energy*, 84/2 p187-201
- Dorer V., Weber A. (2007) 'Methodology for the Performance Assessment of Residential Cogeneration Systems', *IEA/ECBCS Annex 42 Report*, ISBN No. 978-0-662-46950-6, Catalogue No. M154-14/1-2007E-PDF, available <http://www.cogen-sim.net>
- Ecoinvent, <http://www.ecoinvent.org>, Release 2.0, November 2007, accessed 07/12/20
- Frank T. (2005), 'Climate change impacts on building heating and cooling energy demand in Switzerland', *Energy and Buildings* 37/11 1175-1185
- Hofstetter P. (1998), 'Perspectives in Life Cycle Impact Assessment - A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valuesphere', *Kluwer Academic Publishers*, Boston/Dordrecht/London, 359-373
- IPCC (2001). 'Climate Change 2001: Working Group I: The Scientific Basis'. *Intergovernmental Panel on Climate Change*
- Lehmann B., Dorer V., Koschenz M. (2007) 'Application range of thermally activated building systems tabs', *Energy and Buildings* 39, 593-598
- PolySMART, *POLYgeneration with advanced Small and Medium scale thermally driven Air-conditioning and Refrigeration Technology*, <http://www.polysmart.org>
- SIA 2024 (2006), *Guidelines for standard internal loads for energy and building services engineering*, Swiss Society of Engineers and Architects (sia), Zurich
- TRNSYS 16 (2005), *Transient System Simulation Program, SEL*, University of Wisconsin USA, TRANS-SOLAR, Stuttgart