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MICRO-GENERATION FOR 2050: EMISSIONS PERFORMANCES OF MICRO-GENERATION SOURCES DURING OPERATION

Spyros SKARVELIS-KAZAKOS, Liana M. CIPCIGAN, Nicholas JENKINS

School of Engineering, Cardiff University, Queen’s Buildings, The Parade, CARDIFF,
CF24 3AA, Wales, United Kingdom, e-mail: Skarvelis-KazakosS@Cardiff.ac.uk

Abstract: Micro-generation has the potential of reducing CO_2 emissions from the power sector. This study investigates the emissions performances of some cases of domestic micro-generation during operation. By comparison to the conventional generation options, savings of 10-45% were found, depending on the energy mix. Waste heat recovery by the micro-CHP was found to be the largest carbon saver in this study, along with the zero-carbon wind and photovoltaic micro-generation. Some carbon savings were also attained by avoiding energy losses throughout the transmission and distribution system.

Keywords: Micro-generation, carbon emissions, carbon footprint, micro-CHP, micro-sources, renewable energy, biomass

1. Introduction

The UK Government has set a goal of reducing greenhouse gas emissions by 80% by 2050 [1]. The main aim of this study is to investigate to what extent micro-generation sources can contribute to achieving this goal.

The objective of this study is to calculate the CO_2 emissions of micro-sources during their operation, using a number of simulated case studies. A comparison is made with respect to conventional generation.

In order to achieve that, a micro-generation system is defined, and the emissions savings potential of a number of micro-generation mixes is evaluated.

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2. Background

Distributed generation can be categorized according to the power rating. Micro-generation can be defined as generation of electrical output up to 5 kW [2]. The most carbon efficient micro-generation technologies are the wind turbines and the photovoltaic generators. Another micro-generation technology is the Combined Heat and Power, or otherwise referred to as micro-CHP.

Micro-CHP takes advantage of the waste heat from power generation systems, reciprocating engines for instance. It utilizes this heat locally, to avoid other heat generation such as boiler operation. Available technologies include [3, 4]:

- Reciprocating internal combustion engines;
- Micro-turbines;
- Fuel cells;
- Stirling engines.

Micro-CHP systems currently are either heat-led, or with a stable production profile. Other control strategies also exist and are presented in [5]. Wide employment of those technologies is still a challenge. Field trials are being performed throughout the EU, to assist in overcoming the obstacles [4].

As micro-CHP recovers heat that would otherwise be wasted, an increased overall efficiency of the system is therefore achieved. This, in turn, leads to reduced fuel consumption and, thus, reduced emissions. The Carbon Trust reports that 5% - 10% reduction in emissions is possible [6] and other studies suggest 10% - 40% savings [7].

Regarding the CO_2 emissions per unit of energy produced, these vary from the more carbon-efficient fuel cell, to the more polluting micro-turbine. The emission factors for three of the micro-CHP technologies, as well as a typical gas boiler are presented in Table I. Data have been gathered from four literature sources.

Table I

Carbon Dioxide emissions per kWh produced from each technology according to literature review

Emission source	CO_2 emissions (g/kWh) - [Reference]				Average CO_2 (g/kWh)
	[8]	[9]	[10]	[11]	
Fuel Cell	477	460	499	460	474.0
Micro Turbine	725	724	703	720	718.0
Diesel ICE	695	650	680	650	668.8
Boiler (Gas)	201	-	-	-	201.0

Finally, in a micro-CHP system, one of the most important parameters to take into account would be the heat to power ratio (HPR) [8]:

$$\mathrm{HPR} = \frac{\text{energy produced as heat}}{\text{energy produced as electricity}} \tag{1}$$

It is important to understand and identify the HPR of the source and the demand, so that both the electrical and thermal loads can be met. In cases where the thermal demand cannot be met, a boiler is used. Typical HPR for a fuel cell is 1.4, for a micro-turbine 2.6 while for a Diesel engine 1.6 [8].

3. Research study process

In a nutshell, the research study process followed seven steps (also see Fig. 1):

(i) The appropriate software were identified and the required input parameters were clarified.
(ii) The values for the software inputs were gathered from the literature, and were compiled in a database.
(iii) The modeled system was defined.
(iv) Modeling was performed
(v) The results from using different software tools and methods were compared.
(vi) Conclusions were drawn
(vii) The methodology was refined and the calculations were repeated.

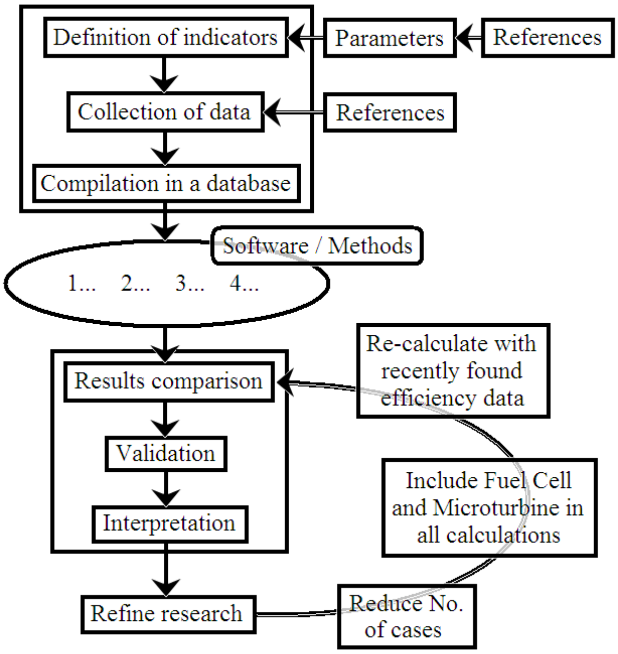

Fig. 1. Study process diagram

4. System Description

In this study, micro-generation is considered as small wind turbines, photovoltaic generators, as well as conventional and biomass fuel micro-CHP.

The system under study is based on the data provided by [12]. It includes one micro-grid comprised of 96 domestic customers, connected to the grid. Micro-generation is considered as aggregated. The studied system is illustrated schematically in Fig. 2.

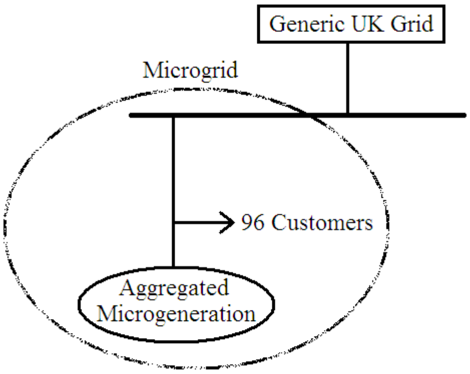

Fig. 2. Schematic of the system under study.

Three study cases are defined, taking into account the penetration level of micro-generation sources in percentage:

- Case 1 consists of 25% wind turbine and 100% micro-CHP penetration, a total of 125% penetration. Fossil fuels are used.
- Case 2 consists of 25% wind turbine and 50% micro-CHP penetration, a total of 75% penetration. Fossil fuels are used.
- Case 3 consists of 25% photovoltaic and 25% micro-CHP penetration, a total of 50% penetration. Biomass fuels are used.

Three distinct sub-cases are defined for each case by considering the micro-CHP technology as being (a) Fuel Cell, (b) Microturbine or (c) Diesel Engine. The study cases are also characterized by the fuel used by the micro-CHP. The fuel cell and the microturbine use natural gas in Cases 1 and 2 and biogas in Case 3. The diesel engine uses diesel in Cases 1 and 2 and biodiesel in Case 3.

It should be noted that 100% penetration, in this system, corresponds to 1.1 kW installed micro-generation capacity per customer, or 105.6 kW aggregated. Respectively, 50% penetration corresponds to 0.55 kW.

The purpose for the above cases is to assess the carbon performance of micro-CHP generation in different penetration levels. Wind turbines and photovoltaic generators are given a secondary role with regard to emissions, as the study is more focused on micro-CHP. The three cases and their power mixes are detailed in Table II.

Table II
Penetration cases for each source, expressed in percentage (%).

Case	Renewable Energy		Micro-CHP		Total Power Penetration
	Type	Penetration	Technology / Fuel	Penetration	
1	Wind	25% (27.5 kW)	a) Fuel cell / natural gas b) Microturbine / natural gas c) Diesel engine / diesel fuel	100% (105.6 kW)	125%
2	Wind	25% (27.5 kW)		50% (52.8 kW)	75%
3	PV	25% (27.0 kW)	a) Fuel cell / biogas b) Microturbine / biogas c) Diesel engine / biodiesel	25% (26.4 kW)	50%

The micro-sources are considered to generate at their optimal levels, and not following the load. Annual half-hour profiles obtained from the United Kingdom Generic Distribution System (UKGDS) are used for the modeling [13]. From these profiles, the annual average power values are derived, which are later being used for finding the annual energy of a typical unit from each technology. All the calculations are based on annual energy values.

According to [12], the typical value for the power of domestic micro-CHP is 1.1 kW. A small 2.5 kW wind turbine, or a 1.5 kW photovoltaic installation, is also considered. The Electricity Association [12] gives a load range of 0.16 kVA - 1.3 kVA per customer. The corresponding values are used for the aggregated resource.

The three micro-CHP technologies are chosen in accordance to the following criteria: Micro-turbines have high heat output, due to their low electrical efficiency. This makes them suitable for low penetration domestic installations, as discovered after refining the study. The diesel engine is an established and flexible technology, which requires little modifications for transition to bio-fuels. In contrast, the fuel cell is a promising high-efficiency low-emissions technology, in the first stages of commercialization [3, 4].

Electrical efficiency values for all the micro-CHP technologies are drawn from the bibliography [8, 9, 10, 11], and their average is used in the calculations. The values for the electrical efficiencies are presented in Table III.

Table III
Generating efficiencies of the different technologies*

Micro-CHP source	Efficiency (%) – [Reference]				Average (%)
	[8]	[9]	[10]	[11]	
Fuel Cell	38	39.5	39.5	44.5	40.4
Micro Turbine	25	25	26	27.5	25.9
Diesel ICE	35	38	37.5	39.5	37.5

* The gas boiler efficiency was considered to be 90%, from [8].

The overall annual electrical energy demand, considering 96 customers, is calculated to be **520.8 MWh**. For the calculation of the annual heat demand, a value of 18.000 kWh is considered per customer [14], adding up to **1728 MWh** annual demand for the 96 customers.

Finally, electricity generated by the micro-sources, but not consumed on-site, is considered to be fed to the grid. Excess heat is considered to be dissipated.

5. Methodology

Three software tools and a manual method are used for the calculations:

- RETScreen International, Clean Energy Project Analysis Software;
- Homer, from NREL;
- CHP Emissions Calculator by Energy and Environmental Analysis Inc. – EEA (developed for the United States EPA's CHP partnership) and
- A manual calculation method, without any specialized software.

Homer is a GUI based software, while the other two are embedded in Microsoft Excel sheets. In the manual method, the annual energy generation is used to verify the results obtained from the software tools

Two parameters are being calculated with these tools:

- the total CO_2 emissions from the micro-generation for each case;
- the CO_2 emissions savings that would be achieved by displacing emissions from grid electricity generation and gas boiler heat.

The calculation method used by all the software is similar and can be described as follows: Having the efficiency of the generation technology and the energy content of the fuel, the fuel consumption is found. This can then be used along with the fuel emission factors to calculate the emissions. The above method is illustrated in Fig. 3.

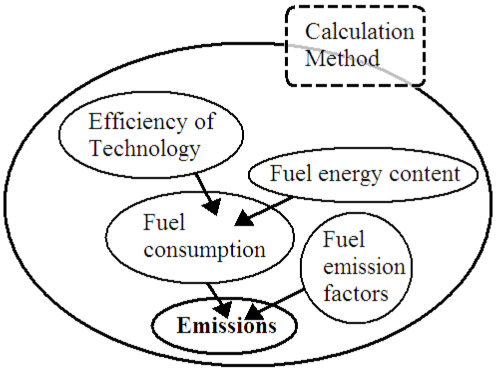

Fig. 3. Emissions calculation method.

The displaced conventional grid generation emissions are found by multiplying the total energy produced in each case with the grid electricity emission factor. The displaced emissions from the heat load covered by the boiler are also calculated using the same method. Finally, the displaced emissions are subtracted from the micro-generation system emissions to find the emission savings.

All the inputs and fuel data are drawn from the literature. The efficiencies used are the averages from [8], [9], [10] and [11]. The fuel emission factors are drawn from the Intergovernmental Panel for Climate Change - IPCC [15]. The energy content of the fuels is found from the Carbon Trust [16], as well as the emission factor for the UK power network (**430 gCO_2/kWh)**, and the unit conversion factors. An exception is the energy content of biodiesel, which according to the UK Department of Transport is 92% of the regular Diesel [17]. Also, the density of biodiesel is found to be 0.88 kg/L, from the Oak Ridge National Laboratory [18].

The emission factors for the fuels are input as CO_2 equivalent, where possible, including CH_4 and N_2O emissions equivalence as Greenhouse Gases, as found from the IPCC [15].

It is noted that the CO_2 emission factor for biogas and biodiesel is assumed to be zero, for simplicity. According to the Carbon Cycle theory, the biomass fuel CO_2 emissions are absorbed by the next generation of biomass producing plants. Consequently, despite that biofuels emit CO_2 when they burn, this is considered as neutralized or offset. However, the CH_4 and N_2O carbon equivalent emissions are not offset. There is some controversy regarding the neutrality of biomass CO_2 emissions.

Finally, the Transmission and Distribution losses had to be accounted for, as micro-generation is situated near the load, avoiding T&D losses. The calculations were performed with no losses and with 8% losses, according to [19].

6. Results

Table IV presents the CO_2 emission factors for each of the micro-CHP technologies, as well as the gas boiler. Values from the literature are averaged and compared to the calculated values. They are found to be similar, which provides a first validation of the calculations.

Table IV
Emissions for each technology

Emission source	CO_2 emissions (g/kWh) - [Reference]				Average CO_2 (g/kWh)	Calculated CO_2 (g/kWh)
	[8]	[9]	[10]	[11]		
Fuel Cell	477	460	499	460	474.0	455.2
Micro Turbine	725	724	703	720	718.0	706.8
Diesel ICE	695	650	680	650	668.8	667.1
Boiler (Gas)	201	-	-	-	201.0	204.2

Fig. 4 shows the CO_2 emissions from the micro-generation system for the first case, calculated with four methods. It can be seen that the results obtained from the four methods seem consistent. The CHP Emissions Calculator systematically provides slightly higher emission values than the rest of the methods.

Fig. 5 presents the emissions savings from the micro-generation, when compared to the grid electricity and boiler heat emissions. The results from the four methods were averaged.

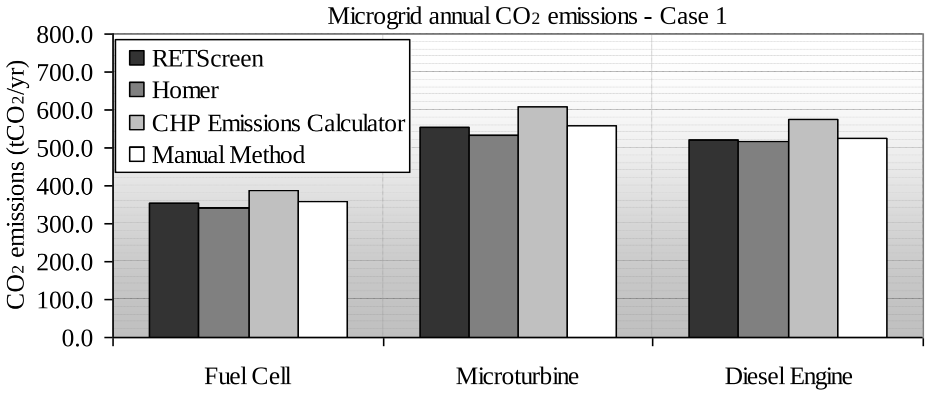

Fig. 4. CO_2 emissions from the microgeneration system, in Case 1 for all micro-CHP technologies. All emissions are shown in tonnes CO_2 per year

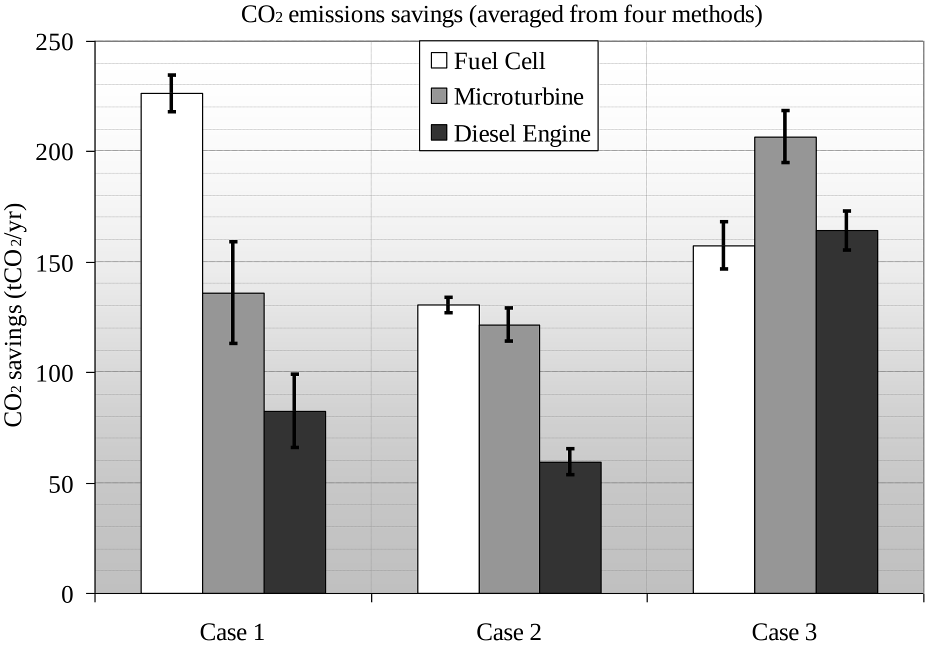

Fig. 5. CO_2 savings from the micro-generation system, when compared to the UK conventional grid generation emissions, plus the boiler emissions. Error bars show the standard deviation as calculated from the averaged four methods

It is noted that in Case 1, the Micro-turbine produces too much heat, which cannot be utilized by the customers, and is therefore wasted. This limits the savings, thus microturbine penetration over 50% (Case 2) seems to have little value in terms of CO_2 emissions.

If the transmission and distribution losses were taken into account, additional CO_2 savings would be achieved, due to avoided conventional generation. These savings would amount to 20.3 tCO_2/yr, 14.5 tCO_2/yr and 7.6 tCO_2/yr for Cases 1, 2 and 3 respectively.

The emissions savings shown in Fig. 5 are also determined as a percentage of the initial emissions from the conventional generation. It is found that they range approximately from 10% up to 45% in Cases 1 and 2, depending on the micro-CHP technology. In Case 3, the relative savings reach approximately 98%. On the same basis, including the transmission and distribution losses in the calculations would increase the savings by an additional 1-3%.

Finally, wind turbines contribute to the savings by 28.1 tCO_2/yr, while photovoltaic generators by 9.7 tCO_2/yr.

7. Conclusions

The emissions savings, in this study, vary from 10% up to 45%, for Cases 1 and 2, and reach about 98% for Case 3. Other studies also suggest a similar range [7], only considering micro-CHP, though, and with different displaced generation scenarios. The Carbon Trust [6] gives a respective range of 5% to 10%, only for micro-CHP.

Diesel is found to give the least savings when fossil fuels are used. This is due to its high emission rate, which, combined with the relatively low heat recovery, does not give a carbon footprint much lower than the grid and boiler. However, diesel engines have the advantage of being a very much established and cheap technology, compared to the other two. The greatest value of this technology is the ability of a relatively simple transition to biodiesel.

The largest part of the savings from a micro-generation system like this is obtained by the recovery of waste heat from the micro-CHP. This is essentially saving boiler emissions that would otherwise be required to cover the heat load.

Therefore, the choice for every installation should be made according to both power and heat demand. Otherwise, if the waste heat recovery advantage would not be exploited, the overall carbon performance would drop significantly.

This advantage makes technologies with low heat recovery a more suitable option for high power penetration levels, and vice versa, as heat cannot be utilized off-site.

The order of the savings in Case 3 is different than Cases 1 and 2. The reason is that in Case 3, the lower per kWh emissions of the fuel cell no longer give an advantage, since the emissions are already low, due to biomass. In contrast, the lower heat to power ratio [8] is disadvantageous, thus saving less boiler emissions.

Overall, the fuel cell seems to be the most carbon efficient option, but it is also the most expensive. The next best option is the microturbine, provided that the recovered heat is utilized. Although the Diesel engine seems to provide lower savings, its greatest value is its simplicity and cost-effectiveness.

To conclude, low-carbon micro-generation technologies in conjunction with energy efficiency measures, as presented in [20] for instance, have the potential to lead the way to a low-carbon civil energy sector.

8. Future Work

The next step in this research will be to investigate the carbon footprint of a micro-generation system, preferably a real operational micro-grid. This will be done by means of Life Cycle Assessment, according to the procedures identified in the initial review. Component breakdown will be part of this process, using databases such as the Inventory of Carbon and Energy (ICE) from the University of Bath [21].

9. References

[1] Directgov Newsroom, http://www.direct.gov.uk/en/Nl1/Newsroom/DG_172368, (visited 25/03/2009)

[2] Ackermann, T., Andersson, G. and L. Söder, (2000). "Distributed generation: a definition." Electric Power Systems Research **57**(3): 195-204.

[3] Onovwiona, H. I. and V. I. Ugursal (2006). "Residential cogeneration systems: review of the current technology." Renewable and Sustainable Energy Reviews **10**(5): 389-431.

[4] Kuhn, V., Klemes, J. and I. Bulatov, (2008). "MicroCHP: Overview of selected technologies, products and field test results." Applied Thermal Engineering **28**(16): 2039-2048.

[5] Peacock, A. D. and M. Newborough (2007). "Controlling micro-CHP systems to modulate electrical load profiles." Energy **32**(7): 1093-1103.

[6] Carbon Trust, (2007), “Micro-CHP Accelerator”, Interim Report, November 2007, Publication ID: CTC726

[7] De Paepe, M., D'Herdt, P. and D. Mertens, (2006). "Micro-CHP systems for residential applications." Energy Conversion and Management **47**(18-19): 3435-3446.

[8] Strachan, N. D. and A. E. Farrell (2006). "Emissions from distributed vs. centralized generation: The importance of system performance." Energy Policy **34**(17): 2677-2689.

[9] Bluestein, J. (2000). "Environmental Benefits of Distributed Generation", Energy and Environmental Analysis, Inc.

[10] Greene, N. and R. Hammerschlag (2000). "Small and Clean is Beautiful: Exploring the Emissions of Distributed Generation and Pollution Prevention Policies." The Electricity Journal **13**(5): 50-60.

[11] International Energy Agency - IEA, (2002), “Distributed Generation in Liberalised Electricity Markets”, Paris, 2002.

[12] Ingram, S.; Probert, S. and Jackson, K. (2003), “The Impact Of Small Scale Embedded Generation On The Operating Parameters Of Distribution Networks”, Department of Trade and Industry, Contractor: PB Power, Report No. K/EL/00303/04/01.

[13] DTI Centre for Distributed Generation and Sustainable Electrical Energy, “United Kingdom Generic Distribution System (UKGDS)”, http://www.sedg.ac.uk/ukgds.htm (visited 25/03/2009)

[14] Brown, A.; Maryan, P. and Rudd, H., "Renewable Heat and Heat from Combined Heat and Power Plants - Study and Analysis", Report from AEA Technology for DTI and Defra, http://www.berr.gov.uk/files/file21141.pdf (visited 25/03/2009)

[15] Intergovernmental Panel on Climate Change - IPCC, (2006), "2006 IPCC Guidelines for National Greenhouse Gas Inventories", National Greenhouse Gas Inventories Programme, Volume 2: Energy, Chapter 2: Stationary Combustion.

[16] Carbon Trust, (2007), Measuring CO_2 Methodologies. http://www.carbontrust.co.uk/resource/measuring_co2/Measuring_CO2_Methodologies.htm (visited 25/03/2009)

[17] Department of Transport, (2007), UK Report to European Commission under Article 4 of the Biofuels Directive (2003/30/EC), Section 4: UK Production, Sales and Availability, UK Sales for 2006. http://www.dft.gov.uk/pgr/roads/environment/ukreptoecbiofuels2003301?page=7 (visited 25/03/2009)

[18] Oak Ridge National Laboratory, Energy Conversion Factors List. http://bioenergy.ornl.gov/papers/misc/energy_conv.html (visited 25/03/2009)

[19] Ferreira, S., (2008), "Eco-sheet: 1kWh generated using different energy sources", European Copper Institute, via Leonardo ENERGY, September 2008. http://www.leonardo-energy.org/drupal/node/3665 (visited 25/03/2009)

[20] Kistelegdi, I. (2008). "Concert and conference center — Pécs; Energetic and ecological concept." Pollack Periodica **3**(3): 19-29.

[21] Hammond, G. and Jones, C., (2006), "Inventory of Carbon and Energy (ICE)", University of Bath.