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Parametric comparative analysis of lifetime energy demand and CO_2-eq savings of a SOFC m-CHP unit.

Dimitrios Giannopoulos and Maria Founti
Laboratory of Heterogeneous Mixtures and Combustion Systems
Thermal Engineering Section, School of Mechanical Engineering
National Technical University of Athens, Greece
Heroon Polytechneioy 9, Polytechnioupoli Zografou, Athens 15780, Greece
Tel.: +30-210-7723605
Fax: +30-210-7723527
mfou@central.ntua.gr

Abstract

The present paper utilises the results of an environmental impact assessment through Life Cycle Analysis (LCA) for a Solid Oxide Fuel Cell (SOFC) microCHP unit for the determination of a critical operational threshold, over which the m-CHP unit lifetime primary energy demand and CO_2-eq emissions are lower than two reference cases: (a) a conventional system (gas boiler and grid electricity) and (b) a competitive m-CHP unit, powered by a gas fuelled Internal Combustion Engine.

Towards this objective, several runs of the built LCA model were performed under variable operational conditions (m-CHP electric efficiency and annual thermal load coverage). The results acquired were inter- and extra-polated within an operational range of the selected parameters. The contour graphs produced provide vital and comprehensive information regarding how to ensure and realise the environmental advantages of the SOFC technology in m-CHP applications.

Despite the weak environmental aspect of the SOFC unit identified (being – at present – powered exclusively by a fossil fuel – natural gas), the feasibility to outperform both competitive cases is herewith demonstrated. The overall environmental advantage of the SOFC unit modelled is realised through avoiding central generation emissions when the m-CHP electricity surplus is exported to the grid and achieving higher electric efficiency potential than m-CHP competition. The comparative Life Cycle Analysis performed identified a clear potential towards decreasing the Cumulative Energy Demand and the Global Warming Potential of covering domestic power loads.

Introduction

Achieving sustainable development in the energy sector in general and in domestic energy consumption in particular, requires the reduction of non-renewable primary energy input and greenhouse gas emissions. One possible developmental path is decentralization of the electricity system. Distributed power generation in small, decentralized units is expected to help reducing emissions and saving grid capacity, providing also opportunities for renewable energy [1].

Recent technological advances have led to an increased interest in small CHP units, with the prospects of developing units that can provide electricity and heat for individual buildings. Micro cogeneration (micro CHP or mCHP) is defined as the simultaneous generation of heat, or cooling energy and power in an individual building, based on small energy conversion units below 15 kWel. Whereas the heat produced is used for space and water heating/cooling inside the building, the electricity produced is used within the building or fed into the public grid.

The present work utilises the results of an environmental impact assessment through Life Cycle Analysis (LCA) for a Solid Oxide Fuel Cell (SOFC) microCHP unit [2]. Its major objective is the determination of a critical operational threshold, over which the m-CHP unit lifetime primary energy demand and CO_2-eq emissions are lower than two reference cases: (a) a conventional system (gas boiler and grid electricity) and (b) a competitive m-CHP unit, powered by a gas fuelled Internal Combustion Engine.
The paper is structured in the following sections: (a) Description of the main points of the LCA methodology and important technical issues such as the allocation of impact in both the electric and thermal output and the impact categories selected; (b) Definition of the case studies examined and presentation of assumptions and assessment scenarios regarding efficiencies, annual utilisation, electric and thermal output, etc.; (c) LCA results referring to the SOFC unit lifecycle scenarios and the comparison with both competitive systems and (d) Conclusions regarding the environmental performance of the systems examined and the influence of important parameters.

The work herewith presented is a follow-up of a previous paper [2], where the systems examined and the life cycle modeling are described in detail. Both papers refer to work performed in the frame of the EU funded projects “FlameSOFC” and “FC-DISTRICT”.

1. Methodological Approach

Life Cycle Assessment [3-5] is a methodology aiming: (a) to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment and (b) to identify and evaluate opportunities to bring about environmental improvements. The International Standard ISO 14040 provides the methodological framework for LCA applications, as well as the definitions of the four main LCA phases (Figure 1):

Goal Definition and Scoping (1): The functional unit chosen for the current study is 1 kWh of electricity delivered for domestic consumption. In the case of m-CHP, the co-generated heat has also to be considered. For each technology a unique functional unit has been defined, since the ratio of heat and electricity depends on the system’s configuration and the engine's efficiency. However, the results of a LCA should be comparable to other systems of electricity and heat generation. An allocation between electricity and heat is necessary to get the specific emissions, for example the emissions of CO_2 per kWh of electricity and per kWh of heat. A widely adopted [6,7] allocation method between electricity and heat is implemented on the basis of exergy. The allocation factors depend on the CHP efficiencies and the predominant system operating temperatures.

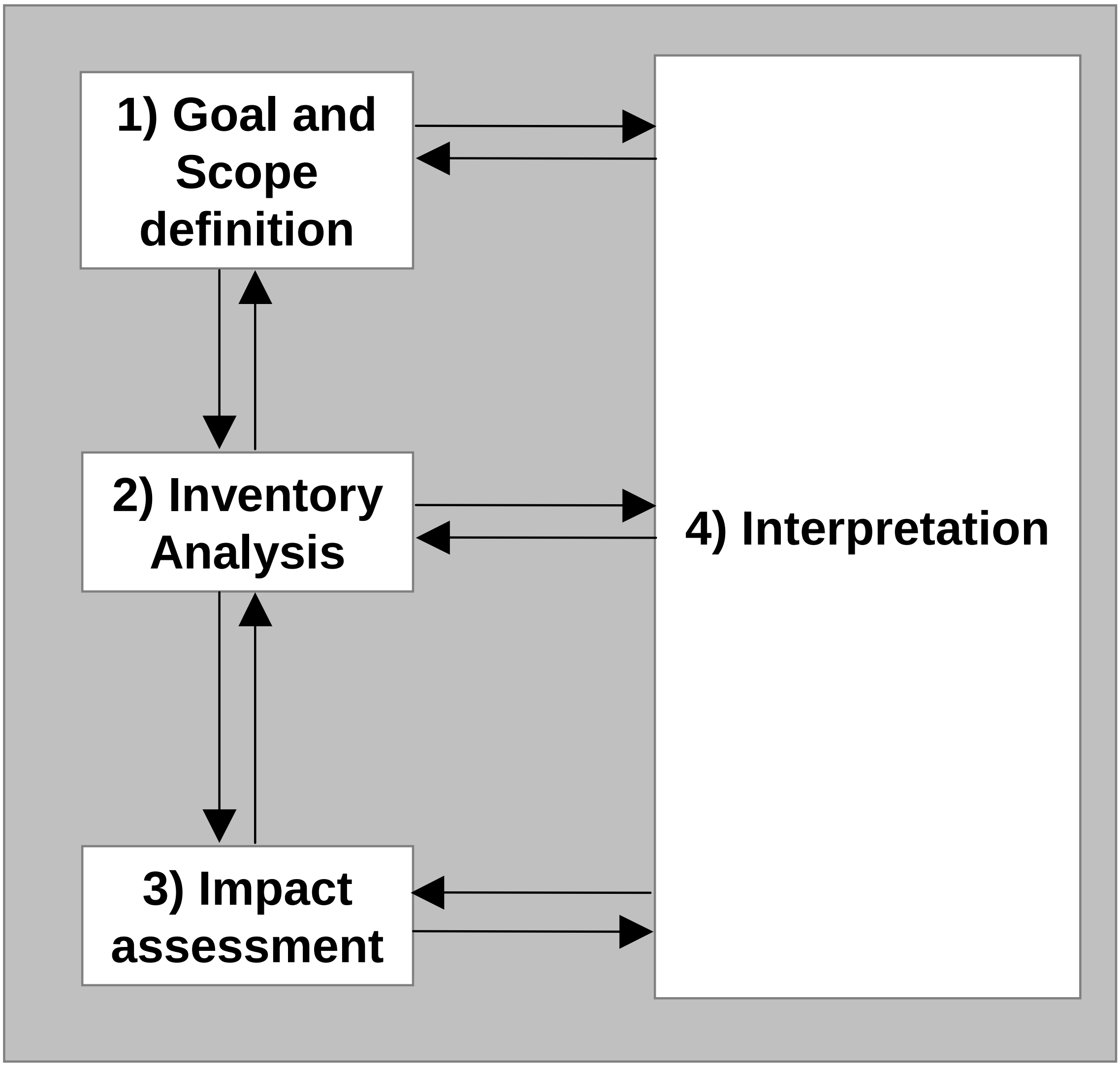

Figure 1: LCA Phases

For the present work, the selected predominant system operating temperatures were: Outgoing temperature=80°C, Return temperature=30°C. The ambient temperature (9°C) is set according to Central European reference data. It is assumed that a single-family dwelling has an annual requirement of 5 MWhel and 20MWhth [8]. Results refer to a near future (~2015-2020) situation when the SOFC unit is expected to be installed. Therefore, the timeframe of all input data (electricity mix, natural gas transport, electric and thermal loads, etc) refer to the present time, or at least after the year 2000.

Inventory Analysis (2): In this phase, the energy, water and materials usage and environmental releases (e.g. air emissions, solid waste disposal, wastewater discharge) are identified and quantified.

Impact Assessment (3): The inventory is processed in order to calculate total energy demand, emissions and resource consumption. The emissions (CO_2, NO_x, VOCs, etc.) are transformed to impacts (Global Warming Potential, Acidification, Human Toxicity, etc.) through the implementation of certain impact assessment methodologies [9] (Table 1).

Impact Assessment Methodology	Impact category	Content
Energy Demand	Cumulative Energy Demand (CED)	Sum of all energy used for extraction, transportation, manufacturing, assembly, recycling of raw materials; natural gas supply; electricity grid interconnection
	Fossil Energy Demand (FED)	The fraction of CED including only fossil primary energy
EPD 2007	Global Warming Potential (GWP)	Ability of certain atmospheric gases to retain heat, which is radiating from earth. Factors are expressed for time horizon 100 years (GWP100), in kg CO_2-eq/kg emission.

Table 1: Impact Assessment methodologies and categories used

Interpretation (4): For the evaluation of the results of the inventory analysis and impact assessment the comparison to two reference competitive cases was examined: (a) a Standard Case, where the annual electric and thermal loads of a single family dwelling are covered by grid electricity and a gas boiler (Figure 2) and (b) a competitive m-CHP unit, powered by a gas fuelled Internal Combustion Engine. Towards determining the SOFC unit critical operational thresholds, several runs of the built LCA model were performed under variable operational conditions (m-CHP electric efficiency and annual thermal load coverage). The results acquired were inter- and extra-polated within an operational range of the selected parameters.

2. Definition of case studies examined

Details regarding the systems and the corresponding life cycle modeling are presented in [2]. The assessment of the environmental impact of the operation stage of each case examined accounted for the influence of the following parameters:

- Electrical efficiency of the SOFC unit: The cogeneration efficiency is considered 91% in all cases. Two seasonal cases of 25% and 35% electrical efficiency were also examined.
- Level of annual heat load coverage. The foreseen operational strategy is to follow the heat demand. Considering the latter, two cases have been examined (figures 3 and 4), covering the full and half of the annual heating load (peak boiler for the rest of the load). Detailed load profiles were not presently considered.

Assessment Case A – SOFC unit vs Standard Case

The major assumptions regarding the annual operation of the two systems are presented in Table 2. In order to examine the effect of the aforementioned parameters, four scenarios were formulated. Table 3 presents the details of the Assessment Case A scenarios. Indicator “b” refers to a case where only half of the annual thermal load is covered by the

SOFC unit and the rest by a peak gas boiler with the same efficiency with the Standard Case boiler. Covering half of the heat load has a direct connection to the annual unit utilization (working hours per year – Table 4).

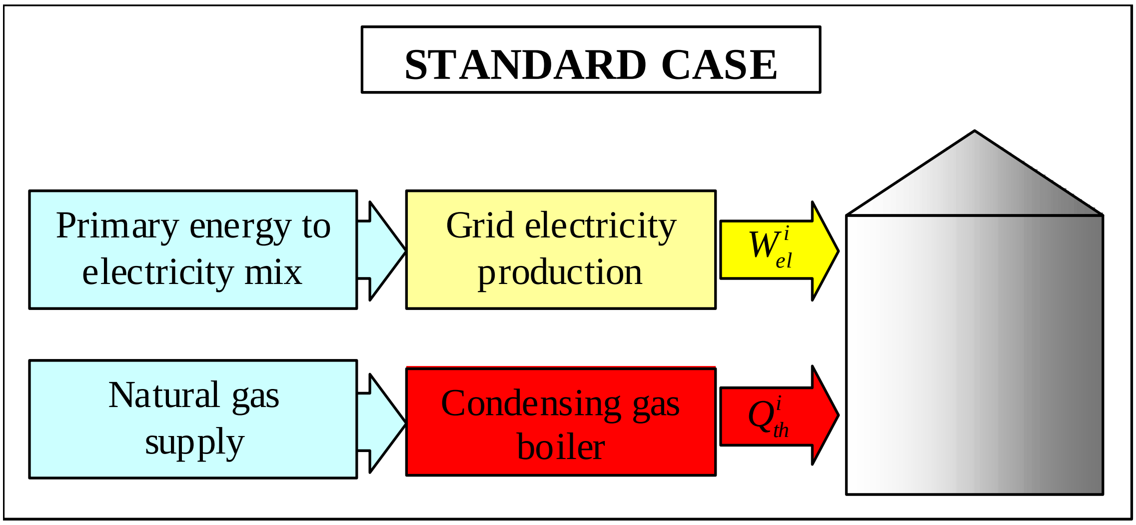

Figure 2: Layout of the Standard Case examined

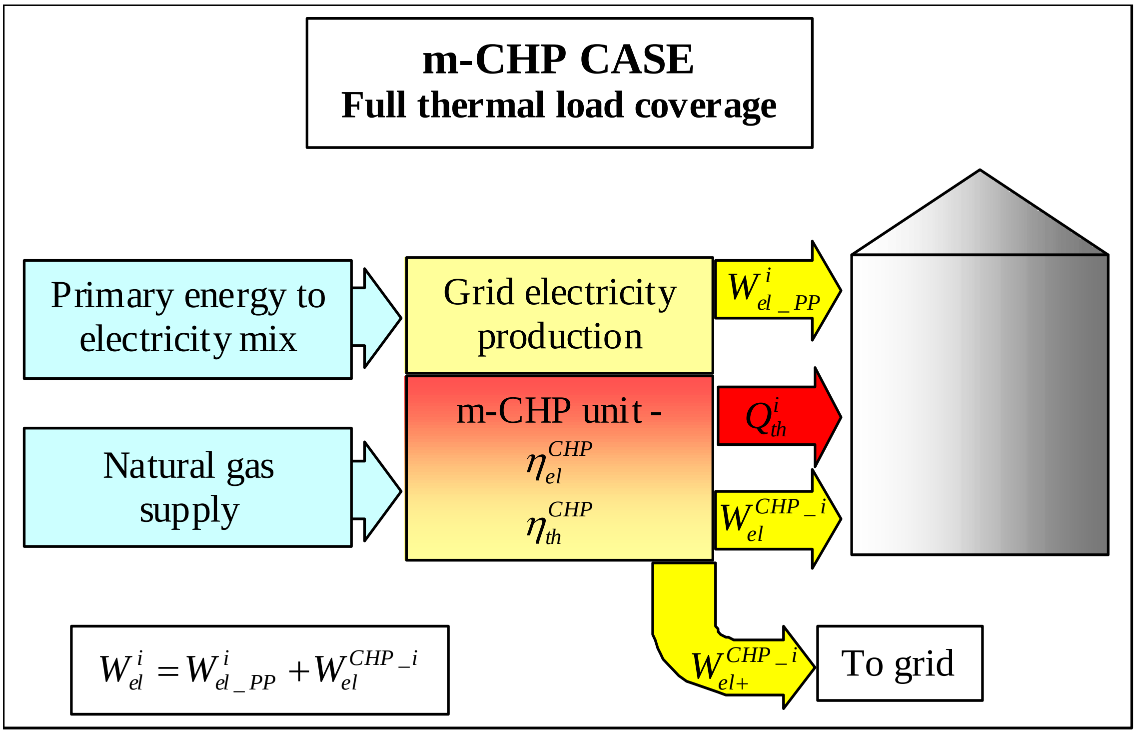

Figure 3: Layout of the mCHP case with total annual thermal load coverage.

The timeframe of the analysis is set according to the estimated operational lifetime of the two competing cases (Table 2). Due to that, more than one stack will be required throughout the SOFC unit lifecycle. The rest of the SOFC components are assumed to have a lifetime that matches the working hours of the competitive case. Table 4 presents estimations for the required number of stacks, alongside with the calculated annual operating hours.

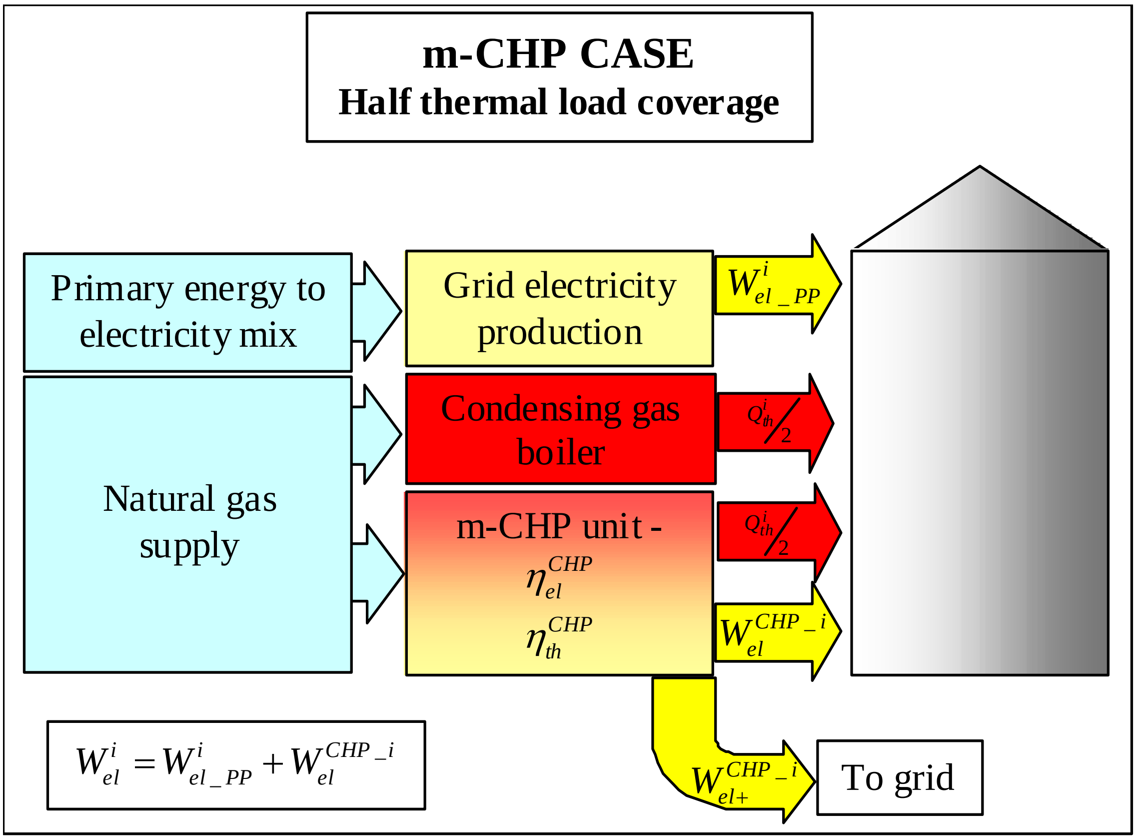

Figure 4: Layout of the mCHP case where half of the annual thermal load is covered

	SOFC Unit	Standard Case	Comments – Data Source
Domestic installation	SOFC m-CHP unit	Gas boiler	
Load coverage	Power: m-CHP output+grid Heat: m-CHP output (+heat buffer)	Power: grid Heat: Gas boiler output (+heat buffer)	
Operation mode	Full capacity operation		
Operational lifetime (hrs)	30000 (stack)	50000	FlameSOFC project specifications.
Annual electric import from grid	10% of annual electric load + possible negative balance	100% of annual electric load	Due to the thermally driven operational strategy, grid import is inevitable, even when an electricity surplus is produced by the SOFC unit.
Thermal losses (storage etc.)	15% of thermal load covered		Both systems produce 115% of the thermal load covered.

Table 2: Major assumptions of Assessment Case A

	SOFC unit				Gas Boiler
	Scenario 1		Scenario 2		
Annual electric eff.	25%		35%		-
	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	
Operational target	Full coverage of annual thermal load	Half coverage of annual thermal load	Full coverage of annual thermal load	Half coverage of annual thermal load	-
Annual thermal eff.	66%		56%		95%
Max. electric output	2.0 kWel				-
Max. thermal output	5.3 kWth		3.2 kWth		8 kWth

Table 3: Assessment Case A - Scenarios examined

SOFC unit								Gas boiler
Scenario 1a		Scenario 1b		Scenario 2a		Scenario 2b		
Stacks	h/year	Stacks	h/year	Stacks	h/year	Stacks	h/year	h/year
2.52	4356	1.26	2178	4.16	7188	2.08	3594	2875

Table 4: Number of stacks required and operational hours/year during SOFC unit lifetime

The assumptions of the four scenarios described in tables 2, 3 and 4 lead to four different annual electric balances, which are presented in figure 5. As observed, in scenario 1b, which has the least annual utilisation, the SOFC unit generation is not enough to provide a surplus for grid export. On the contrary, in the “high utilisation” scenario 2a, the exports approximate twice the dwelling annual load.

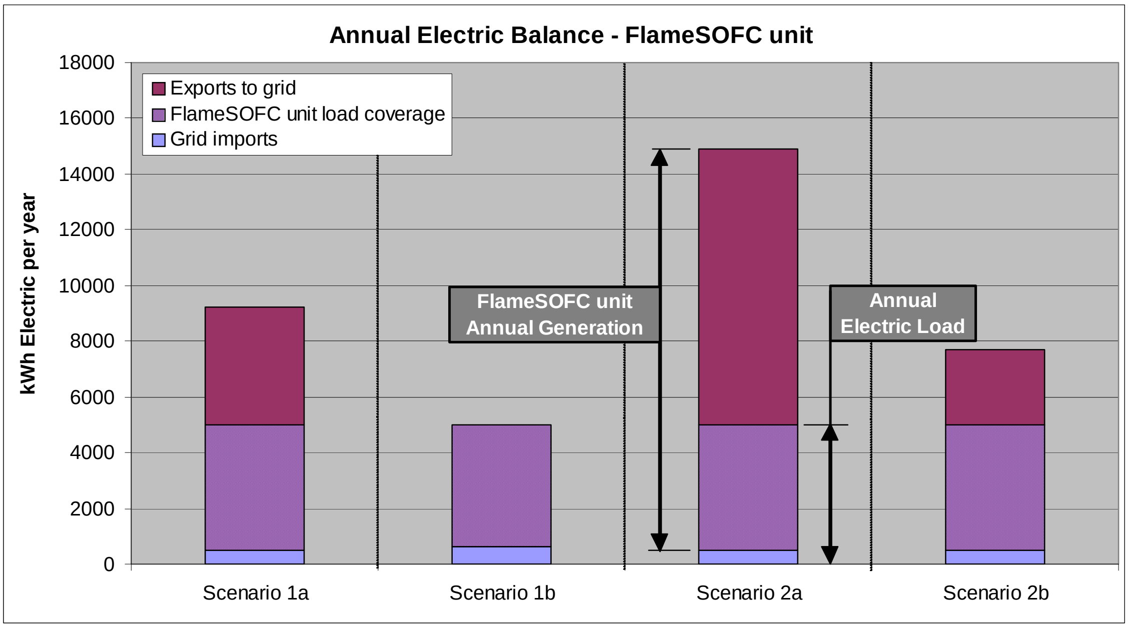

Figure 5: Annual Electric Balance – SOFC unit

Reference [9] and the Ecoinvent 2.0 LCA database provided the emission factors used for the estimation of the operational emissions (details provided in [2]). Natural gas is used in all cases. The emissions related to the grid electricity consumed were considered accordingly to the German electricity mix (relevant data from the Ecoinvent LCA Database).

The allocation of impact between the produced electricity and heat is performed in the basis of exergy. This allocation does not pertain to the Standard Case, where electricity and heat are separately produced. Table 5 presents the corresponding allocation factors. Scenario 2 provides increased allocation for the electric kWh of the FlameSOFC unit, due to the higher Power to Heat ratio.

Exergetic Allocation Factors (AF)			
Scenario 1		Scenario 2	
Electric AFel	Thermal AFth	Electric AFel	Thermal AFth
0.746	0.254	0.829	0.171

Table 5: Exergetic allocation factors for the two functional units used.

Assessment Case B – SOFC unit vs IC Engine

In parallel to the previous Assessment Case, the assumptions of the comparison with the ICE (Internal Combustion Engine) are herewith presented in the following Tables 6-10 and fig. 6.

	SOFC Unit	IC engine	Comments – Data Source
Domestic installation	SOFC m-CHP unit	IC m-CHP engine	-
Load coverage	Power: m-CHP output+grid Heat: m-CHP output (+heat buffer)		-
Operation mode	Full capacity operation		-
Operational lifetime (hrs)	30000 (stack)	50000	FlameSOFC project specifications.
Annual electric import from grid[1]	10% of annual electric load + possible negative balance	5% of annual electric load	Higher nominal electricity output of ICE
Thermal losses (storage etc.)	15% of thermal load covered		Both systems will produce 115% of the thermal load covered.

Table 6: Major assumptions of Assessment Case B.

The four scenarios examined are set between two extreme situations of very low (Scenario 1b) and very high (Scenario 2a) annual SOFC unit utilisation. Lower annual utilisation is expected for the ICE, due to the higher thermal output.

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[1] Refers to the case where m-CHP electricity production exceeds the annual load.

	SOFC unit			
	Scenario 1		Scenario 2	
Annual electric eff.	25%		35%	
	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b
Operational target	Full coverage of annual thermal load	Half coverage of annual thermal load	Full coverage of annual thermal load	Half coverage of annual thermal load
Annual thermal eff.	66%		56%	
Max. electric output	2.0 kWel			
Max. thermal output	5.3 kWth		3.2 kWth	

Table 7: Assessment Case B – SOFC unit data and assumptions on the scenarios examined

	ICE (Ecopower)			
	Scenario 1		Scenario 2	
Annual electric eff.	25%			
	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b
Operational target	Full coverage of annual thermal load	Half coverage of annual thermal load	Full coverage of annual thermal load	Half coverage of annual thermal load
Annual thermal eff.	65%			
Max. electric output	3.0 kWel			
Max. thermal output	8.0 kWth			

Table 8: Assessment Case B - ICE data and assumptions on the scenarios examined

SOFC unit							
Scenario 1a		Scenario 1b		Scenario 2a		Scenario 2b	
Stacks	h/year	Stacks	h/year	Stacks	h/year	Stacks	h/year
2.52	4356	2.52	2178	4.16	7188	4.16	3594

Table 9: Number of stacks required during SOFC unit lifetime and annual operating hours

IC Engine			
Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b
h/year	h/year	h/year	h/year
2875	1438	2875	1438

Table 10: Annual operating hours of the IC Engine

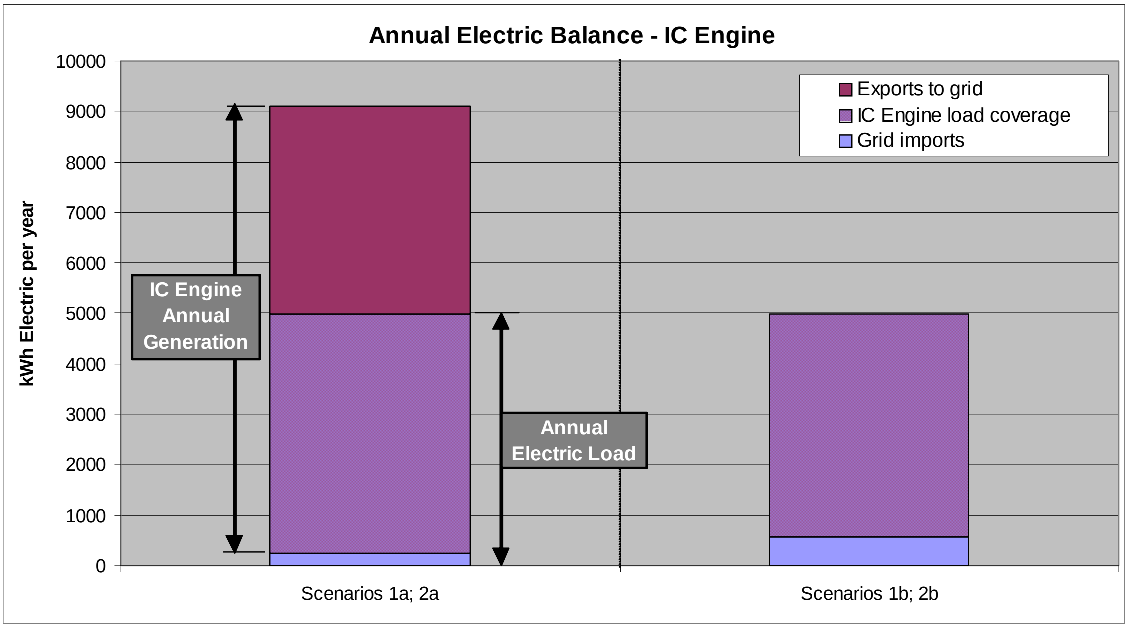

Figure 6: Annual Electric Balance – IC engine

The emission factors for the ICE operation are correspondingly accessed from [9]. In Assessment Case B, the allocation factors of Table 5 apply to both systems examined.

3. Results

In the following section, the results of the impact assessment of the SOFC unit life cycle are presented. Additionally, two competitive life cycles were analysed and calculated, as described above. The presentation of the results follows the distinct assessment cases and scenarios formulated in the previous section. All results are reduced to the functional units determined (1 kWh of electricity and heat). The Life Cycle analysis was performed using SimaPRO 7.0, which is a widely accepted software tool, containing up-to-date and reliable databases.

Assessment Case A – SOFC unit vs Standard Case

In Case A the SOFC unit is compared to a Standard Case, where the annual electric and thermal loads of a single family dwelling are covered by grid electricity and a gas boiler. As described above, Scenario 1 and 2 consider a low (25%) and a high (35%) electric efficiency SOFC unit. Indicators “a” and “b” refer to covering the full or the half of the annual thermal load by the SOFC unit, respectively. In the half coverage case, a peak gas boiler is considered, having the same efficiency with the Standard Case boiler.

Figure 7 presents the comparison of the SOFC life cycle scenarios with the Standard Case life cycle (dark brown bar on the right side of each block), aiming to assess the effect of covering half of the annual thermal load and to determine strong and weak environmental aspects of the SOFC unit. In order to quantify the effect of the electricity surplus being exported to the grid, a faded area per impact category illustrates the impact reduction when considering the relevant benefit. The accurate estimation of the environmental benefit of the displaced grid electricity is quite difficult, since it is uncertain what kind of generation takes place at the specific time of the m-CHP export to the grid. In other words, one cannot be confident how “dirty” is the grid kWh at any specific moment. As explained earlier, the benefit shown in fig. 7 was calculated according to the generation mix of Germany. As shown in fig. 7, no export benefit occurs for scenario 1b (also in fig. 6).

Under all cases examined, covering half of the annual thermal load leads to worse environmental indices than full coverage. This is explained by the lower electric production, which increases all results presented in a "per electric kWh" basis. Additionally, the benefits of electricity exports are limited (scenario 2b) or eliminated (scenario 1b). A direct qualitative correlation is thus identified between the SOFC unit annual utilisation and the corresponding life cycle environmental impact.

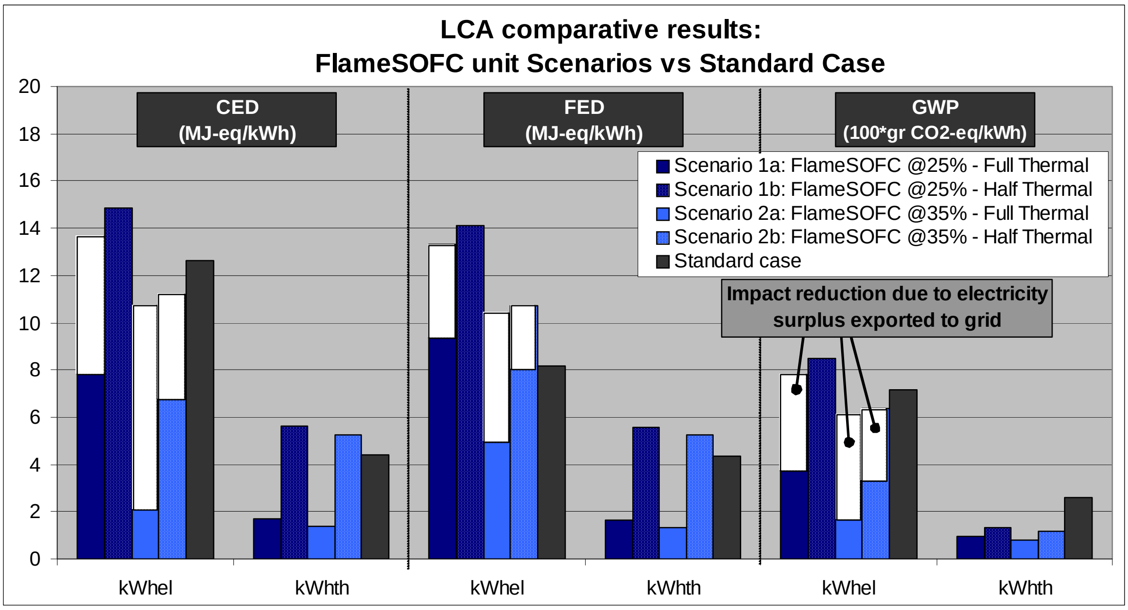

Figure 7: LCA comparative results: SOFC unit scenarios vs Standard Case – Reference country: Germany

Improving the electric efficiency (scenarios 2a, b) can provide a definite environmental advantage over the Standard Case when considering the CED and GWP indices. The improvement may be obvious for the Fossil Energy Demand, not enough however to counterbalance the "100% fossil" fuel of the SOFC unit without the grid export benefit. The incorporation of the environmental benefit associated with the electricity exports to the grid has proven critical towards reducing the impact of the SOFC case, since it provided a better CED and GWP than the Standard Case, even without the assumption of an enhanced electric efficiency. However, more have to be accomplished in order to achieve a lower FED.

In order to provide a total overview of the environmental performance of the SOFC unit lifecycle and to estimate a "red line" of operational parameters, under which the environmental indices examined are negative compared to the Standard Case, the results acquired have been inter- and extra-polated within an operational range of electric efficiencies and thermal coverage ratios. Due to the fact that only four cases have been calculated (scenarios 1a,b and 2a,b), the contour graphs of figures 8-13 should not be considered as detailed "operational maps". Nevertheless, they provide vital information regarding how to ensure and realise the environmental advantages of the SOFC technology in m-CHP applications.

Throughout figures 8-13, contour graphs are provided, showing “green” areas where the five indices examined are improved and “grey” areas, where the environmental performance is actually worse than the reference Standard case. The reduction or increase of the environmental impact indices is shown in relative terms. The four scenarios calculated are represented with red marks. Germany has been selected as reference country. Each environmental impact index refers to the production of 1 kWh electric. As presented in the previous sections, the case of zero benefit from electricity exports has also been considered.

The overall conclusion is that achieving an electric efficiency of over 30% and a thermal coverage of at least 60-70% is critical towards ensuring better CED and GWP indices of the SOFC unit lifecycle. Incorporating the grid export benefit is also important, since the m-CHP electricity surplus inevitably produced is “translated” in overall emission and resource usage reductions. When the grid export benefit is not considered, the contour lines are steeper, indicating a reduction in the result sensitivity towards the thermal coverage.

The CED results (figs 8, 9) show the need for at least 30% electric efficiency, which is enough to provide at least a marginal reduction of primary energy demand, even without the benefit of the grid exports. A primary energy demand reduction of 40-50% is considered achievable (with grid export benefit).

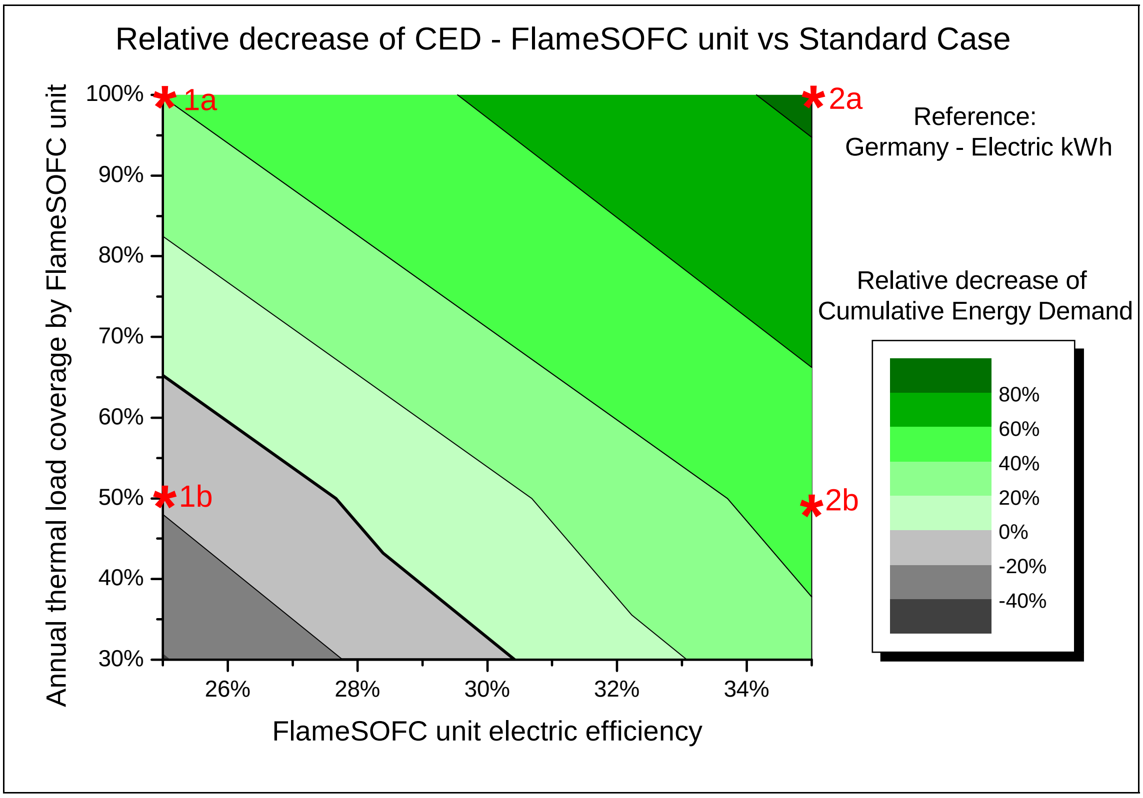

Figure 8: Relative decrease of CED – SOFC unit vs Standard Case – With benefit from exports to grid.

As discussed earlier, the use of a fossil fuel to drive the SOFC unit makes the FED potential reduction a challenging task, especially in the near future, where the renewables contribution in grid generation will rise. However, some reduction is possible to occur only if the grid export benefit is considered (fig 10, 11). Unless a non-fossil fuel is used to drive the SOFC unit, only a small decrease of 5-20% can be expected (with grid export benefit).

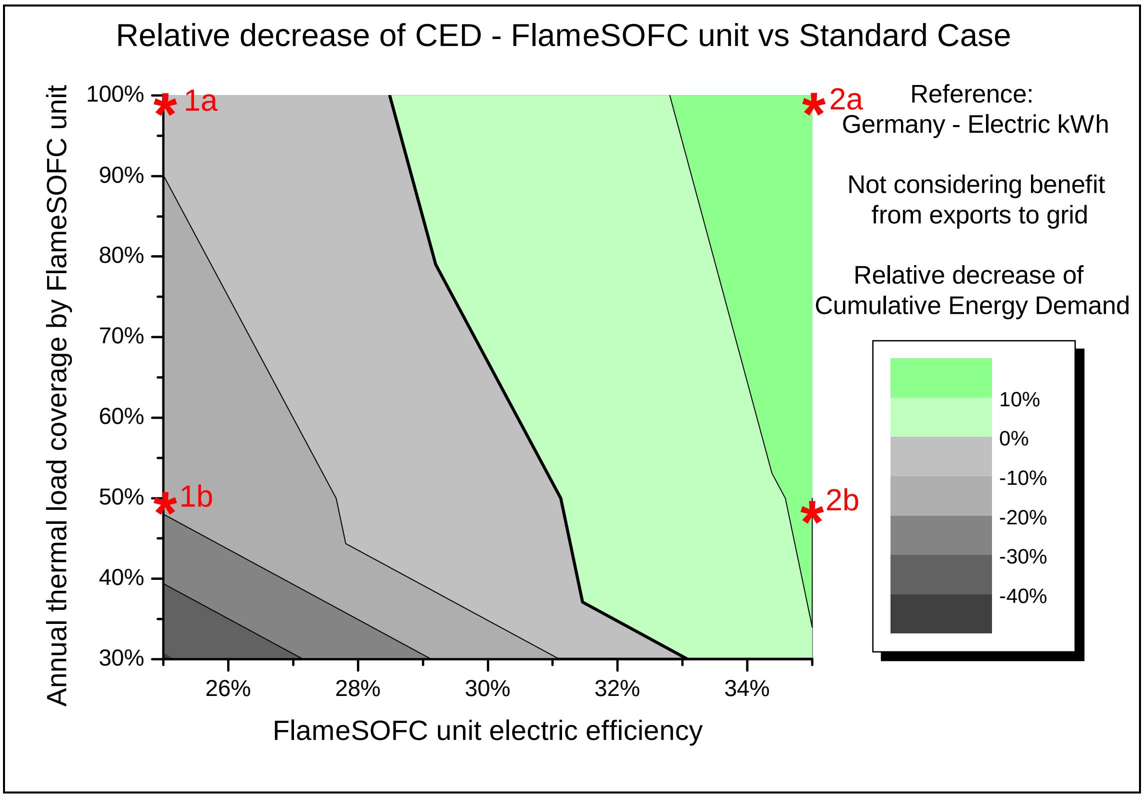

Figure 9: Relative decrease of CED – SOFC unit vs Standard Case –Without benefit from exports to grid.

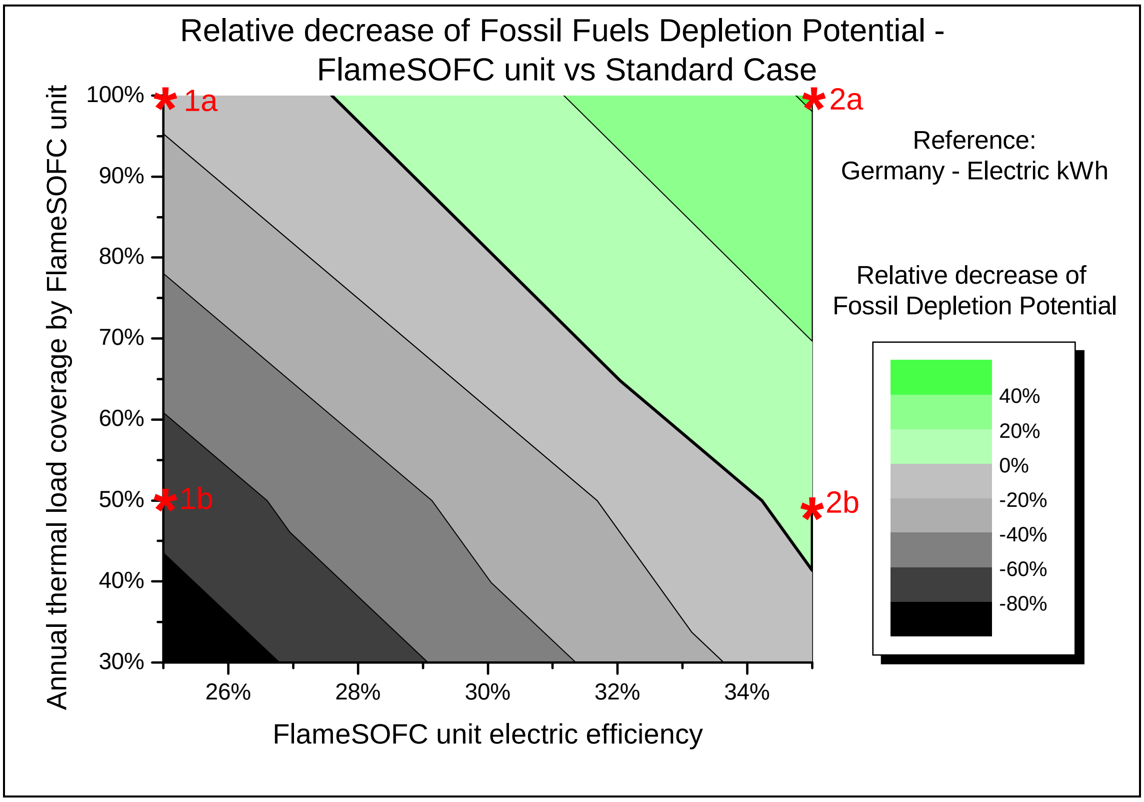

Figure 10: Relative decrease of Fossil Fuels Demand – SOFC unit vs Standard Case – With benefit from exports to grid.

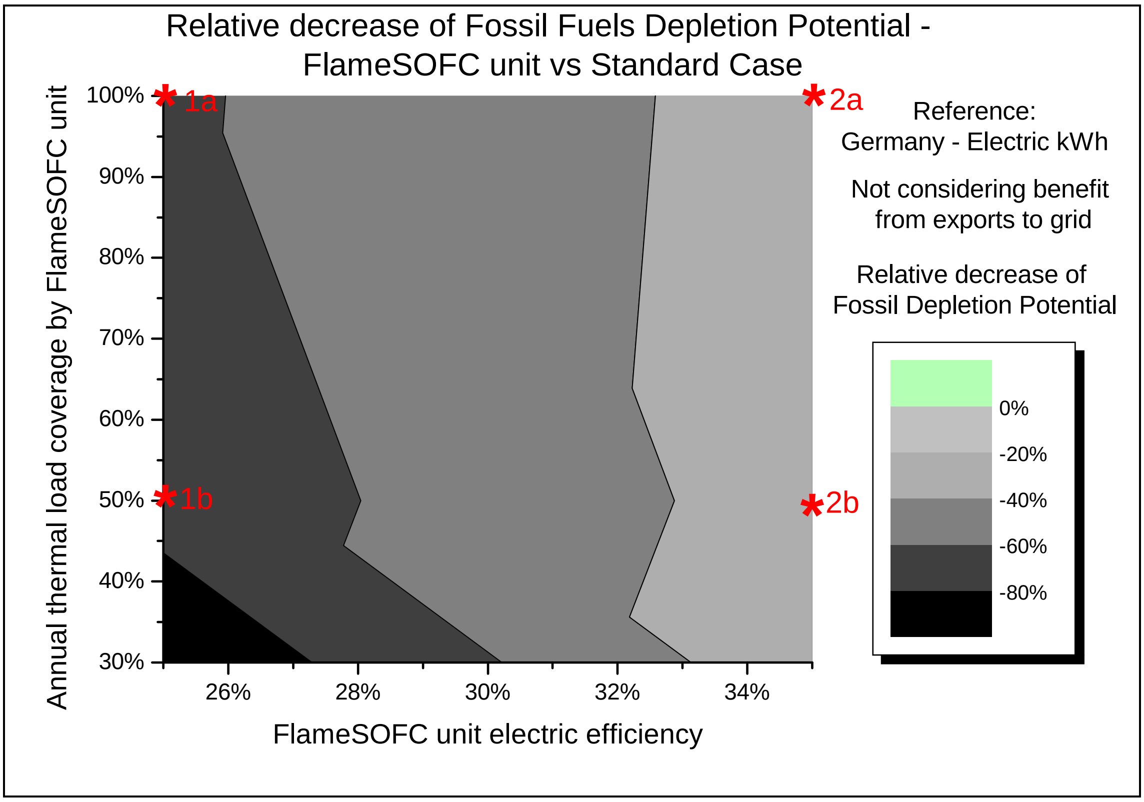

Figure 11: Relative decrease of Fossil Fuels Demand – SOFC unit vs Standard Case – Without benefit from exports to grid.

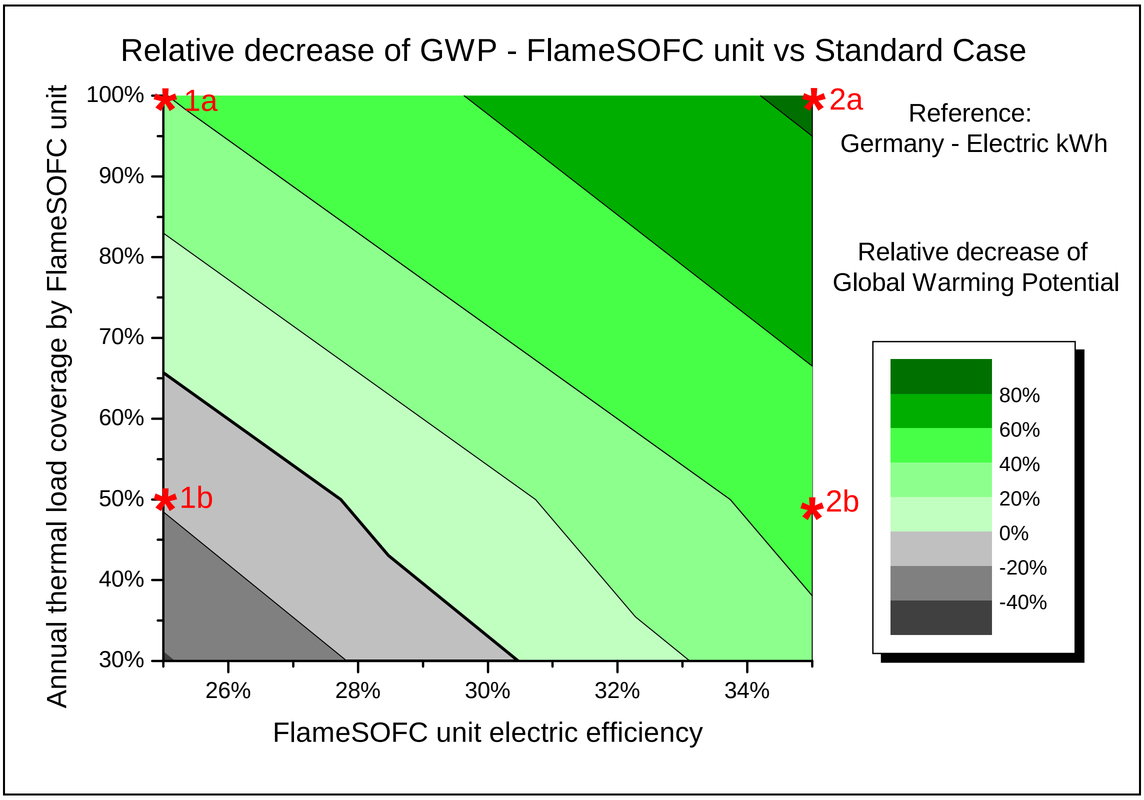

Figure 12: Relative decrease of GWP – SOFC unit vs Standard Case – With benefit from exports to grid.

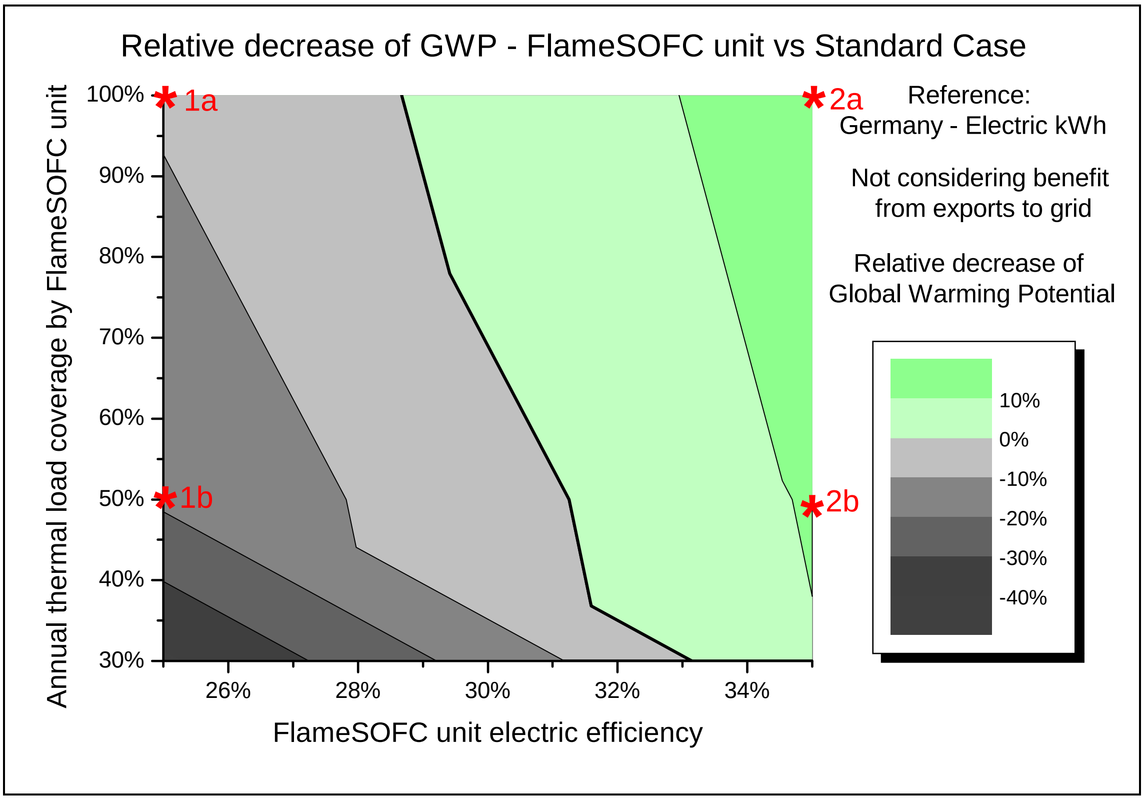

Figure 13: Relative decrease of GWP – SOFC unit vs Standard Case – Without benefit from exports to grid.

The results in figures 12 and 13 are quite similar to figs 8 and 9, due to the contribution of the fossil fuel combustion in generating grid electricity and the total CO_2 emissions. Compared to figures 10 and 11, the picture is much better for the SOFC unit, since the fossil fuels used for grid generation (coal, lignite, diesel) are more CO_2-intensive than natural gas. A reduction in GWP of 40-50% is considered feasible (with grid export benefit).

Assessment Case B – SOFC unit vs ICE System

In Case B the SOFC unit is compared to a m-CHP Internal Combustion engine. As described above, Scenario 1 and 2 consider a low (25%) and a high (35%) electric efficiency SOFC unit. Indicators “a” and “b” refer to covering the full or the half of the annual thermal load by both m-CHP systems. The ICE operational parameters are presented in Tables 6-10. In the half coverage case, a peak gas boiler is considered, having the same efficiency with the Standard Case boiler.

Comparing the two competitive m-CHP technologies is more straightforward than the previous assessment case. The major influential parameter, affecting the comparative results of figure 14 is the improved electric efficiency of the SOFC unit. The latter is decisive in Scenario 2a, towards demanding less primary and fossil energy (both systems work on purely fossil fuel), emitting less greenhouse gases and requiring less minerals consumption. The case of not considering the benefits from exports to grid has also been examined (figure 14). The fact that both systems export to grid, leads to a common effect, without providing any additional information. Of course, the SOFC unit with 35% electric efficiency loses more benefit in this case.

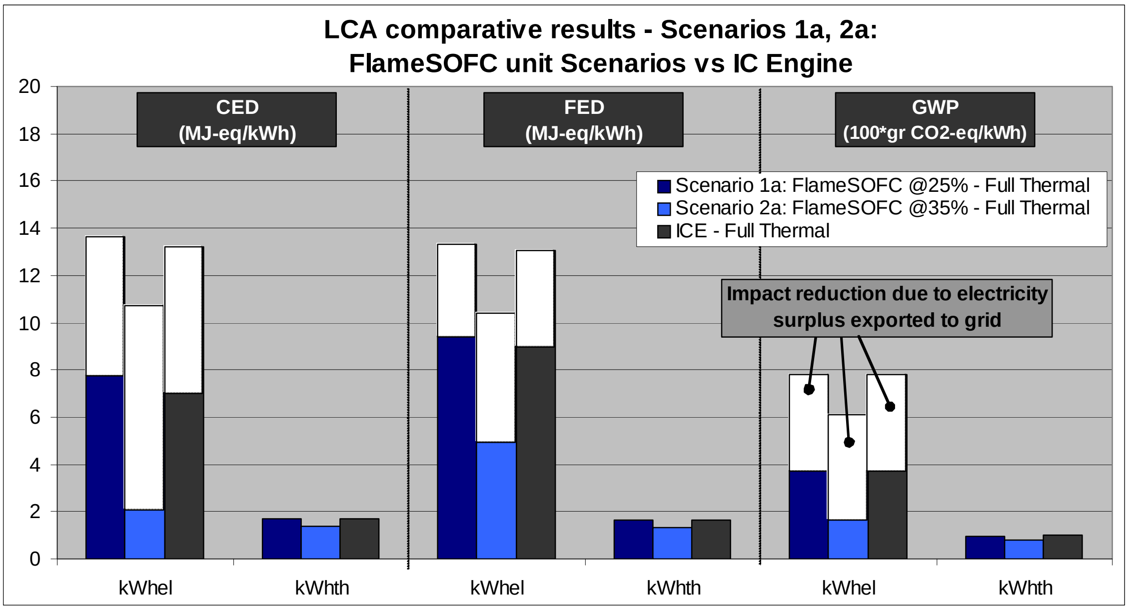

Figure 14: LCA comparative results – Scenarios 1a, 2a: FlameSOFC unit scenarios vs IC engine

In correspondence to the analysis of the previous section, the comparative results of scenarios 1b, 2a are thereafter presented in figure 15. All findings of the previous sections apply here, since covering half the thermal load had similar influence to both m-CHP systems.

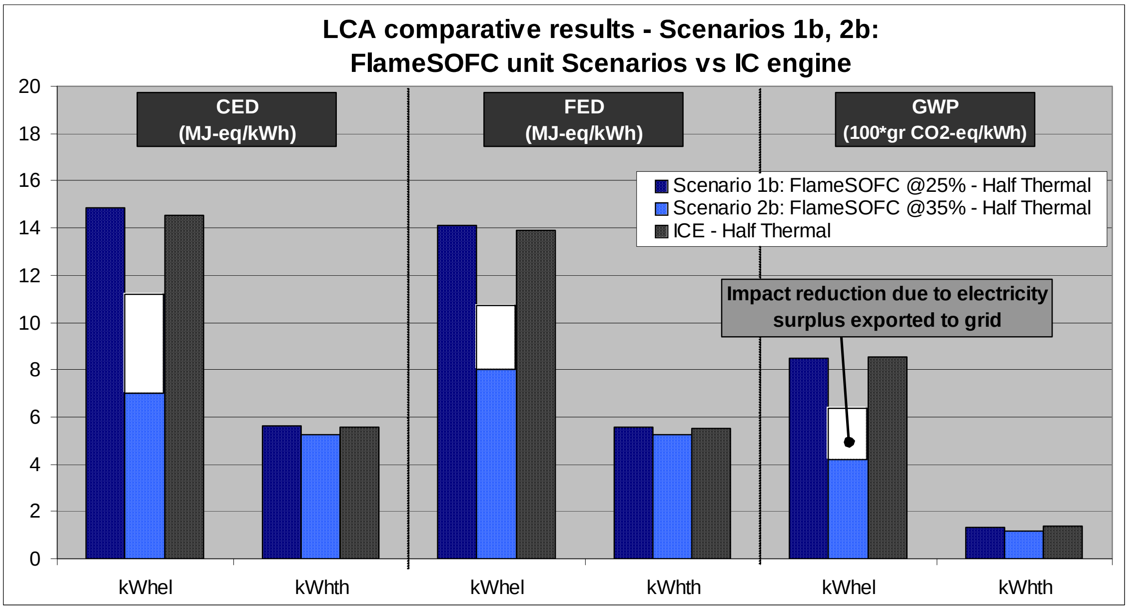

Figure 15: LCA comparative results – Scenarios 1a, 2a: FlameSOFC unit scenarios vs IC engine

In correspondence to the analysis of Assessment Case A, figures 16-21 present the sensitivity analysis of the environmental performance comparison between the two m-CHP systems. The overview of the following figures shows a quite favourable situation towards the SOFC unit.

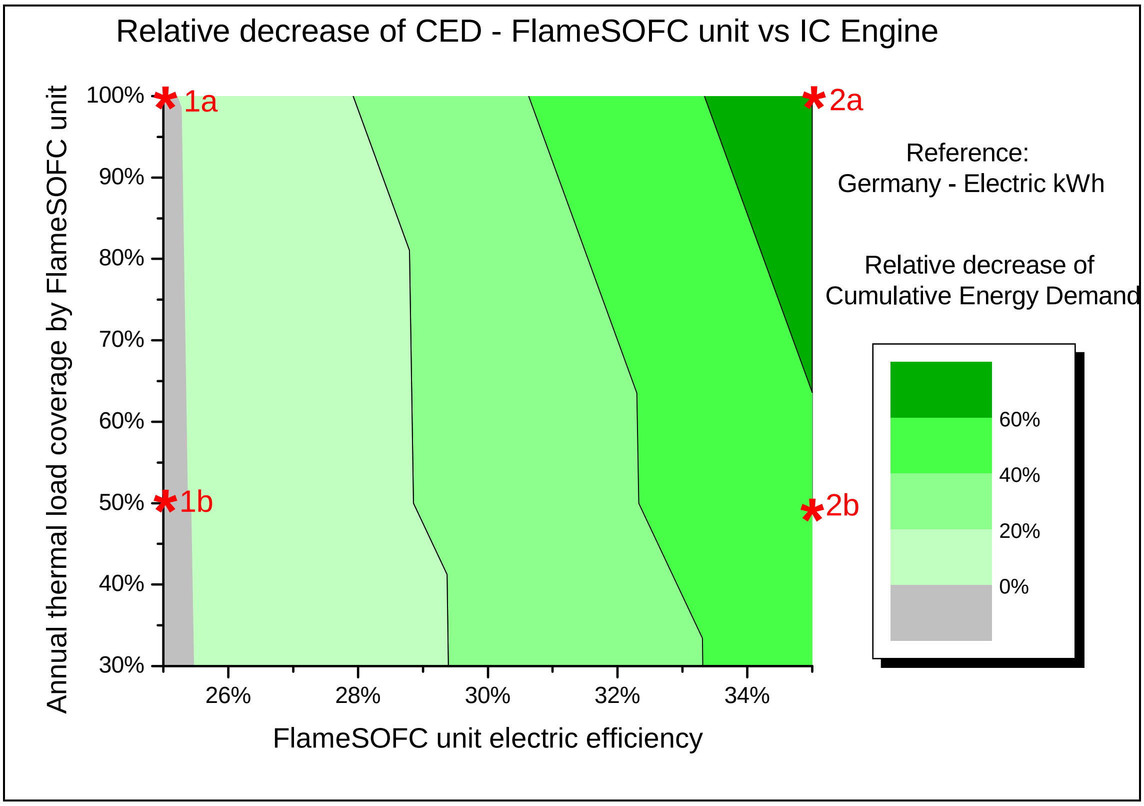

Figure 16: Relative decrease of CED – SOFC unit vs ICE – With benefit from exports to grid.

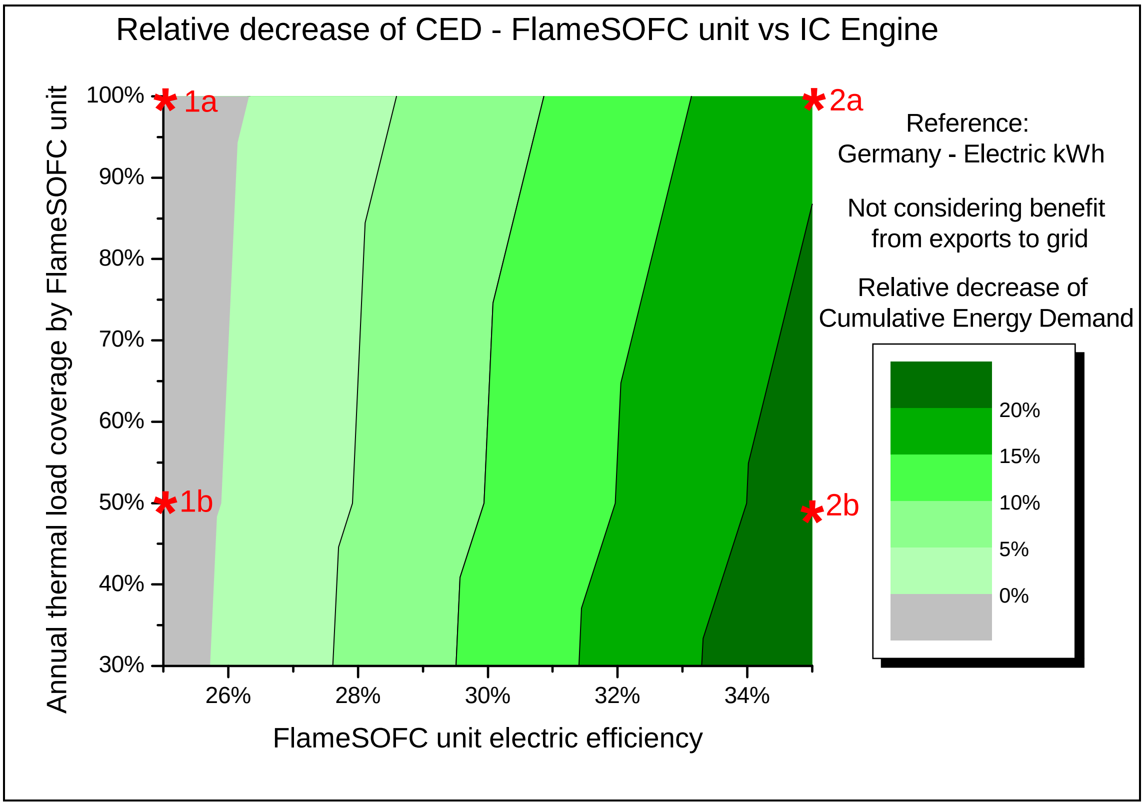

Figure 17: Relative decrease of CED – SOFC unit vs ICE – Without benefit from exports to grid.

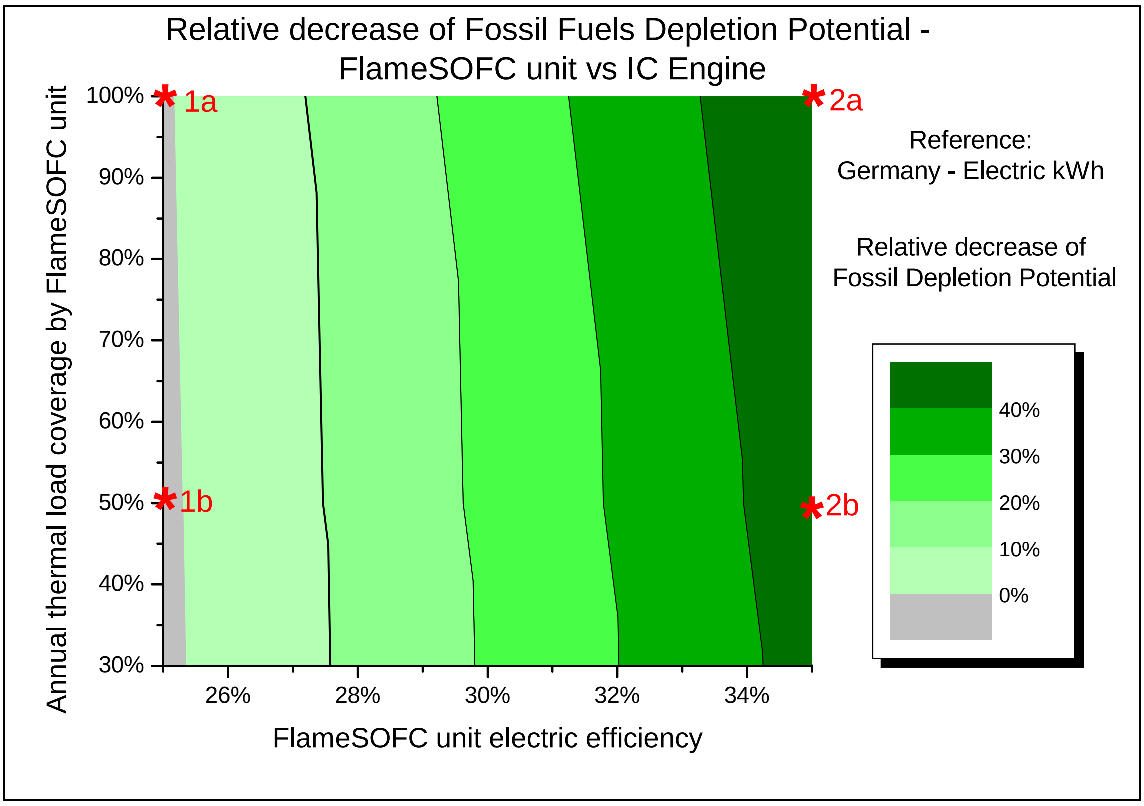

Figure 18: Relative decrease of FED – SOFC unit vs ICE – With benefit from exports to grid.

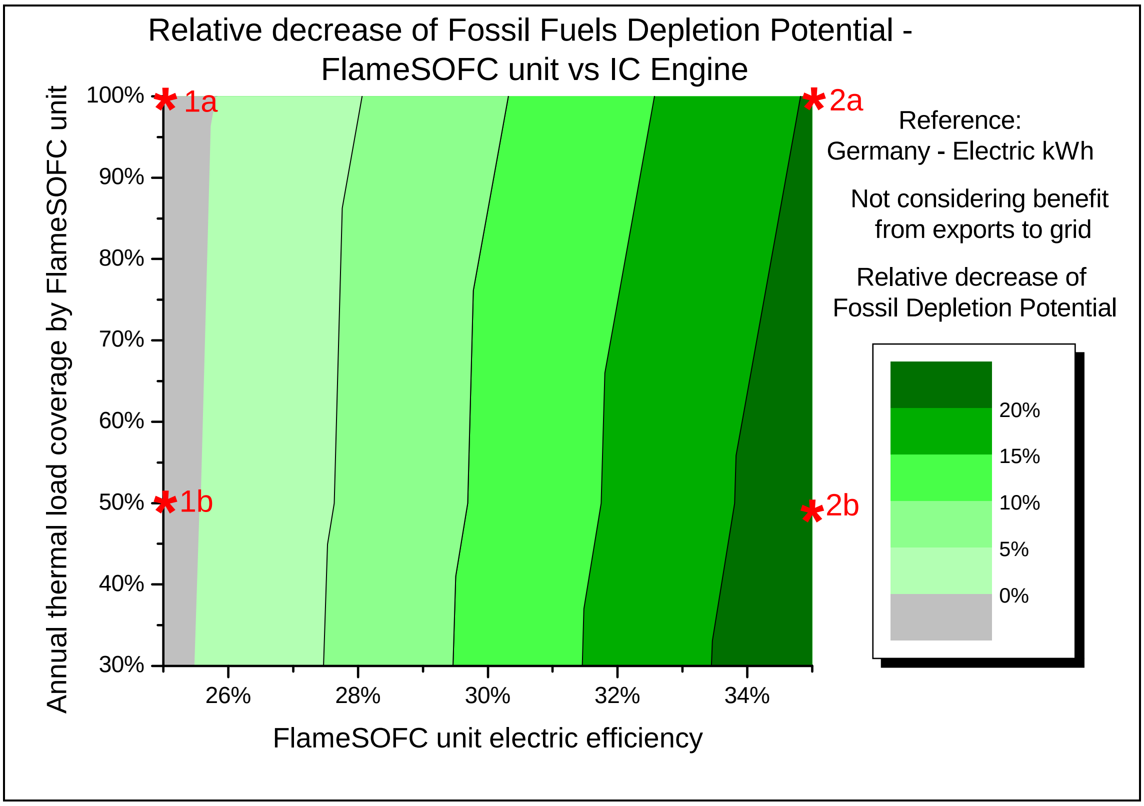

Figure 19: Relative decrease of FED – SOFC unit vs ICE – Without benefit from exports to grid.

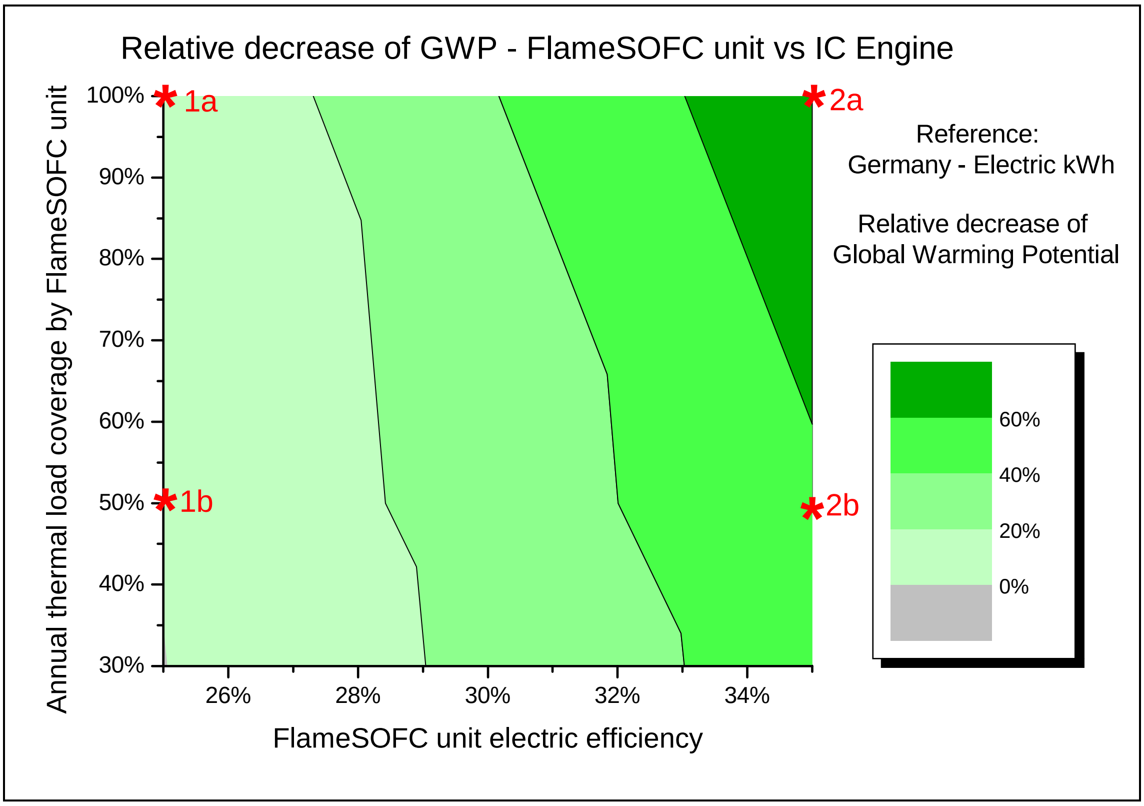

Figure 20 Relative decrease of GWP – SOFC unit vs ICE – With benefit from exports to grid.

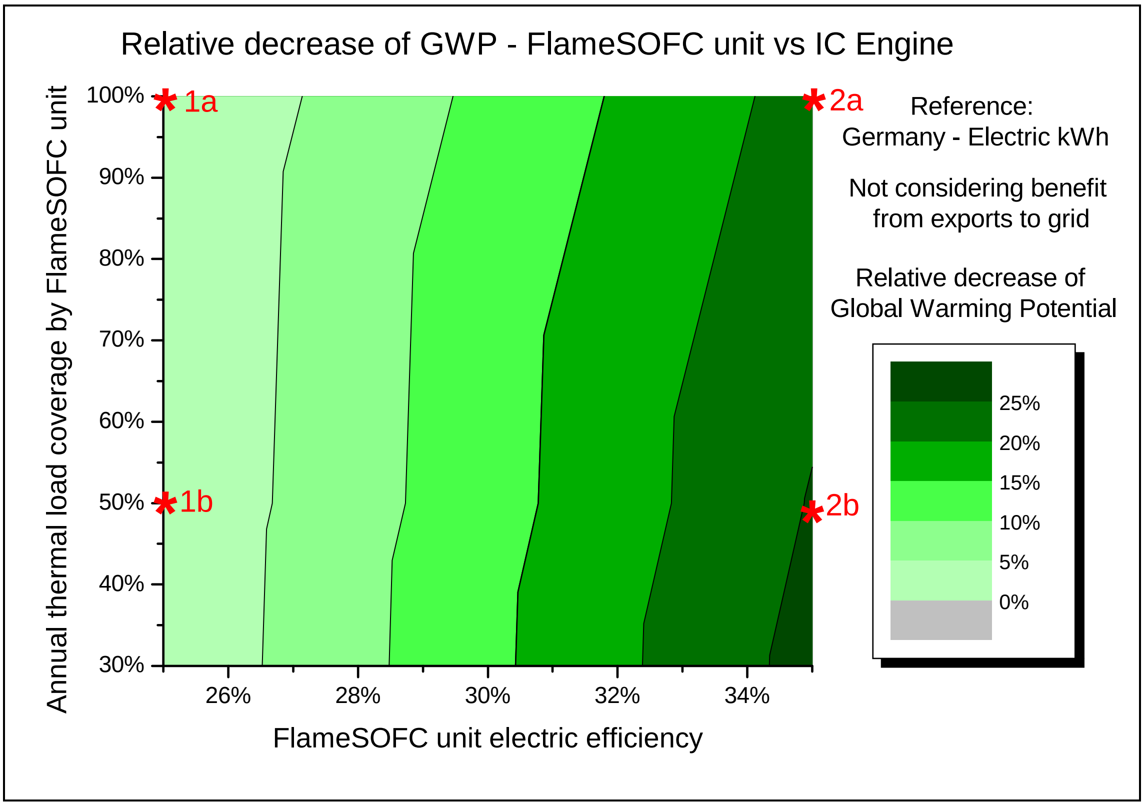

Figure 21 Relative decrease of GWP – SOFC unit vs ICE – Without benefit from exports to grid.

As discussed above, the higher SOFC electric efficiency is enough to provide better environmental indices. The contour lines are much less steeper than the corresponding figures of Assessment Case A (figs 8-13) , showing the little influence of the thermal load coverage, since both m-CHP systems follow partial thermal coverage and export electricity. The trend of negative contribution of the rising thermal coverage has been identified, which is intensified at higher SOFC electric efficiencies (right inclination of contour lines on figures 17, 19, 21). This is explained by the fact that the SOFC utilises fuel to produce more electricity then the ICE, which is not “translated” to emission savings and the corresponding environmental benefit.

4. Conclusions

The results of a thorough Life Cycle Analysis of the SOFC m-CHP unit were utilised, assessing its environmental impact and comparing it to two competitive cases: A) a Standard Case, where the annual electric and thermal loads of a single family dwelling are covered by grid electricity and a gas boiler and B) the most common m-CHP technology, an Internal Combustion gas Engine. The effect of various parameters on both the electric and the thermal kWh has been examined:

- Operational mode. Full and half coverage of the annual heating load (peak boiler for the rest of the load).
- Electrical efficiency of the SOFC unit.
- The environmental benefit of exporting the m-CHP electricity surplus to the grid. Due to the uncertain quantification of this effect, both cases of considering and not considering this benefit have been calculated throughout this study.

Comparing the SOFC unit to the Standard Case (Assessment Case A) shows that a definite environmental benefit is feasible provided that the electric efficiency and the annual utilisation of the unit are as high as possible. The overall conclusion is that achieving an electric efficiency of over 30% and a thermal coverage of at least 60-70% is critical towards ensuring better CED and GWP indices of the SOFC unit lifecycle. Incorporating the grid export benefit is also important, since the m-CHP electricity surplus inevitably produced is “translated” in overall emission and resource usage reductions.

The weak aspect of the environmental performance of the SOFC unit is the exclusive usage of natural gas, which provides a high Fossil Energy Demand index. Considering also the rising contribution of renewables in European grid generation, the comparison seems less favourable for the near future. However, the SOFC unit has the potential of fuel flexibility and the use of biofuels to drive the SOFC unit is expected to have a positive impact towards reducing the Fossil Energy Demand index .

Exporting electricity back to grid indirectly resolves the abovementioned issue. Its influence is decisive in all impact categories examined towards establishing the definite environmental advantage of the SOFC unit. However, the accurate estimation of the environmental benefit of the displaced grid electricity is quite difficult, since it is uncertain what kind of generation takes place at the specific time of the m-CHP export to the grid. In other words, one cannot be confident how “dirty” is the grid kWh at any specific moment.

The comparison of Assessment Case B is more straightforward than the previous assessment case. The critical parameter providing a significant environmental advantage is the improved electric efficiency of the SOFC unit. Its influence is direct and leads towards demanding less primary and fossil energy and emitting less greenhouse gases. Exporting to grid has a common effect on the two m-CHP systems (SOFC and ICE) and does not influence the results significantly.

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