PACE

Pathway to a competitive European Fuel Cell micro-CHP Market

REPORT

Cost and consumption savings in properties with PACE FC mCHP installations – Report 2

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Executive summary

This report will assess the hypothesis that PACE Fuel Cell micro Combined Heat and Power (FC mCHP) units can make a 25% primary energy saving and a 30% CO_2 saving for appropriate European homes.

To evaluate these hypotheses data on consumption of gas and electricity as well as information on cost associated with consumption have been collected from properties eligible for analysis. Based on these data the following parameters have been analysed:

- Primary energy savings
- Electricity consumption savings
- Estimated CO_{2e} savings
- Financial savings

The analyses presented in this report are in all cases based on costs before and after installation of the PACE FC mCHP units in an existing structure.

From the analysis it was found that properties which replaced their heating oil burner with a FC mCHP unit saves significantly more on all parameters, than properties which replaced a gas boiler.

The primary energy savings, when considering all the responses, were on average 6%. For properties which previously used heating oil the primary energy savings were 13,5%, while the primary energy savings for properties previously using natural gas was 2,3%.

CO_2 equivalent (CO_{2e}) saving were on average 16,6%. In cases where domestic heating oil burners were replaced the saving was 37,9% on average. This indicates that a strong environmental case can be made for replacing heating oil burners with FC mCHPs. For the cases where a gas boiler was replaced the resulting CO_{2e} savings were 2,1% on average.

The average cost saving was 12,4%. For cases where a heating oil burner was replaced the annual average saved cost was 24%. The annual cost saving was 7% for properties where a gas boiler was replaced.

All the values reported contain significant uncertainty and large potential biases due to the current quantity and quality of the data. Due to this large uncertainty, we cannot at this point conclude whether the savings targets have been met and we defer the final assessment for the final report where more data is available.

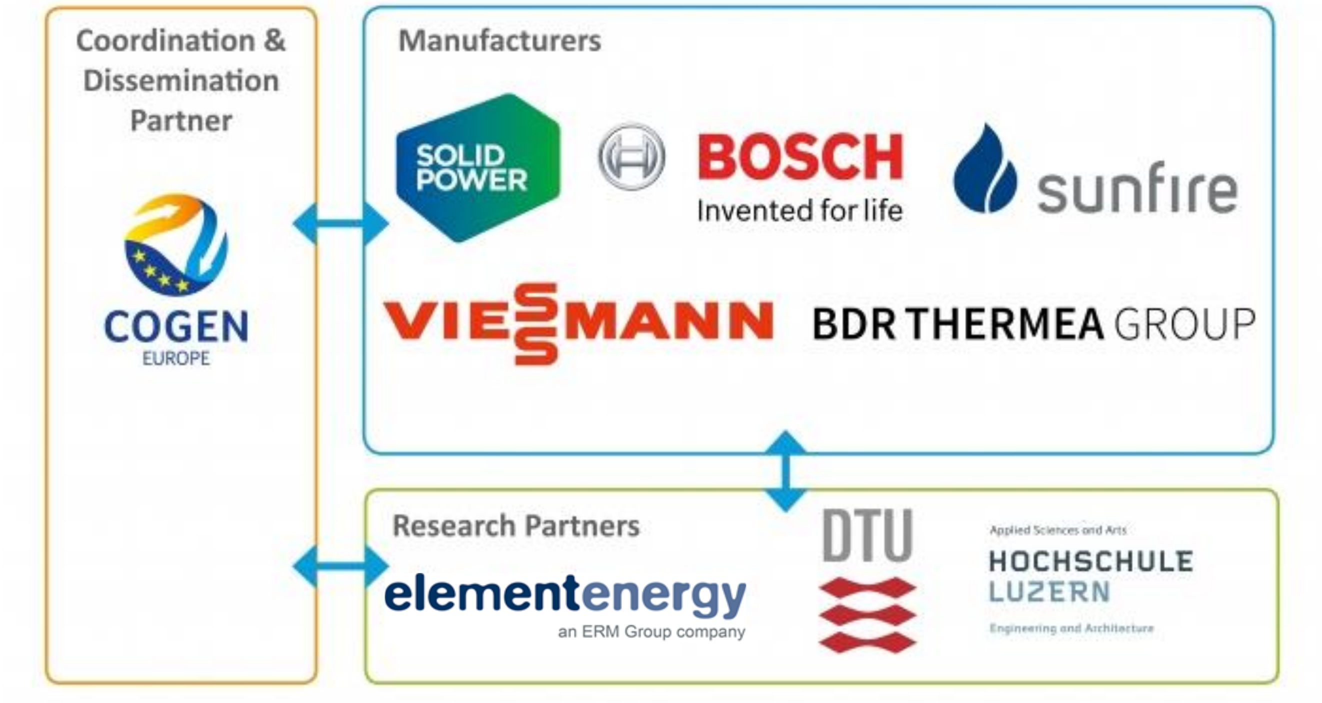
About PACE

PACE is a five-year project that will deploy more than 2.800 of the next generation Fuel Cell Combined Heat and Power (or Fuel Cell micro-cogeneration) units in 10 European countries by 2022.

The project brings together five leading European suppliers (Bosch, Hexis, SOLIDpower, BDR Thermea (Senertec), Sunfire, and Viessmann), and will focus on domestic housing and small enterprises. The manufacturers are supported by associations, consultancies, and research partners providing specific expertise (COGEN Europe, DTU, Element Energy and Hochschule Luzern).

PACE is a € 90 million public-private project co-funded by the *Fuel Cells and Hydrogen 2 Joint Undertaking* (now Clean Hydrogen Partnership).

For more information, visit *www.pace-energy.eu*



1. Background

Summary of the chapter

This report will assess the hypothesis that PACE Fuel Cell micro Combined Heat and Power (FC mCHP) units can make a 25% primary energy saving and 30% CO_2 saving for appropriate European homes.

To evaluate these hypotheses data on consumption of gas and electricity as well as information on cost associated with consumption have been collected from properties eligible for analysis. Based on these data the following parameters have been analysed:

- Primary energy savings
- Electricity consumption savings
- Estimated CO_{2e} savings
- Financial savings

In this, second, version of the costs and savings analysis, all savings are based on costs before and after installation of the PACE FC mCHP units in existing structures.

Objective

The purpose of this report, and its underlying task, is to evaluate potential savings and gains from installing PACE Fuel Cell micro Combined Heat and Power units (FC mCHP units) in households and small businesses. Consumption and costs before and after installation of a PACE unit will be used to calculate primary energy consumption savings, CO_2 emissions savings and financial savings on a household, or small business, basis.

This report will assess the hypothesis that PACE FC mCHP units can make a 25% primary energy saving and 30% CO_2 saving for appropriate European homes.

The long-term aim of this savings analysis task is to collect and analyse data from 5% of the sites where a PACE unit have been installed (i.e., over 130 homes).

About this report

This report is an analysis of the costs and consumptions savings seen as a result of installing PACE FC mCHPs. The analysis is based on costs and consumptions reported by the PACE FC mCHP end-users.

The first report was prepared by Erik Nikolai Udbye and Carsten Brorson Prag. This second report is an updated and edited version of the first report. Veronica Humlebæk Jensen have conducted the analysis and updated the report with Peter Stanley Jørgensen as editor.

What is being reported in this document?

In this report results for individual properties on the following parameters will be presented:

- Primary energy savings
- Electricity consumption savings
- Estimated CO_{2e} savings
- Financial savings

All savings are based on costs before and after installation of the PACE FC mCHP units in an existing structure. Some end-users with installed PACE mCHP units in newly build structures have submitted responses to the questionnaire. However, no robust case for a comparative analysis of these responses exists. DTU has chosen to exclude these responses in this report, as no analysis can be made currently.

What is being collected and how is it analysed?

This report concerns savings as seen on a domestic household or small businesses scale. Throughout this report the term 'property' will be used to cover both domestic households and small businesses.

In order to evaluate financial and consumption savings, data on consumption of gas and electricity as well as information on associated costs was collected from properties eligible for analysis. The data was collected through a questionnaire filled out by the owner or everyday user of the PACE FC mCHP.

In PACE the analysis partners have, by design, no direct access to the individuals buying or using a PACE FC mCHP unit. This allows the analysis partners to perform analyses without knowledge of the identity of the individuals residing in the property in question, making the data, in GDPR terms, pseudoanonymous. In practice, this means that the data is anonymous to all personnel analysing and managing the data. The data is not, again in GDPR terms, truly anonymous as the data in principle can be linked to the information the manufacturers have on the identity of the end-user through the FC mCHP unit ID. For the analysis in question, we comply with all GDPR requirements (data handling agreement in place, inventory and checklist up to date, also the survey service provider promises storage physically located in Denmark etc.).

The data necessary for the analysis does not pertain to the performance of the FC system per se, but to the needs of the property. This could include electricity use for space heating, gas use for a back-up gas condensing boiler covering additional hot water needs etc. This information cannot be inferred from the performance validation data collected in other tasks in the PACE project as this data only covers the consumption of gas and production of electricity of the FC mCHP unit itself. The performance data may however be used to validate the data reported by the end-users and may augment the analysis. Additionally, in order to quantify savings, the analysis requires an input of consumptions and costs from before the installation of the PACE FC mCHP unit since a savings analysis is a comparative analysis.

The data collection

The data needed for the analysis was collected through an online questionnaire. The questionnaire was distributed by an entity with permission to contact end-users, either the systems manufacturers or their distribution collaborations partners. The responses to the questionnaire are only accessible by employees at DTU working directly on PACE tasks and the employees in question have all specifically been granted access to the results by the analysis work package leader.

The manufacturer may know the identity of the end-user, but they have no access to the results connected to a unit ID. The unit ID and response to the questionnaire are known to DTU, but the identity of the end-user is not known to DTU, neither directly through personal information nor in an inferable manner through person identifiable information. However, as consumption data is personal data, and there exists a link between contact information available to the manufacturers and the consumption data collected by DTU, GDPR precautions have been made. The data is stored according to GDPR regulations, and the end-user has the right to contact DTU and have their data deleted.

The data required to conduct the analysis collected in the questionnaire is presented in Error! Reference source not found. below. In general, the end-user was asked to supply the following information:

- ID of the PACE unit(s) installed in the property.
- Fuel consumption for a period before and after installation of the PACE FC unit.
- Net electricity use, in the form of import from the electricity grid before and after installation.
- Costs associated with the fuel consumption and net electricity consumption from the grid.

DTU requests all consumption and cost data reported for 12-month periods, either before or after installation of the PACE FC mCHP unit.

The collected unit ID(s) were used to identify general geographical location of the installed FC mCHP by connecting the survey response to the performance data collected elsewhere in the project. In certain cases, performance data from the fuel cell unit was used to validate or compliment the data reported by the end-user.

General parameters requested:
The brand and model of their FC mCHP
The ID of the unit, or units, installed
Whether the unit(s) was(were) installed in a newly build or existing structure
Parameters requested for existing buildings only:
Which heating and electricity generating appliances were in operation before the installation of the PACE FC mCHP?
The consumption of fuel <u>before</u> installation of the FC mCHP, from firewood, over heating oil and to LPG or natural gas
The net electricity consumption from the grid

The costs associated with fuel and electricity consumptions reported the above
Parameters requested for all buildings:
Which heating and electricity generating appliances were, still, in operation after installation of the PACE FC mCHP?
The consumption of fuel after installation of the FC mCHP, from firewood, over heating oil and to LPG or natural gas[1]
The net electricity consumption from the grid
The costs associated with fuel and electricity consumptions reported the above
Additional parameter requested for existing buildings only:
Whether any improvements had been made to the building or any other changes that could affect consumption had happened between the two reporting periods.

Table 1: This table presents the parameters presented as questions to the end-users in the questionnaire. All end-users were requested to answer some questions while some questions were only answered by end-users with a FC mCHP installed in an existing structure

Potential challenges in data collection

The end-users report their costs and consumptions based on utility bills. This means they have to find the bills for two different periods (in the case of installations in existing buildings) and on these bills locate the information DTU requests and report it in the data collection questionnaire. It is unfortunately not possible to guide the end-users through this process as we have no direct contact with the end-users. It is also challenging to create a guide fitting all, or even most, end-users as layout of bills does not follow a set pattern across utilities and countries. Some end-users start to fill out the questionnaire but stop at the first actual data-reporting step and never resume.

Another challenge is the fact that DTU, and in some cases even the manufacturers, has no direct contact to the end-users. It is therefore challenging to follow up and remind the end-users that they need to fill out the questionnaire. These challenges have resulted in a low response rate and a low rate of useful answers. It is however, expected to receive additional responses that will form the basis of the third and last report. This report is scheduled for late spring 2023.

Challenges in the analysis of the collected data

With the data collected it is not possible to ascertain the electricity export from the household to the electricity grid. It is likewise not possible to quantify the energy demand of the household for space heating and hot water needs. Thus, needs and exports are only implied by the data. This is the result of a trade-off between depth of analysis and response rate of the questionnaire, and in turn breadth

[1] For most, this would only be LPG or natural gas as no other heat or electricity generation appliances were installed.

of the analysis. Early in the savings analysis task, based on conversations with the manufacturers, it was deemed too detrimental to response rates if detailed questions on electricity export and import of the systems had to be included. It was therefore decided that lack of detailed information would be off set as much as possible by referencing to the unit's performance data, where possible. Similar considerations regarding heating and hot water demands were considered.

This lack of export and demand information does result in challenges for the analysis. As an example, it is not possible to analyse primary energy use in the context of the specific demand of the household and to take electricity export into account. The only information available is the net import of electricity to the household. It is therefore better, in terms of primary energy savings, for a household to consume all the generated electricity and limit the electricity export to the grid. Since all gas converted at the household, to heat and electricity, will count towards the primary energy use of the household. At the same time all electricity imported from the grid will also be included in the primary energy use of the household (see the section "**A.3 Calculating Primary** Energy savings:" in Annex 1). Consuming electricity and thereby limiting the import of electricity from the grid, will in this analysis result in higher primary energy savings as we cannot discount exported electricity in the primary energy use of the household.

As mentioned, these challenges are challenging to mitigate, especially when evaluating a low number of complete responses. However, the challenges will be highlighted in a few single standing cases, where the challenges will be mitigated to some extend, e.g., by including performance data as reference or explaining assumptions made.

2. Analysis and Results

Summary of the chapter

Data from 32 properties were analysed with the aim of identifying costs and consumption savings associated with the installation of a PACE supported Fuel Cell mCHP.

The individual cases included in this section illustrates the assumptions made during the analysis and highlights some of the difficulties encountered during the analysis. The individual cases included follows the trends and findings from the statistical analysis, namely that properties which replaced their heating oil burner with a FC mCHP unit saves significantly more on all parameters, than properties which replaced a gas boiler.

The primary energy savings, when considering all the responses, were on average 6%. For properties which previously used heating oil the primary energy savings were 13,5%, while the primary energy savings for properties previously using natural gas was 2,3%.

CO_2 equivalent (CO_{2e}) saving were on average 16,6%. In cases where domestic heating oil burners were replaced the saving was 37,9% on average. This indicates that a strong environmental case can be made for replacing heating oil burners with FC mCHPs. For the cases where a gas boiler was replaced the resulting CO_{2e} savings were 2,1% on average.

The average cost saving was 12,4%. For cases where a heating oil burner was replaced the annual average saved cost was 24%. The annual cost saving was 7% for properties where a gas boiler was replaced.

The data analysis in general terms

The data on costs and consumptions described above forms the basis for a comparative analysis of needs before and after installation of a PACE FC mCHP unit. The collected information on costs and consumptions necessary to cover heating and electricity needs for a property were analysed in order to quantify the impact of the installation of a PACE FC mCHP on primary energy needs, CO_2 emission and costs incurred by the end-user. The results of the analysis are presented in this section.

A detailed description of the exact methodology used for calculating the primary energy savings, CO_2 savings and financial savings are included in; *Annex 1 – Detailed Methodology.*

While the aim of this savings analysis task is to create a statistically relevant analysis of the savings attributable to the installation of PACE FC mCHP's, the data density required for such an analysis is not yet available. Therefore, this report will present three interesting case analyses based on individual installations and three statistical cases that considers average savings and savings based on pre-period technology – analysis which hopefully can be made more reliable and extended to include geography, once the response rate increases and gets closer to 5%.

Underlying assumptions and considerations

When working with data reported by the end-users themselves it is necessary to make a handful of assumptions. In this section the general assumptions and considerations made will be described.

To conduct this analysis, it has been assumed that all demand for heating and hot water for the property is covered by the reported fuel and electricity consumption. This assumption is backed up by a request in the questionnaire asking the end-user to report all heating and power generating technologies installed in the property.

It has been assumed that the gas and electricity prices develop in a manner analogous to the average European inflation. If this is the case, price increases can by extension be assumed negligible, for the period from 2016-2022, when comparing data for consecutive years. Allowing us to directly compare costs incurred between the before and after installation periods in the savings analysis. While this holds true for data from 2016-2020, it is known that this assumption may not hold for data from 2021-2022. The rising/fluctuating gas and electricity prices across Europe in 2021-2022 are however challenging to account for, and thus the overall reported savings might be lower than expected.

Also, it has been assumed that the savings found are the results of the FC mCHP unit installation. However, it should be noted that some of the properties have made insulation improvements and installed photovoltaic cells. Some properties have also increased or decreased the number of residents, something which is known to affect the yearly energy use but are hard to account for.

When calculating CO_2 equivalent savings, it is assumed that only CO_2 is emitted from the FC mCHP. This assumption is based on the low content of methane and N_2O in the exhaust from natural gas combustion. For illustration, the combustion of natural gas in total emits 181,23 g of CO_2-equivalent (CO_{2e}), where CO_2 accounts for 181,04 g. Thus, assuming that only CO_2 is emitted introduces an uncertainty below 1%. In terms of emission from a FC mCHP the combustion may well be cleaner than a direct combustion of natural gas.

In this analysis the data analysed consisted of data from German and Belgian properties. To evaluate the CO_2 emission associated with electricity import yearly average electricity grid mix CO_2 intensities for Germany and Belgium have been used[2]. For periods stretching over multiple calendar years weighted averages have been used instead. The average electricity CO_2 intensity have not been reported yet for the calendar years 2021 and 2022[3], and it is thus assumed to be equal to the average electricity CO_2 intensity of 2020. This assumption leads to uncertainty in the estimation of CO_2 emission

[2] *https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/*. Click *here for direct link to table*

from electricity, however, it is not possible to take this change into account yet. Hopefully for the third and last report this data will be available.

It should also be noted that the pre- and post-installation reporting of gas and electricity do not align temporally. They do however in most cases overlap. This means that results on energy and emissions savings are unreliable. Nevertheless, to not reduce the valid responses from 32 to 20, it has been assumed that the overall yearly consumption should stay constant over the period 2016-2022. This of course is not true as some properties have made changes/improvement over the years and the yearly weather changes induces changes in energy consumption as well.

Individual Installation Analysis

In this section the savings calculated for three individual cases will be described and evaluated. Before analysing and discussing the cost, primary energy and CO2 savings for each of the cases, the initial considerations and assumption made will be described.

Case No. 1

In this case a property has replaced their heating oil burner and wood burning stove with a FC mCHP, as shown in Figure 1. The pre-period data stretches from august 2019 to august 2020, while the data for the post-period stretches from September 2020 to September 2021.

Initial Considerations: The property owner reported the natural gas usage for the post-period in litres (L) instead of the standard kWh. As the reported number is similar to other properties gas usage, it has been assumed that the unit must be a typo.

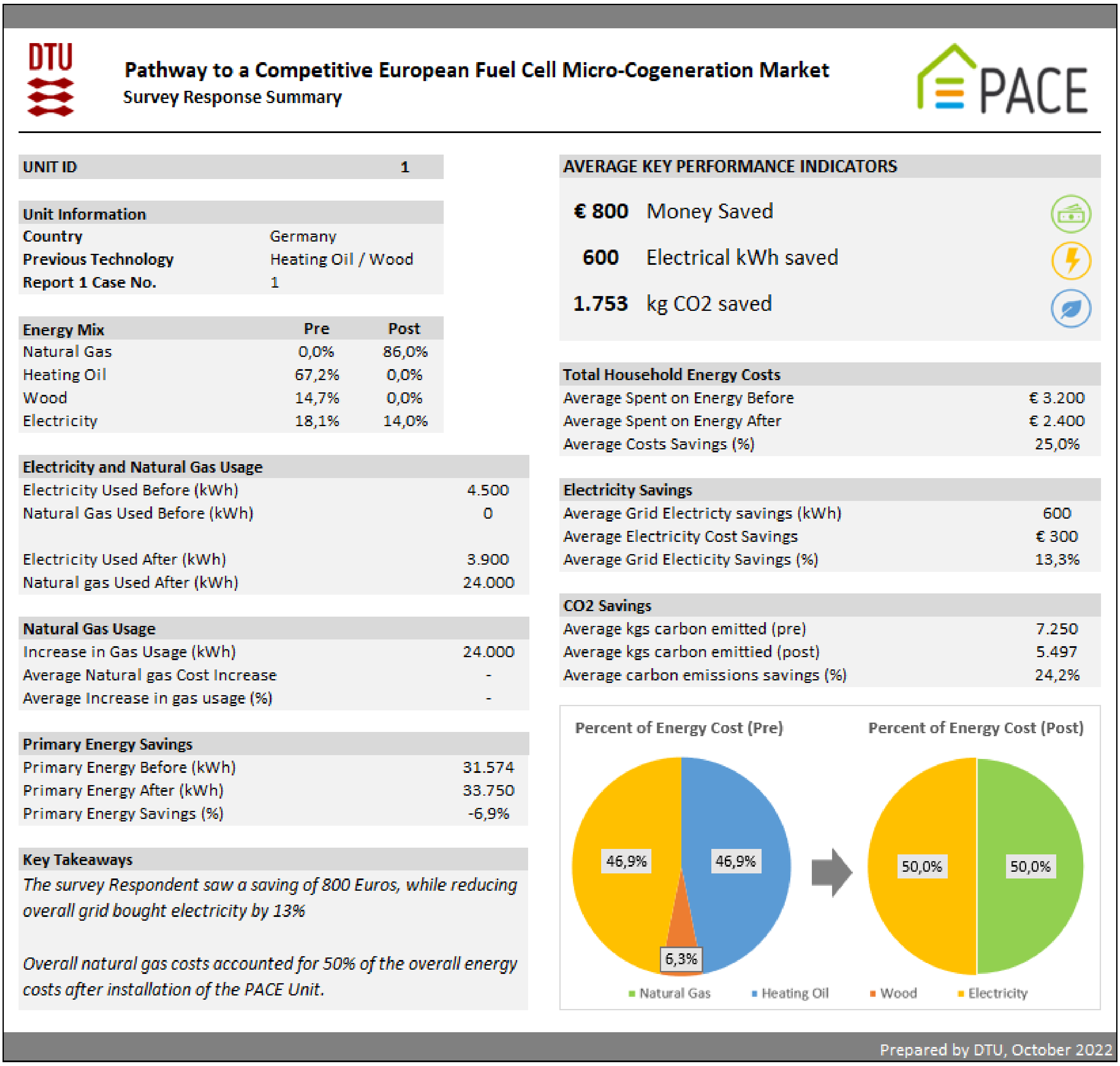
Cost savings: The reported costs result in a yearly saving of € 800, equivalent to a 25% saving. No changes to the property or household were reported.

As the difference between grid electricity consumption before and after is 600 kWh and the costs incurred related to electricity consumption are 31 ¢/kWh, a value close to the average electricity price in Germany in 2021[3], it is likely that feed-in tariffs for grid export have not been considered. From the performance validation analysis, it is known that this unit produced roughly 4600 kWh in the given time interval. Assuming a feed-in tariff of 16[4] ¢/kWh, the close to 4000 kWh produced but not self-consumed would yield an additional yearly financial benefit of € 640 when exported to the grid.

It should be noted that the pattern mentioned above indicates that more electricity is generated at the property to little benefit of the property owner. Should the owner, or occupants, of the property change their electricity consumption pattern to better suit the electricity generation of the FC mCHP the increased self-consumption would secure a larger financial benefit. Assuming they could reduce

[3] https://www.cleanenergywire.org/factsheets/what-german-households-pay-power
[4] Assuming reimbursement as per the *KWK-Gesetz revisions of 2020*

the electricity export by 2000 kWh, at a rate of 31 ¢/kWh, this would secure an additional financial benefit € 620.



DTU

Pathway to a Competitive European Fuel Cell Micro-Cogeneration Market
Survey Response Summary

PACE

UNIT ID	1	
Unit Information		
Country	Germany	
Previous Technology	Heating Oil / Wood	
Report 1 Case No.	1	

Energy Mix	**Pre**	**Post**
Natural Gas	0,0%	86,0%
Heating Oil	67,2%	0,0%
Wood	14,7%	0,0%
Electricity	18,1%	14,0%

Electricity and Natural Gas Usage	
Electricity Used Before (kWh)	4.500
Natural Gas Used Before (kWh)	0
Electricity Used After (kWh)	3.900
Natural gas Used After (kWh)	24.000

Natural Gas Usage	
Increase in Gas Usage (kWh)	24.000
Average Natural gas Cost Increase	-
Average Increase in gas usage (%)	-

Primary Energy Savings	
Primary Energy Before (kWh)	31.574
Primary Energy After (kWh)	33.750
Primary Energy Savings (%)	-6,9%

Key Takeaways

The survey Respondent saw a saving of 800 Euros, while reducing overall grid bought electricity by 13%

Overall natural gas costs accounted for 50% of the overall energy costs after installation of the PACE Unit.

AVERAGE KEY PERFORMANCE INDICATORS

€ 800	Money Saved
600	Electrical kWh saved
1.753	kg CO2 saved

Total Household Energy Costs	
Average Spent on Energy Before	€ 3.200
Average Spent on Energy After	€ 2.400
Average Costs Savings (%)	25,0%

Electricity Savings	
Average Grid Electricty savings (kWh)	600
Average Electricity Cost Savings	€ 300
Average Grid Electicity Savings (%)	13,3%

CO2 Savings	
Average kgs carbon emitted (pre)	7.250
Average kgs carbon emittied (post)	5.497
Average carbon emissions savings (%)	24,2%

Prepared by DTU, October 2022

Figure 1: Summary of the results obtained from the data processing of data from unit 1.

Primary Energy savings: As reported, the property sees a 600 kWh saving on electricity imported from the grid, but a 2176 kWh (6,9%) increase in primary energy use. As mentioned above, there is good reason to believe that this property has a low self-consumption of the electricity produced by the FC mCHP resulting in a high electricity export and analogous high electricity import. Increasing the self-consumption would ensure a greater primary energy saving. Reducing the export of electricity by 2000 kWh would change the primary energy savings from -6,9% to +9%.

CO_2 savings: The move from heating oil and firewood as fuel to natural gas results in a saving of 1,75 ton CO_2/year, a 24,2% reduction in carbon emission. There is thus a clear environmental benefit connected with the substitution of heating oil and firewood, even with low utilisation of the electricity generation afforded by the FC mCHP. The above-mentioned increase in self-consumption of 2000 kWh would result in a further reduction of environmental impact and reduce the CO_2 emission with 0,8 ton a year, yielding a total saving of 2,55 ton CO_2/year.

Conclusions: This property is primed for a large benefit on all three axes: costs reductions, primary energy savings and environmental impact. Not all benefits are realised currently due to the low self-consumption of electricity observed. For such a case a focus on increasing self-consumption is highly advised.

Case No. 2

In this case a gas boiler was replaced with a FC mCHP, as shown in Figure 2. The pre-period data on natural gas consumption is from January 2018 to December 2018 and the electricity consumption from February 2016 to February 2017. The data for the post-period is from January 2020 to December 2020.

Initial considerations: This property reports a grid electricity use of -291 kWh after installation of the FC mCHP, and cost of € 379,20 associated with electricity consumption. With an electricity consumption of 3923 kWh before installation of the FC mCHP and a unit producing 4653 kWh after installation this may be a result of a net electricity export, but not a 100% self-consumption. The property may have exported around 1400 kWh of electricity and imported 1100 kWh in turn. This would fit with an electricity cost of 34 ¢/kWh for the imported electricity and a negligible feed-in tariff. Thus, the net export would still entail a cost. It has been evaluated that this scenario most likely explains the reported numbers.

It should also be noted that the pre-installation use of gas and electricity reported do not align temporally. There is no clear indication that this has impacted the results, but it may affect the consumption patterns of electricity and gas.

Cost savings: The property owner of case 2 saves € 374 annually (14.2%). Compared to case 1 the savings are significantly lower for a property which before installation used a gas burner.

Primary Energy savings: The property sees its electricity demand fully covered by the generated electricity and a net electricity export. This results in a, somewhat theoretical, electricity import saving of 107%. When the natural gas use is considered an overall reduction in primary energy need of 7093 kWh (17.9%) is seen. This improvement naturally stems primarily from the 107% decrease in electricity import.

CO_2 savings: The replacement of a natural gas boiler with a FC mCHP in this case yields a saving of 1162 kg CO_2/year, a 14,2% reduction in carbon emission.

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Pathway to a Competitive European Fuel Cell Micro-Cogeneration Market
Survey Response Summary

UNIT ID		3
Unit Information		
Country	Germany	
Previous Technology	Natural Gas	
Report 1 Case No.	3	

Energy Mix	**Pre**	**Post**
Natural Gas	88,4%	100,9%
Heating Oil	0,0%	0,0%
Wood	0,0%	0,0%
Electricity	11,6%	-0,9%

Electricity and LPG Usage	
Electricity Used Before (kWh)	3.923
Natural Gas Used Before (kWh)	29.771
Electricity Used After (kWh)	-291
Natural gas Used After (kWh)	33.213

Natural Gas Usage	
Increase in Gas Usage (kWh)	3.442
Average Natural gas Cost Increase	€ 379
Average Increase in gas usage (%)	11,6%

Primary Energy Savings	
Primary Energy Before (kWh)	39.579
Primary Energy After (kWh)	32.486
Primary Energy Savings (%)	17,9%

Key Takeaways

The survey Respondent saw a saving of 374 Euros, while reducing overall grid bought electricity by 107%

Overall natural gas costs rose by 12% and accounted for 83% of the overall energy costs.

AVERAGE KEY PERFORMANCE INDICATORS

€ 374 Money Saved

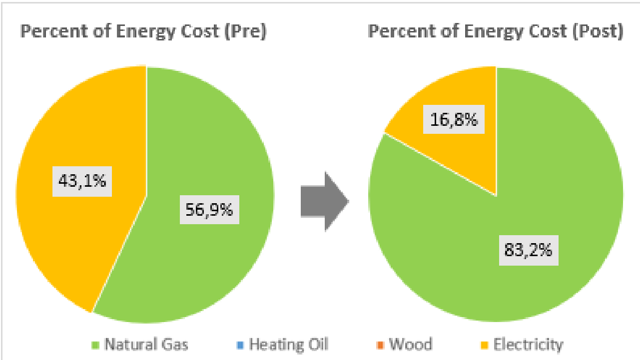
4.214 Electrical kWh saved

1.162 kg CO2 saved

Total Household Energy Costs	
Average Spent on Energy Before	€ 2.629
Average Spent on Energy After	€ 2.255
Average Costs Savings (%)	14,2%

Electricity Savings	
Average Grid Electricty savings (kWh)	4.214
Average Electricity Cost Savings	€ 753
Average Grid Electicity Savings (%)	107,4%

CO2 Savings	
Average kgs carbon emitted (pre)	6.982
Average kgs carbon emittied (post)	5.821
Average carbon emissions savings (%)	16,6%



Prepared by DTU, October 2022

Figure 2: Summary of the results obtained from the data processing of data from unit 3.

Conclusions: This property experiences savings on all accounts. The negative electricity import cannot be fully determined. However, even with an assumed net import of 1100 kWh the installation of the FC mCHP is beneficial on all accounts.

Case No. 3

In this case an oil burner is replaced with a FC mCHP, as shown in Figure Figure **3**: Summary of the results obtained from the data processing of data from unit 9. The pre-period data on heating oil is from January 2018 to December 2018 and the electricity consumption from April 2017 to March 2018. The data for the post-period on gas and electricity consumption is from March 2020 to March 2021.

Pathway to a competitive European Fuel Cell micro-CHP Market

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Pathway to a Competitive European Fuel Cell Micro-Cogeneration Market

Survey Response Summary

PACE

UNIT ID	9	
Unit Information		
Country	Germany	
Previous Technology	Heating Oil	
Report 1 Case No.	7	

Energy Mix	**Pre**	**Post**
Natural Gas	0,0%	97,6%
Heating Oil	86,7%	0,0%
Wood	0,0%	0,0%
Electricity	13,3%	2,4%

Electricity and LPG Usage	
Electricity Used Before (kWh)	2.472
Natural Gas Used Before (kWh)	0
Electricity Used After (kWh)	454
Natural gas Used After (kWh)	18.589

Natural Gas Usage	
Increase in Gas Usage (kWh)	18.589
Average Natural gas Cost Increase	-
Average Increase in gas usage (%)	-

Primary Energy Savings	
Primary Energy Before (kWh)	22.320
Primary Energy After (kWh)	19.724
Primary Energy Savings (%)	11,6%

Key Takeaways

The survey Respondent saw a saving of 274 Euros, while reducing overall grid bought electricity by 82%

Overall natural gas costs accounted for 83% of the overall energy costs after installation of the PACE Unit.

AVERAGE KEY PERFORMANCE INDICATORS

€ 274 Money Saved

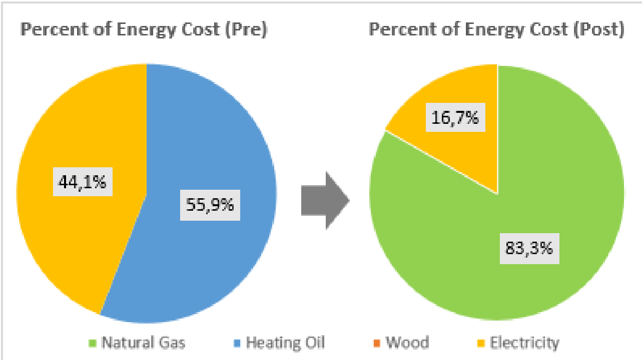
2.018 Electrical kWh saved

1.998 kg CO2 saved

Total Household Energy Costs	
Average Spent on Energy Before	€ 1.790
Average Spent on Energy After	€ 1.516
Average Costs Savings (%)	15,3%

Electricity Savings	
Average Grid Electricty savings (kWh)	2.018
Average Electricity Cost Savings	€ 536
Average Grid Electicity Savings (%)	81,6%

CO2 Savings	
Average kgs carbon emitted (pre)	5.450
Average kgs carbon emittied (post)	3.451
Average carbon emissions savings (%)	36,7%



Prepared by DTU, October 2022

Figure 3: Summary of the results obtained from the data processing of data from unit 9.

Initial considerations: It should be noted that the pre-installation reporting periods fits poorly with a 3-month overlap. Thus, the reported use and costs of heating oil and electricity are in practice not from the same period. It is uncertain whether these periods are comparable in terms of fuel and electricity demand, and this should be kept in mind when evaluating the results below.

Cost savings: The reported costs result in a yearly saving of € 274, which is equivalent to a saving of 15,3% yearly.

The electricity demand of the property is very low, both before and after installation of the FC mCHP. As a result, less is gained by installing the PACE FC mCHP unit in the property compared to the other cases presented in the report.

It is worth noting that the reported costs associated with the consumption of heating oil are very low. For this case one litre of heating oil is reported to cost 0,67 €/L. The property in **Error! Reference source not found.** reports a cost of 0,97 €/L. This low price has a significant impact on the financial savings seen for this case. An oil price of 0,97 €/L would in this case increase the savings by € 455 per year. This translates to a saving of € 729 which is equivalent to an average cost saving of 40,7%.

Primary Energy savings: The installation of the FC mCHP ensures a saving of 2018 kWh imported electricity. The primary energy saving is 2596 kWh (11.6%).

CO_2 savings: The choice of replacing an oil burner with a FC mCHP unit using natural gas in this case saves 2 ton CO_2/year, a 36,7% reduction in CO_2 emissions.

This case and case 1 thus clearly demonstrate the environmental benefit of moving away from the decentralised consumption of heating oil.

Conclusions: The property saw savings on all accounts. Of note are the environmental benefits of installing a FC mCHP unit. Covering heating and hot water demands with natural gas while consuming electricity generated on premises in total saves the environment from 2 tons of CO_2 yearly. The environmental savings coupled with financial savings makes a compelling case for replacing a heating oil burner with a FC mCHP, assuming a readily available natural gas supply and a German location. A less favourable heating oil price would make the financial prospects much more attractive.

Statistical Analysis

With 32 responses different statistical cases have been investigated in the search of trends in cost, consumption and CO2 savings. In this report savings based on the properties previous technology

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(heating oil burner or gas boiler) and an overall average of all 32 units have been included to summarise the overall general savings.

Not enough data was available to perform a statistical analysis based on geography at this point

Statistical Analysis Based on the Properties Previous Technology

In the statistical case displayed in Figure 1 oil burners have been replaced with a FC mCHP. Out of 32 responses 10 properties have replaced oil burners with a FC mCHP unit.

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Questionnaire Response Summary - Properties Previously Using Heating Oil

PACE

TOTAL SURVEY RESPONSES	**10**		

Type of Fuel (Existing buildings, Pre PACE unit)			
Natural Gas	0	Wood	3
Heating Oil	10		

Electricity and Natural Gas Usage			
Average Electricity Used Before (kWh)	4.951	±	1.706
Average Natural Gas Used Before (kWh)	0	±	0
Average Electricity Used After (kWh)	2.366	±	1.382
Average Natural Gas Used After (kWh)	32.971	±	12.088

Natural Gas Usage			
Average increase in gas usage (kWh)			-
Average Natural gas Cost Increase			-
Average Increase in gas usage (%)			-

Primary Energy Savings			
Average Primary Energy Before (kWh)	45.008	±	16.125
Average Primary Energy After (kWh)	38.886	±	14.322
Primary Energy Savings (%)	13,60%		

Total Household Energy Costs			
Average Spent on Energy Before	€ 3.202	±	€ 1.273
Average Spent on Energy After	€ 2.443	±	€ 883
Average Costs Savings	€ 759	±	€ 1.125

Key Takeaways

Survey Respondents saw an average savings of 759 Euros, while reducing overall grid bought electricity by 52%

Overall natural gas accounted for 75% of the overall energy costs after installation of PACE Unit, on average.

AVERAGE KEY PERFORMANCE INDICATORS

€ 759	Money Saved
2.585	Electrical kWh saved
4.005	kg CO2 saved

Electricity Savings			
Average Grid Electricty savings (kWh)	2.585	±	1.244
Average Electricity Cost Savings	€ 639	±	€ 449
Average Grid Electicity Savings (%)	52,2%		

CO2 Savings			
Average kgs carbon emitted (pre)	10.570	±	3.891
Average kgs carbon emittied (post)	6.565	±	2.351
Average carbon emissions savings (%)	37,9%		

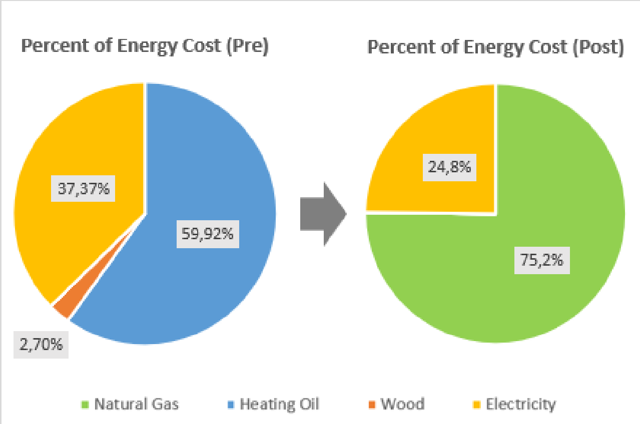

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Figure 4: Statistical summary of all responses where heating oil were used as fuel in the pre-period.

Also, a statistical analysis has been conducted for properties where gas boilers have been replaced with a FC mCHP as shown in Figure 5. Out of 32 responses in total 22 properties have replaced gas boilers with a FC mCHP unit.

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Questionnaire Response Summary - Properties Previously Using Natural Gas

PACE

TOTAL SURVEY RESPONSES	22

Type of Fuel (Existing buildings, Pre PACE unit)			
Natural Gas	22	Firewood	0
Heating Oil	0		

Electricity and Natural Gas Usage			
Average Electricity Used Before (kWh)	4.622	±	2.816
Average Natural Gas Used Before (kWh)	30.155	±	16.172
Average Electricity Used After (kWh)	2.372	±	2.255
Average Natural Gas Used After (kWh)	34.811	±	12.279

Natural Gas Usage			
Average increase in gas usage (kWh)	4.656	±	8.807
Average Natural gas Cost Increase	€ 362	±	€ 604
Average Increase in gas usage (%)	15,4%		

Primary Energy Savings			
Average Primary Energy Before (kWh)	41.711	±	20.499
Average Primary Energy After (kWh)	40.741	±	16.361
Primary Energy Savings (%)	2,32%		

Total Household Energy Costs			
Average Spent on Energy Before	€ 2.908	±	€ 1.208
Average Spent on Energy After	€ 2.713	±	€ 916
Average Costs Savings	€ 195	±	€ 801

Key Takeaways

Survey Respondents saw an average savings of 195 Euros, while reducing overall grid bought electricity by 49%

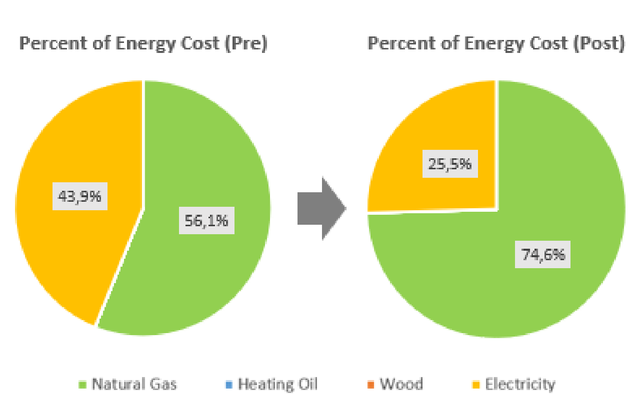
Overall natural gas costs rose by 15% percent and accounted for 75% of the overall energy costs, on average.

AVERAGE KEY PERFORMANCE INDICATORS

€ 195	Money Saved
2.250	Electrical kWh saved
146	kg CO2 saved

Electricity Savings			
Average Grid Electricty savings (kWh)	2.250	±	2.353
Average Electricity Cost Savings	€ 557	±	€ 534
Average Grid Electicity Savings (%)	48,7%		

CO2 Savings			
Average kgs carbon emitted (pre)	7.027	±	3.217
Average kgs carbon emittied (post)	6.881	±	2.459
Average carbon emissions savings (%)	2,1%		



Prepared by DTU, October 2022

Figure 5: Statistical summary of all responses where natural gas were used as fuel in the pre-period.

Cost savings: In the case where a property replaces an oil burner with a FC mCHP unit the respondents saved € 759 yearly, meaning that on average a property saves 23,7%.

On the other hand, the properties which have replaced a gas boiler with a FC mCHP unit on average saved € 195, which is equivalent to an average yearly saving of 6,7%.

It is worth noting that the reported costs associated with the consumption of heating oil varies drastically. The 10 respondents included in this statistical investigation have reported their oil use in 12 month periods throughout 2017-2020, which due to the increasing energy prices have resulted in a heating oil litre price which ranges from 0,42-0,97 €/L. A price variation this large will have a significant impact on the average savings.

The savings observed when switching from a gas burner to a FC mCHP is significantly lower than the savings observed when replacing an oil burner.

Primary Energy savings: The installation of FC mCHP units in properties previously using heating oil ensures an average saving of 2585 kWh imported electricity, a value equivalent to 52,2%. The primary energy saving is 6122 kWh (13,6%).

The installation of FC mCHP units in properties previously using natural gas ensures an average saving of 2250 kWh imported electricity, a value equivalent to 48,7% - an average value similar to the one reported for properties previously fuelled with heating oil. The primary energy saving is 970 kWh (2,32%).

CO_2 savings: Changing from heating oil to a FC mCHP on average saves approximately 4 ton of CO_2/year, which is equivalent to an average carbon emissions reduction of 37.9%. All properties which replaced their oil burners saved between 24,2-63,5% CO_2/year, except one property which only saved 5,2%. This property also had photovoltaic cells installed which made it challenging to estimate the actual electricity use and electricity import/export.

Replacing a gas burner with a FC mCHP unit (both fuelled with natural gas) on average saves approximately 150 kg of CO_2/year, which is equivalent to an average carbon emissions reduction of 2,1%. The low CO_2 savings is not a surprise since the properties do not change their fuel type. However, based on the average increase in gas usage, one could expect an increase in CO_2 emission. Yet the lower import of electricity from the grid on average more than makes up for this increase.

Conclusions: The properties which replaced their oil burners with a FC mCHP unit saw savings on all accounts. Like case no. 3 this clearly demonstrate the environmental and financial benefits of moving away from heating oil, assuming that a readily available natural gas supply is present.

The properties which replaced their gas burners with a FC mCHP unit experienced a significant reduction in grid imported electricity, while minor savings were obtained according to cost and CO_2 emission.

Our preliminary conclusion is that a property using heating oil will experience greater benefits and savings on all accounts by replacing their oil burner with a FC mCHP unit.

Total Average

In Figure 6: Summary of all 32 cases. all 32 properties with valid and complete data have been gathered in one analysis, which makes it possible to estimate and summarise the overall average savings relating to cost, CO_2 emission and primary energy.

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Questionnaire Response Summary - All PACE Units

TOTAL SURVEY RESPONSES	**32**

Type of Fuel (Existing buildings, Pre PACE unit)			
Natural Gas	22	Firewood	3
Heating Oil	10		

Electricity and Natural Gas Usage *			
Average Electricity Used Before (kWh)	4.622	±	2.816
Average Natural Gas Used Before (kWh)	30.155	±	16.172
Average Electricity Used After (kWh)	2.372	±	2.255
Average Natural Gas Used After (kWh)	34.811	±	12.279

Natural Gas Usage *			
Average increase in gas usage (kWh)	4.656	±	8.807
Average Natural gas Cost Increase	€ 362	±	€ 604
Average Increase in gas usage (%)	15,4%		

Primary Energy Savings			
Average Primary Energy Before (kWh)	42.741	±	19.041
Average Primary Energy After (kWh)	40.161	±	15.545
Primary Energy Savings (%)	6,04%		

Total Household Energy Costs			
Average Spent on Energy Before	€ 3.000	±	€ 1.216
Average Spent on Energy After	€ 2.629	±	€ 901
Average Costs Savings	€ 371	±	€ 934

Key Takeaways

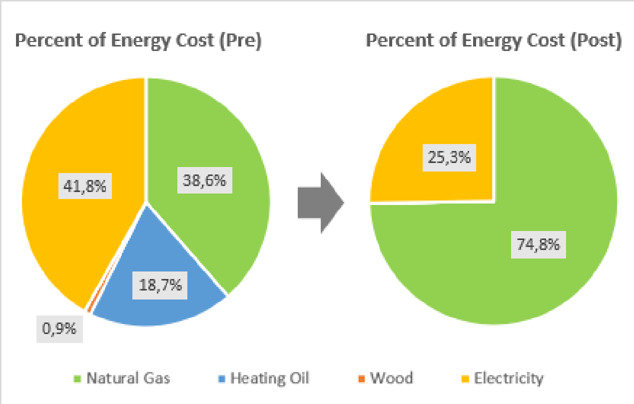
Survey Respondents saw an average saving of 371 Euros, while reducing overall grid bought electricity by 50%

Overall natural gas costs rose by 15% percent and accounted for 75% of the overall energy costs, on average.

AVERAGE KEY PERFORMANCE INDICATORS	
€ 371	Money Saved
2.355	Electrical kWh saved
1.352	kg CO2 saved

Electricity Savings			
Average Grid Electricty savings (kWh)	2.355	±	2.055
Average Electricity Cost Savings	€ 582	±	€ 503
Average Grid Electicity Savings (%)	49,8%		

CO2 Savings			
Average kgs carbon emitted (pre)	8.134	±	3.767
Average kgs carbon emittied (post)	6.782	±	2.392
Average carbon emissions savings (%)	16,6%		



*Numbers calculated using data from properties previously using natural gas.

Prepared by DTU, October 2022

Figure 6: Summary of all 32 cases.

On average a property saves € 371 yearly after installation of a FC mCHP unit, reduces its electricity consumption by 2355 kWh and saves 1,352 ton CO2 each year by installing a Fuel Cell mCHP.

As seen previously in the cost comparison between replacing oil or gas burners with a FC mCHP unit, the savings vary significantly depending on what energy source was replaced. The average results for all units are thus influenced by the population of useable questionnaire answers consisting of a majority of gas boiler replacements (22 gas observations versus 10 oil observations).

Uncertainties

The reported savings above contain considerable uncertainties mainly stemming from the source of data being an anonymous questionnaire that contains human error and incomplete entries. The complexity and detail level of the questions also results in certain assumptions that must be made. Additionally, the low number of complete and valid questionnaire responses makes a statistical analysis borderline feasible now. The expected additional data for the final report will be a great help in reducing some of these uncertainties along with update data on grid electricity CO_2 emissions. E.g. Germany have reduced the electricity grids CO_2 emission by 28% from 2017 to 2020[5].

It can be argued whether the cost savings reported are reasonable, due to the energy crisis and fluctuating energy prices. From the data it is not possible to see how much electricity is sold back to the grid or at what price. These factors affect the overall cost savings and primary energy savings significantly.

[5] Click here for *direct link to average CO2 intensity of German grid mix*

3. Conclusions

The analysis presented in this report have been conducted to test whether PACE Fuel Cell micro Combined Heat and Power (FC mCHP) units can make a 25% primary energy saving and reduce the CO_2 emission of appropriate European homes by 30%.

The preliminary data shows, that for most cases savings on all parameters (primary energy-, cost- and CO_2 saving) have been observed. However, it can be concluded that properties that exchange their oil burner with a FC mCHP unit saves significantly more than properties that have exchanged their gas boiler with a FC mCHP unit.

The primary energy savings, when considering all the responses, were on average 6%. For properties which previously used heating oil the primary energy savings were 13,5%, while the primary energy savings for properties previously using natural gas was 2,3%.

CO_2 equivalent (CO_{2e}) saving were on average 16,6%. In cases where domestic heating oil burners were replaced the saving was 37,9% on average. This indicates that a strong environmental case can be made for replacing heating oil burners with FC mCHPs. For the cases where a gas boiler was replaced the resulting CO_{2e} savings were 2,1% on average.

The average cost saving was 12,4%. For cases where a heating oil burner was replaced the annual average saved cost was 24%. The annual cost saving was 7% for properties where a gas boiler was replaced.

All the values reported contain significant uncertainty and large potential biases due to the current quantity and quality of the data. Due to this large uncertainty, we cannot at this point conclude whether the savings targets have been met and we defer the final assessment for the final report where more data is available.

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Annex 1 – Detailed Methodology for Savings Analysis

In this appendix the methodology used in the analysis will be outlined and described. The main equations used, and assumptions made to determine the cost, CO_2 and primary energy savings will be given and described thoroughly as well.

A.1 Data Collection for Property Level Savings Analysis

This analysis is based on self-reporting of consumed fuel and electricity, as well as the costs associated with this consumption. The reporting has been performed using an online questionnaire where the end-user reports the following:

In general:

- Maker and mark of the FC mCHP.
- Unit-ID(s) of the unit(s) installed in the property.

For a period of 12 months at a time before installation of the PACE unit:

- Heating and electricity generating appliances installed in the household.
- Fuel use associated with these appliances.
- Net consumed electricity from the grid (all export discounted).
- Costs associated with the fuel consumed and the electricity imported.

For a period of 12 months at a time after installation of the PACE unit:

- Heating and electricity generating appliances installed in the household, besides the PACE FC unit.
- The make and brand of the FC unit.
- Fuel use associated with these appliances.
- Net consumed electricity from the grid (all export discounted).
- Costs associated with the fuel consumed and the electricity imported.

The collected data can through the unit-ID of the installed units be connected to a country and postal code of installation. The postal code is only used in cases where regional data is available on parameters like CO_2 intensity from the grid. So far this has not been the case. For some units, and if analysis would benefit from this, it may be possible to access performance data for the unit. The performance data can be used to verify or contextualise the consumption reporting for the unit.

Currently, savings are only calculated for 'existing', i.e., not newly build, buildings. The analysis requires data on previous consumption, as making the desired comparative analysis for new-build houses requires a comparison case. A case which is not trivial to define in a satisfactory manner.

A.2 Calculating (Operational) CO_2 Savings:

CO_2 savings are calculated based on fuel and electricity consumption for hot water, heating and electricity demand in a 12-month periods before and after installation of the PACE FC unit. The calculation method varies based on incumbent technology.

When calculating CO_2 emissions for a property, both CO_2 produced at location and emissions related to electricity consumed from the grid must be considered.

For all fuel types reported in this investigation, except for firewood, the Global Warming Potential (GWP) contribution from methane and N_2O are negligible compared to the GWP contribution of CO_2. This simply due to the cleanness of the combustion of fossil fuels, emitting multiple kilograms of CO_2 but only grams of CH_4 and N_2O. For illustration, the combustion of 1 kWh of natural gas emits 181.04 g of CO_2 but 181.23 g of CO_2-equivalent (CO_{2e}) when taking the impact of CH_4 and N_2O into account[6]. For firewood, CH_4 and N_2O must be considered as CH_4 and N_2O are produced in substantial quantities. In conclusion, all CO_{2e} factors are set to be equal to the emission factor of CO_2, except in the case of firewood.

Before Fuel Cell Installation

The calculation of CO_2 emissions before installation of one or more PACE units depends on the previously used heating technology. In cases where a fuel cell system or a gas boiler was the incumbent technology, the methodology presented for LPG and natural gas in the subsection "**After fuel cell installation**" will be used. Heat pumps or electric heating will use the methodology detailed for CO_2 from grid in the same section.

For heating oil CO_2 emissions are estimated using a general emission value. Values from IEA and EPA range from 0.250 – 0.252 $kgCO_2/kWh$ (161.3 lbs/MBtu[7] or 73.96 kg/mmBtu[8]). For this analysis it was chosen to use a value of 0.250 $kgCO_2/kWh$ to ensure that heating oil is not penalised unnecessarily in the analysis.

Emissions from burning firewood can be estimated from wood and wood residuals[9]. Doing this, and including methane and N_2O, gives an emission of 0.324 $kgCO_2/kWh$ (93.80 kg/mmBtu + 0.0072·25 kg/mmBtu + 0.0036·298 kg/mmBtu). As firewood is usually bought and delivered in steres (reported as m^3 of firewood) kWh needs to be recalculated into m^3. Using middle-of-the-road values[10] (birch firewood, 18% moisture content, 70% packing efficiency of the firewood) one obtains:

[6] Calculated based on information from *https://www.epa.gov/sites/default/files/2015-07/documents/emission-factors_2014.pdf*
[7] *https://www.eia.gov/tools/faqs/faq.php?id=73&t=11*
[8] *https://www.epa.gov/sites/default/files/2015-07/documents/emission-factors_2014.pdf*
[9] *https://www.epa.gov/sites/default/files/2015-07/documents/emission-factors_2014.pdf*
[10] *http://seacourse.dk/wiki/tiki-index.php?page=Calculating+in+KWh*

$$\text{kWh/m}^3 = 620 \text{ kg/m}^3 \cdot 4.2 \text{ kWh/kg} \cdot 70\% \text{ packing efficiency}$$

$$= 1{,}822.8 \text{ kWh/m}^3$$

$$\text{kg } CO_2/\text{m}^3 = 0.324 \text{ kg}CO_2/\text{kWh} \cdot 1{,}822.8 \text{ kWh/m}^3$$

$$= 590.6 \text{ kg } CO_2/\text{m}^3.$$

More details will be given in the section "*Calculating Primary Energy savings*".

After fuel cell installation

It is assumed that the carbon footprint from heating and electricity in the properties only stems from two sources: gas and grid electricity used to cover the demands of the house.

$$CO_2(total) = CO_2(fuel) + CO_2(grid)$$

As we cannot be certain to have electricity production data for a given unit, in general it will be assumed that electricity production of the FC unit will be reflected in the data as a lack of electricity import from the grid.

CO_2 from house/fuel: The gas used by the FC mCHP will either be Liquefied Petroleum Gas (LPG) or natural gas.

In the case of LPG, a calorific value of 46.1 MJ/kg (12.8 kWh/kg)[11] will be used. For natural gas it will be assumed that all available energy comes from methane. This is a reasonable assumption for large values of Higher Heating Values (HHV) but may be problematic for lower values of HHV. Calculations of enthalpy of combustion (kWh/kg_{fuel}) based on information on HHV and normal density from Energinet[12] show values within a range of 97-99% of the theoretical value of pure CH_4 (15.42 kWh/kg_{CO2}). This 1-3% point deviation may need to be considered if the savings margin is low.

In the case where the consumption is given in kWh; it is possible to calculate CO_2 from the consumed fuel:

$$CO_2(fuel) = K_{CO_2} \cdot CF_{kWh}$$

Where CO_2(fuel) is the CO_2 emission in kg (per reporting period), K_{CO2} the amount of CO_2 consumed per kWh (0.181 kg/kWh)[13] and CF_{kWh} the amount of consumed fuel in kWh (in the reporting period).

[11] *https://energypedia.info/wiki/Liquefied_Petroleum_Gas_(LPG)*
[12] *https://energinet.dk/Gas/Gasdata/Braendvaerdier*
[13] Here only CO_2 is considered. If working with CO_{2e} the number becomes 0.266. See *https://www.epa.gov/sites/default/files/2015-07/documents/emission-factors_2014.pdf*

K_{CO2} can also be calculated from the enthalpy of combustion of pure methane (-890.4 kJ/mol = -15.42 kWh/kg_{CH4}) and the molar mass ratio of CO_2 and CH_4 (as CO_2 is produced in 1:1 molar quantity from CH_4). The result is:

$$K_{CO_2}(HHV) = \frac{M_{CO_2}}{M_{CH_4}} \cdot \frac{1}{\Delta_c H^\circ} = \frac{44.01 \frac{g_{CO_2}}{mol}}{16.042 \frac{g_{CH_4}}{mol}} \cdot \frac{1}{15.42 \frac{kg_{CH_4}}{kWh}} = 0.178 \frac{kg_{CO_2}}{kWh}$$

A similar calculation using the lower heating value of methane (-802.3 kJ/mol = -13.89 kWh/kg_{CH4}) gives a K_{CO2} of 0.1975 kg_{CO2}/kWh. In this analysis a value of 0.181 kg/kWh will be used.

In the case where the consumption is given in Nm^3 , the consumption must be converted to kWh. To recalculate the consumption form Nm^3 to kWh the (net) calorific value is needed:

$$CO_2(fuel) = K_{CO_2} \cdot NCV \cdot CF_{Nm^3}$$

Where NCV is the net calorific value in kWh/Nm^3 and CF_{Nm3} is the amount of fuel consumed in the unit in Nm^3 for the reporting period. An international convention value[14] of 10.55 kWh/Nm^3 has been used.

CO_2 from grid: To calculate the CO_2 emission from the grid a CO_2 intensity factor is needed.

$$CO_2(grid) = CIF \cdot NCE_{kWh}$$

Where CIF is known as the CO_2 intensity factor in gCO_2eq /kWh and NCE_{kWh} the net consumed electricity in kWh. All export to the grid must be subtracted if known. Average yearly CIF values are available[15,16] however, more locally applicable values would be of great interest to find.

Complications: If additional heat or electricity producing equipment is in operation this must be considered if possible. So far, this have not been considered, as the actual contribution from additional equipment is not evident form the data available.

Cascading systems would require diligence regarding consumption data. So far, no such cascading systems have been reported.

Overall CO_2 Savings

Savings will be calculated as a comparison between the calculated emissions before installation of the PACE unit and after installation of the PACE unit. The data can be normalised to years and days, as well

[14] W. Vogel, H. Kalb," Large-Scale Solar Thermal Power: Technologies, Costs and Development", Wiley-VCH Verlag (2010), ISBN: 978-3-527-40515-2, Appendix C
[15] *https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-5*
[16] *https://www.electricitymap.org/?page=map*

as per kWh consumed. Usefulness of these two types of normalisations depends on use-case. So far, normalisation has only been done on yearly basis.

A.3 Calculating Primary Energy savings:

In the cases presented in the report all primary energy consumption and conversion is done on the premises of the property, with one exception. Electricity imported from the grid carries with it a primary energy conversion at the power plant. This conversion is accounted for using a Primary Energy Factor (PEF) to recalculate electricity consumed at the property to primary energy needed to produce said electricity. The PEF includes conversion losses at the power plant as well as transmission and distribution losses.

In this preliminary analysis the politically defined PEF of 2.5 set out in the EC Energy Efficiency Directive (EED) of 2012[17] have been used. Since this work started the EED has been revised and the standard PEF has been lowered to 2.1. This will prompt a thorough review of the PEF used in subsequent reports. The aim going forward is to use PEF's calculated for the regional electricity grid in the region of installation and for the time interval of the electricity consumption. As the data needed for these calculations is hard to come by and calculations tends to be contentious, it was not feasible to include them in this report.

Thus, the calculation of the primary energy saving (PES) is as follows:

$$PES = (CF_{kWh} + 2.5 \cdot NCE_{kWh})_{before} - (CF_{kWh} + 2.5 \cdot NCE_{kWh})_{after}$$

Where CF_{kWh} is the amount of consumed fuel in kWh for the given reporting period, and NCE_{kWh} is the net consumed electricity in kWh.

When calculating primary energy consumption for wood burning stoves the following conversion factor is used:

$$\text{Primary energy per Nm}^3 \text{ (kWh/Nm3)} = 620 \text{ kg/Nm}^3 \cdot 4.2 \frac{kWh}{kg} \cdot\ 0.7 = 1{,}822.8 \frac{kWh}{Nm3}$$

This conversion factor is calculated assuming birch firewood with an 18% moisture content and a packing density of the firewood of 70% (70% wood and 30% air per m^3 of firewood bought)[18].

The energy content of firewood and the packing density of the stere of firewood bought can vary significantly based on wood type, water content and packing diligence. The value calculated here is in the range mid to high compared to other estimates[19]. The largest difference is the packing density,

[17] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32012L0027
[18] http://seacourse.dk/wiki/tiki-index.php?page=Calculating+in+KWh
[19] https://hbemo.dk/haandbog-for-energikonsulenter-hb2019-gaeldende/bilag-4-energimaerkning-af-eksisterende-bygninger/vejledende-tekniske-bilag-og-tabeller/braendsel/braendvaerdier-og-co2-emissionsfaktorer

which have been assumed to not be excessively large. See section "**Before fuel cell installation**" above for further calculations and information.

A.4 Calculating (operational) cost savings:

Cost savings can be calculated either as a flat saving in expenditure, or as a reduction in cost per kWh covered. The former method will simply subtract the incurred costs after installation of the PACE unit from the incurred costs before installation. In this preliminary only flat savings are calculated.

The flat cost saving is calculated as:

$$Saving\ (€) = Cost_{before} - Cost_{after}$$

This number will most likely not provide a significant amount of information, but if this number is positive for all investigated units this will be an indication that the installation of a PACE unit does result in a reduction of the energy costs.

While it might be interesting to calculate levelized costs of energy (LCoE), this has not been possible. Figures such as costs of operation (maintenance) and investment expenditure (cost of purchase) are confidential figures not available to DTU.