PhD defense

The role of residential micro-cogeneration fuel cells in the energy transition

- A case study in Belgium -

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Introduction

The role of residential micro-cogeneration ②

③ fuel cells in the energy transition ①

- A case study in Belgium -

Background – Part 1 – The energy transition

Studied fuel cells are supposed to help the energy transition…

- What is it exactly ?

  Before this thesis (5 years ago), my **knowledge** of the energy transition **was limited to** :

  “We must reduce Greenhouse Gases (GHG) emissions to net-zero…”

- How could I assess the environmental performance of the systems without a deep understanding energy transition metrics and the issues at stake ?

  I did not want my work to be accused of “**techno-solutionism**”

Background – Part 1 – The energy transition (in Belgium)

Also, which energy transition are we talking about ?

Global ?

European ?

Belgian ? Wallonia ?

No "*one size fits all*" in terms of energy transition [1]

→ scope limited locally, to **Belgium** (Wallonia)

→ There was a need to limit the scope and look in national/regional climate strategies, i.e. **Nationally Determined Contributions** (NDCs), to see :

- Are they in line with "Science" regarding the energy transition ?
- If and how they can integrate (residential) fuel cells ?

[1] 10.1016/j.isci.2022.105260

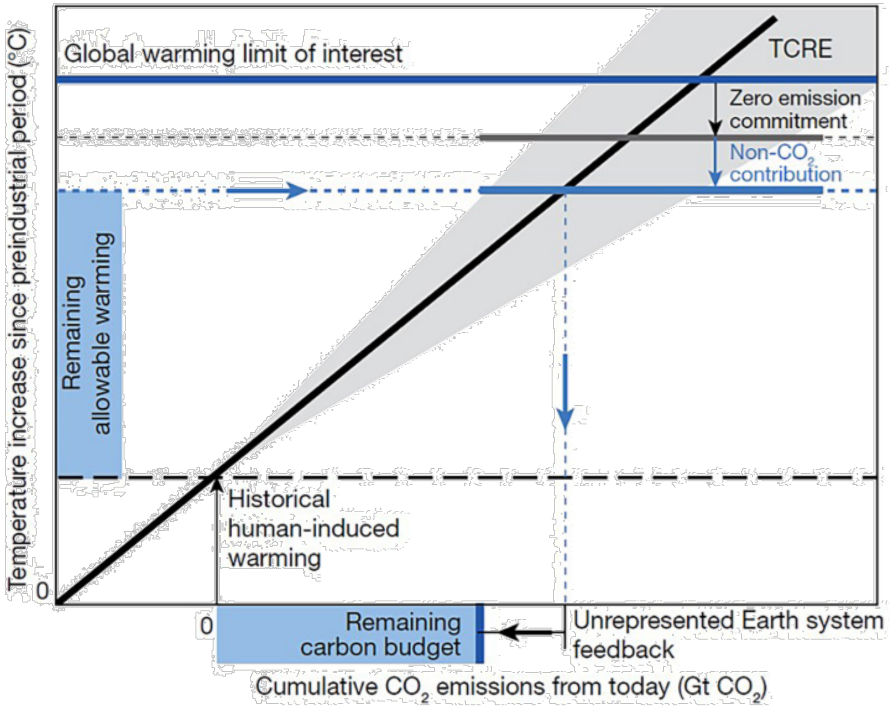
Background – Part 1 – The energy transition

Paper 1 :

Confronting Nationally Determined Contributions to IPPC's +2 °C Carbon Budgets through the Analyses of France and Wallonia Climate Policies, *Journal of Ecological Engineering*, 24(6), 214–225, 2023, doi : 10.12911/22998993/162984

(France has been studied for comparison purposes)

Energy transition – What "Science" (IPCC) says ?



Ref : IPCC WG1, 2021

Based on the +1.5°C and +2°C temperature limits sets in the "Paris Agreement" (2015), "**carbon budgets**" are defined through the transient climate response to cumulative emissions (TCRE), similar to a financial budget that you **cannot overcome**

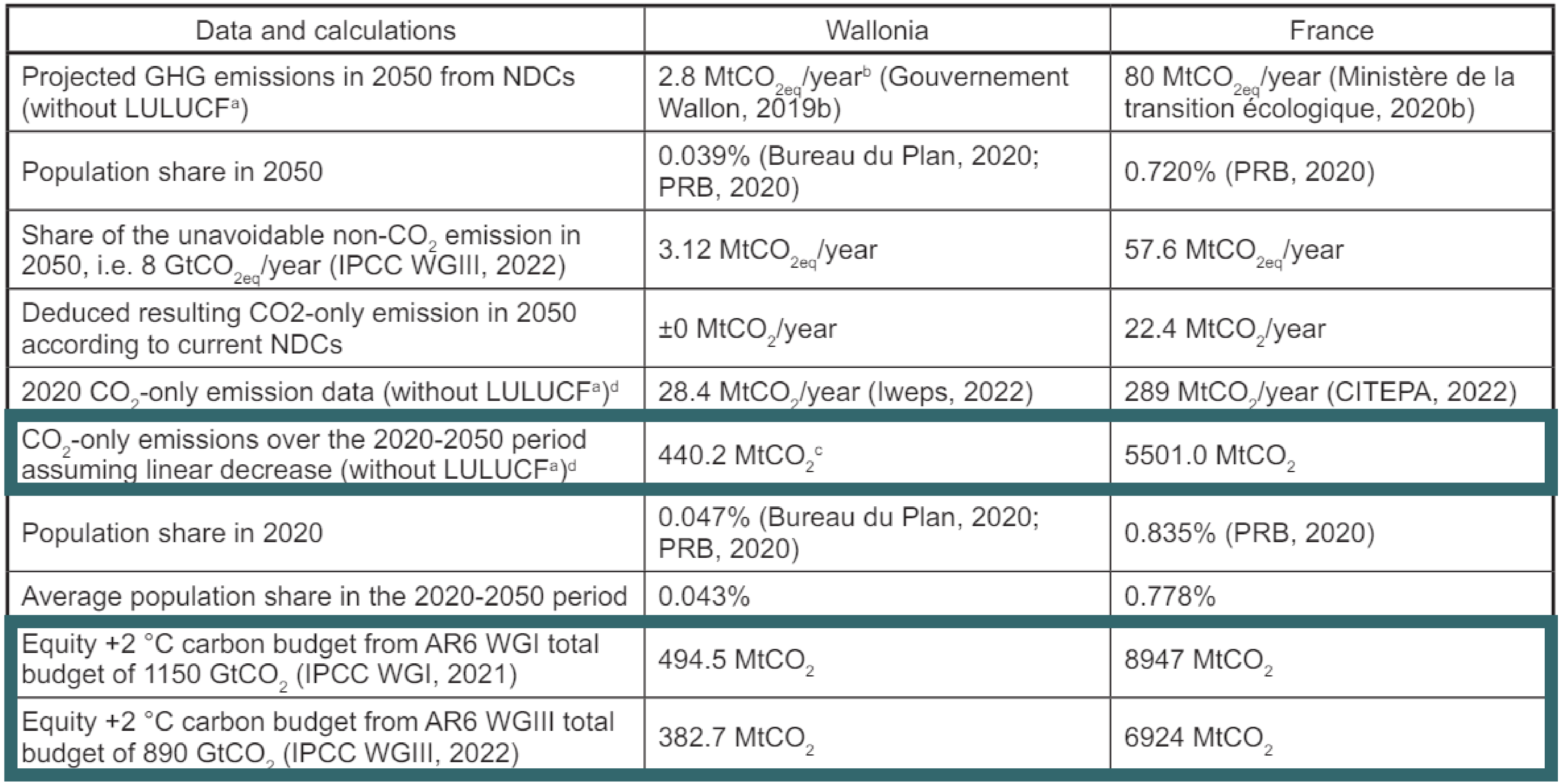
→ Humanity carbon emissions allowance till net-zero GHG emissions (which shall occur in 2050, 2080, 2100, ??)

Likelihood of limiting global warming to temperature limit	Temperature limit of interest compared to preindustrial levels	Estimated remaining carbon budget from the beginning of 2020 ($GtCO_2$)
50%	+1.5°C	500 (IPCC WGI, 2021) / 510 (IPCC WGIII, 2022)
67%	+2°C	1150 (IPCC WGI, 2021) / 890 (IPCC WGIII, 2022)

Confidence level ≈ uncertainty

Background – Part 1 – The energy transition (in Belgium)

Equity +2 °C carbon budgets from January 1st 2020 against Wallonia and France current NDCs



Data and calculations	Wallonia	France
Projected GHG emissions in 2050 from NDCs (without LULUCF[a])	2.8 $MtCO_{2eq}$/year[b] (Gouvernement Wallon, 2019b)	80 $MtCO_{2eq}$/year (Ministère de la transition écologique, 2020b)
Population share in 2050	0.039% (Bureau du Plan, 2020; PRB, 2020)	0.720% (PRB, 2020)
Share of the unavoidable non-CO_2 emission in 2050, i.e. 8 $GtCO_{2eq}$/year (IPCC WGIII, 2022)	3.12 $MtCO_{2eq}$/year	57.6 $MtCO_{2eq}$/year
Deduced resulting CO2-only emission in 2050 according to current NDCs	±0 $MtCO_2$/year	22.4 $MtCO_2$/year
2020 CO_2-only emission data (without LULUCF[a])[d]	28.4 $MtCO_2$/year (Iweps, 2022)	289 $MtCO_2$/year (CITEPA, 2022)
CO_2-only emissions over the 2020-2050 period assuming linear decrease (without LULUCF[a])[d]	440.2 $MtCO_2$[c]	5501.0 $MtCO_2$
Population share in 2020	0.047% (Bureau du Plan, 2020; PRB, 2020)	0.835% (PRB, 2020)
Average population share in the 2020-2050 period	0.043%	0.778%
Equity +2 °C carbon budget from AR6 WGI total budget of 1150 $GtCO_2$ (IPCC WGI, 2021)	494.5 $MtCO_2$	8947 $MtCO_2$
Equity +2 °C carbon budget from AR6 WGIII total budget of 890 $GtCO_2$ (IPCC WGIII, 2022)	382.7 $MtCO_2$	6924 $MtCO_2$

NDC projection →

Both NDCs **only** pledge to **territorial emissions** reduction

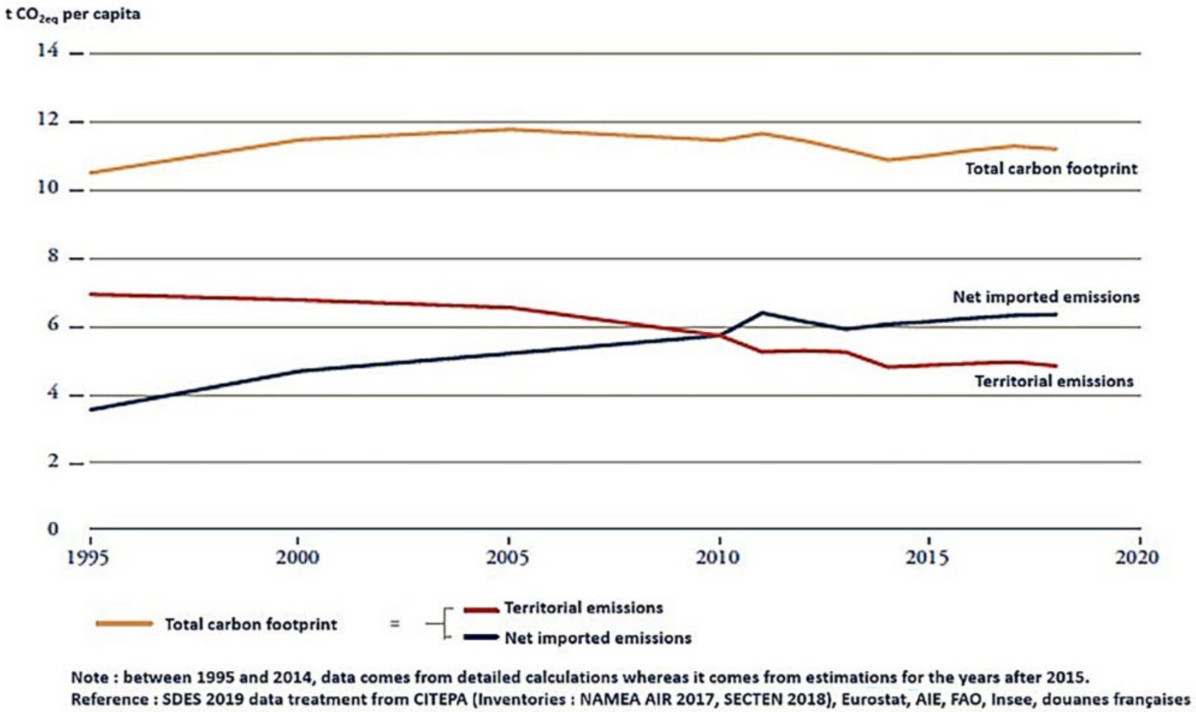
+2°C theorical limits →

Wallonia is expected to overcome +2°C budgets on territorial emissions only (or has little margin)

France has some margin (for part of the imported emissions)

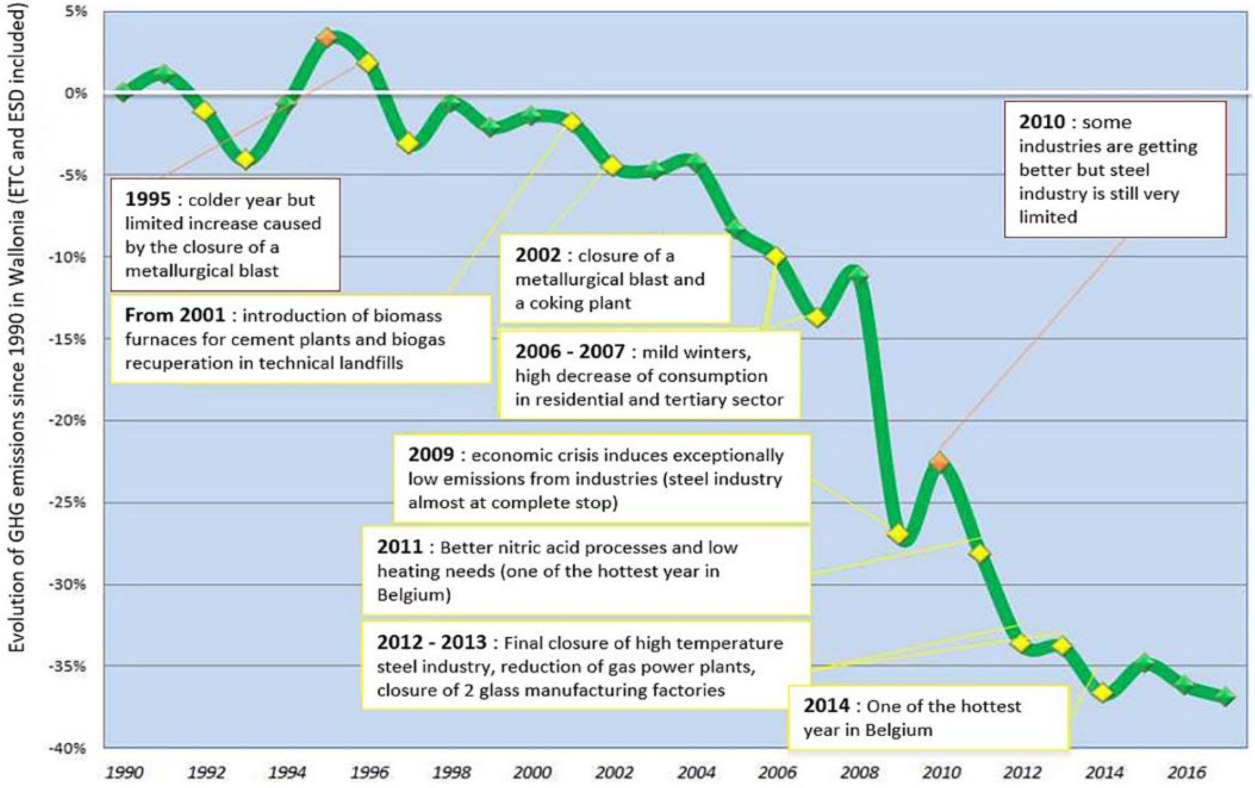
Background – Part 1 – The energy transition (in Belgium)

Both NDCs **only** pledge to **territorial emissions** reduction



Note : between 1995 and 2014, data comes from detailed calculations whereas it comes from estimations for the years after 2015.
Reference : SDES 2019 data treatment from CITEPA (Inventories : NAMEA AIR 2017, SECTEN 2018), Eurostat, AIE, FAO, Insee, douanes françaises

France imported emissions are higher than territorial emissions and increase to a point that this increase compensates the territorial emissions reduction (Haut Conseil pour le Climat, 2020).



1995 : colder year but limited increase caused by the closure of a metallurgical blast

From 2001 : introduction of biomass furnaces for cement plants and biogas recuperation in technical landfills

2002 : closure of a metallurgical blast and a coking plant

2006 - 2007 : mild winters, high decrease of consumption in residential and tertiary sector

2009 : economic crisis induces exceptionally low emissions from industries (steel industry almost at complete stop)

2010 : some industries are getting better but steel industry is still very limited

2011 : Better nitric acid processes and low heating needs (one of the hottest year in Belgium)

2012 - 2013 : Final closure of high temperature steel industry, reduction of gas power plants, closure of 2 glass manufacturing factories

2014 : One of the hottest year in Belgium

According to official documents of its government, Wallonia's territorial emissions structural reduction is mainly due to delocalization of its industries (Gouvernement Wallon, 2019)

Wallonia **is not in line** with the +2°C maximum limit. France **could be** if it pledges to a reduction of imported emissions at least to the extent of its committed territorial emissions reduction.

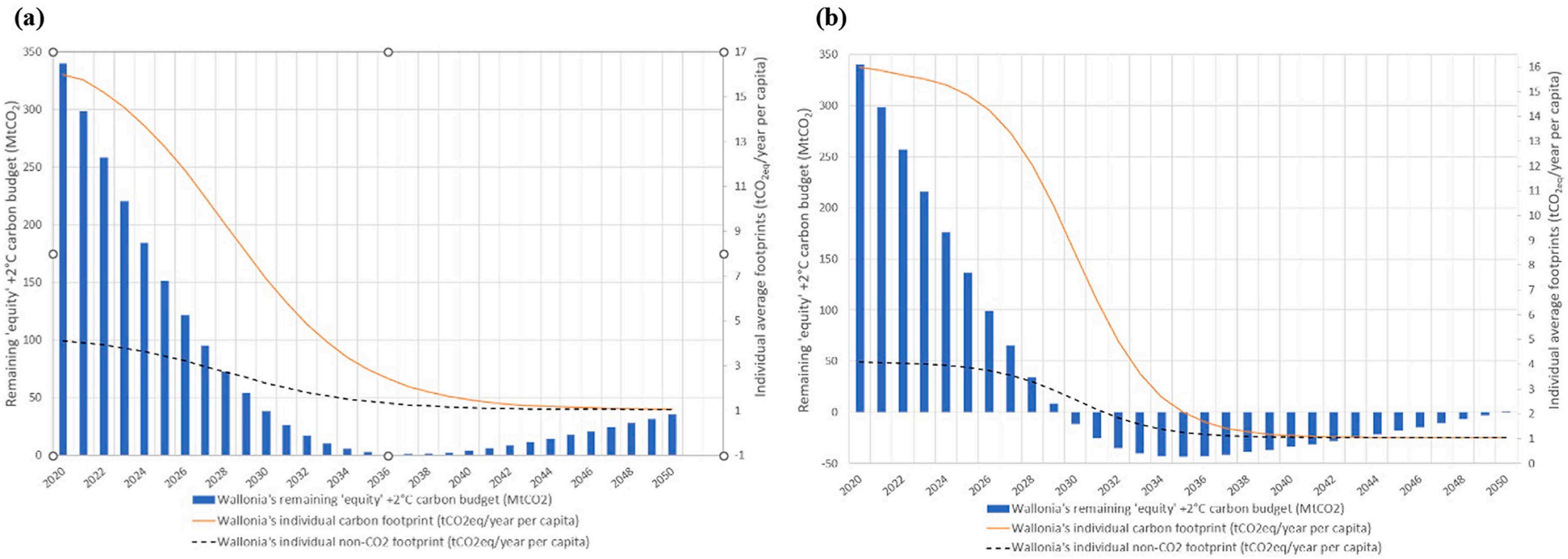
Background – Part 1 – The energy transition (in Belgium)

One of the other common NDC issues : How individuals can relate to collective targets and will they ?

Paper 2 :

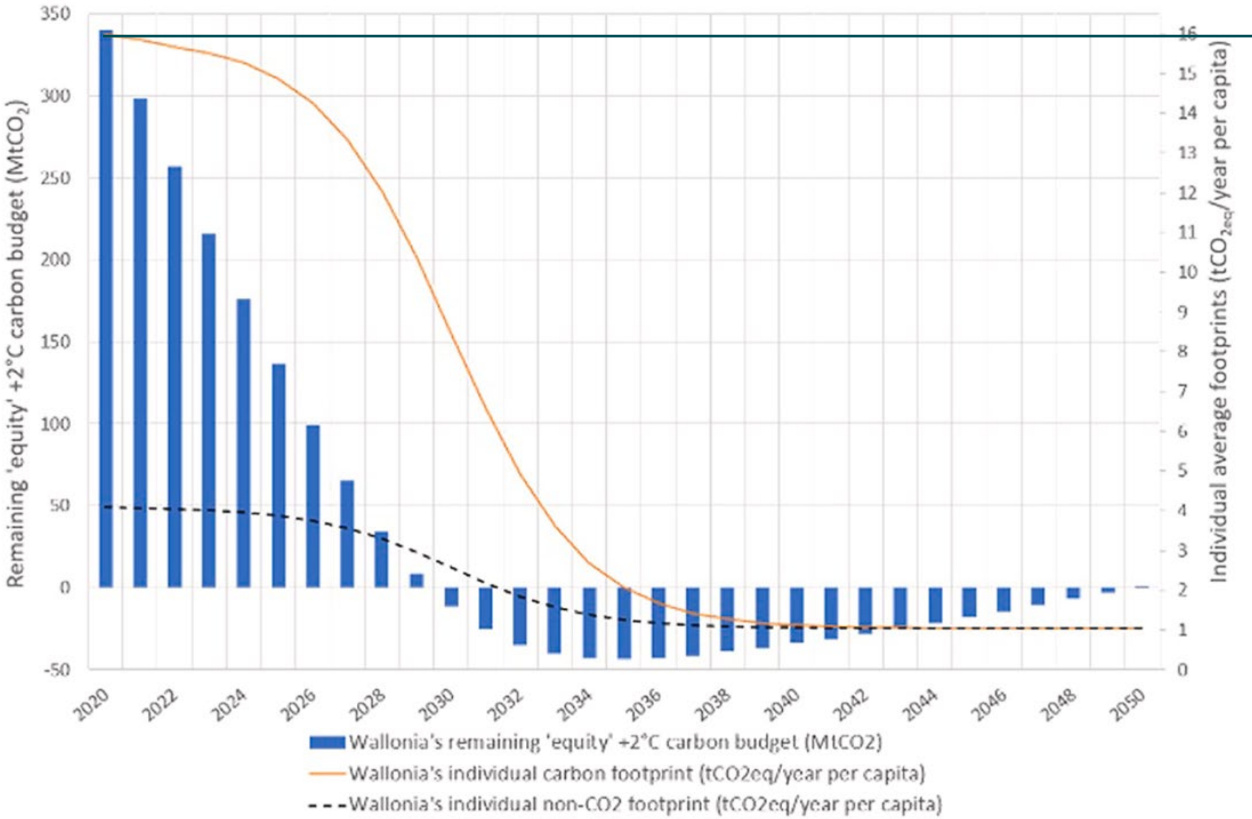
Developing individual carbon footprint reduction pathways from carbon budgets: Examples with Wallonia and France, *Renewable and Sustainable Energy Reviews*, 198(114428), 2024, doi : 10.1016/j.rser.2024.114428

If the NDCs are not relevant with “what Science says”, which GHG mitigation pathways shall I consider ? → I build “my own” study based on IPCC’s +2°C carbon budgets and individual carbon footprints, trying to solve the identified common NDC issues.

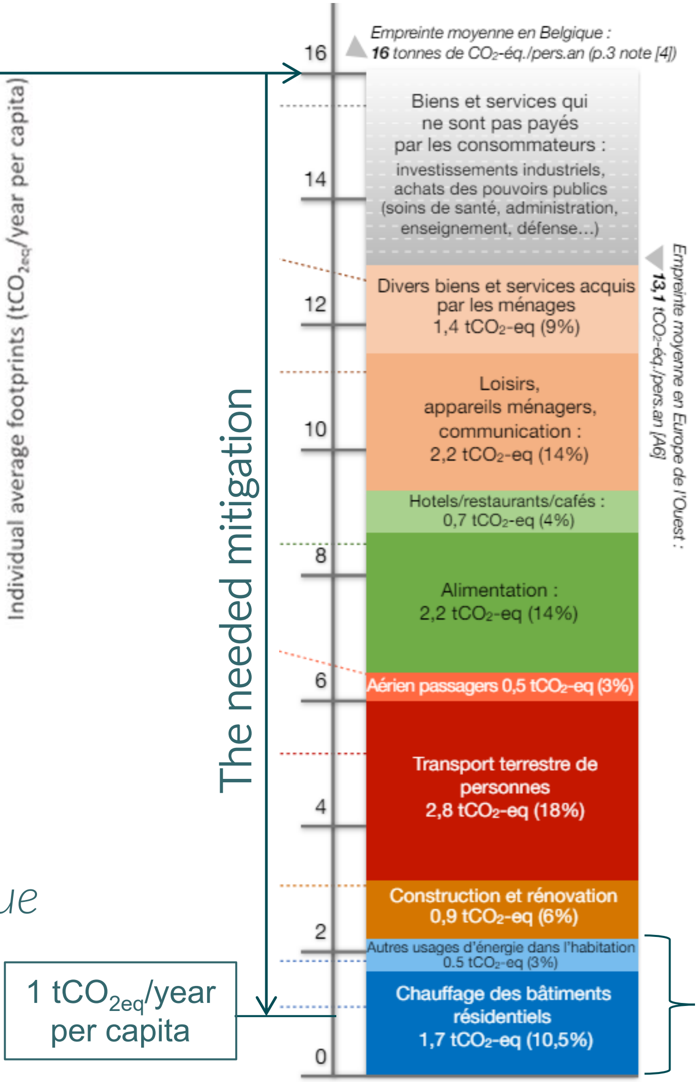


Background – Part 1 – The energy transition (in Belgium)

Results :



Carbon budget momentarily overcome, gets back to positive value by 2050 thanks to (natural) carbon absorption



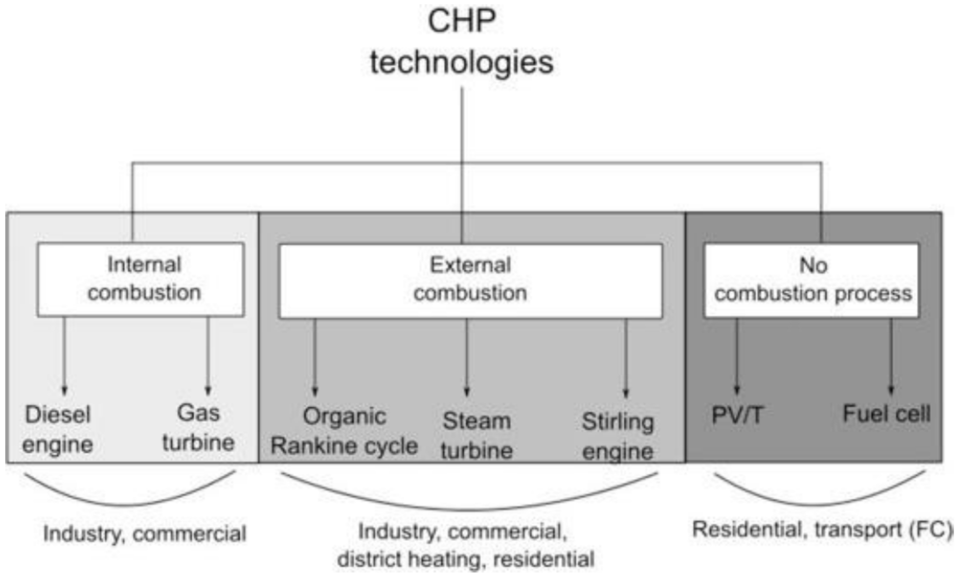
The part for which residential fuel cells can play a role

Wallonia's current individual carbon footprint
https://plateforme-wallonne-giec.be/Lettre9.pdf

Residential fuel cells cannot represent the unique complete solution…
(no "one size fits all")

Background – Part 2 – (Residential) Micro-cogeneration

Cogeneration = CHP = Combined Heat and Power



Ref : Martinez et al., 2017 [2]

According to the Directive 2012/27/EU :

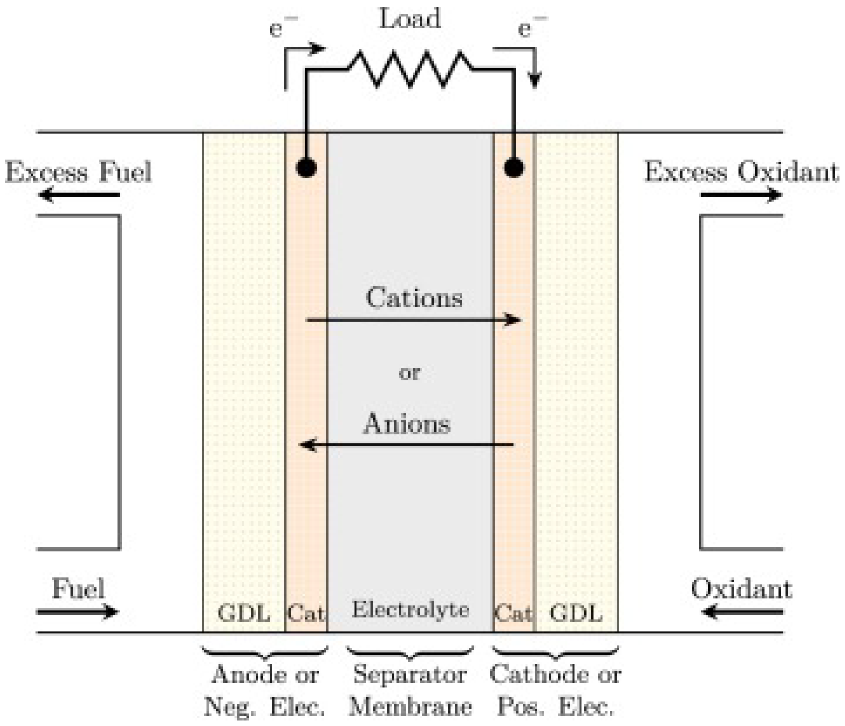
“micro-cogeneration” (micro-CHP or µCHP)	$< 50\ kW_{el}$
“small scale (or mini) cogeneration”	from $50\ kW_{el}$ to $1\ MW_{el}$
“cogeneration”	$>1\ MW_{el}$

Other definitions exist. The micro-CHP limit is often considered at $10\ kW_{el}$ [3].

[2] 10.1016/j.enconman.2017.10.035

[3] 10.1016/j.enpol.2008.09.018

Background – Part 3 – Fuel cells



Schematic representation of a fuel cell core [4]

Definition :
A fuel cell is a galvanic cell (electrochemical reaction - redox) that transforms directly the energy from a fuel and an oxidizing agent (usually oxygen or air) into electrical energy and heat

GDL = Gas Diffusion Layer,
→ consists of porous and electrically conductive structures for gas and electrons transfer that have as main task to allow uniform access for gaseous reactants to the catalyst (abbreviated by Cat. on the figure) layer of both electrodes

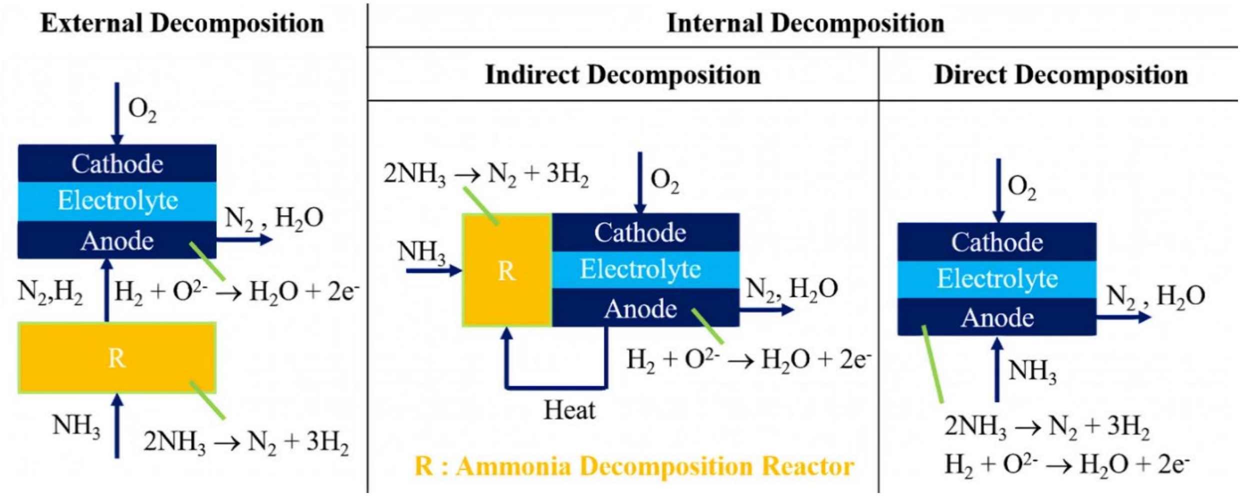
[4] 10.1016/B978-0-32-385762-8.00005-1

Background – Part 3 – Fuel cells

Four types of fuel processing exist and can even be combined [5] :

1. **Direct Utilization (DU):** Direct (electrochemical) oxidation of the fuel at the anode. The “primary fuel” is not converted into one or several “secondary fuels” and participates directly in the anode electrochemical reaction.
2. **External Reforming (ER):** The “primary fuel” is converted/decomposed with heat (externally to the stack) into one or several “secondary fuels” that will participate electrochemically.
3. **Indirect Internal Reforming (IIR):** Implemented in a dedicated channel that is in thermal direct contact with the anode. The “primary fuel” is converted into one or several “secondary fuels” that will participate electrochemically. occurs internally to the fuel cell stack embodiment, but into a dedicated reactor and not onto the anode.
4. **Direct Internal Reforming (DIR):** Conducted directly within the anode chamber. The “primary fuel” is converted (internally to the stack, onto the anode catalyst) into one or several “secondary fuels” that will participate electrochemically.

ER and IIR are upstream processes that can be added to any fuel cell type. To classify fuel cells, let’s focus on DU and DIR.

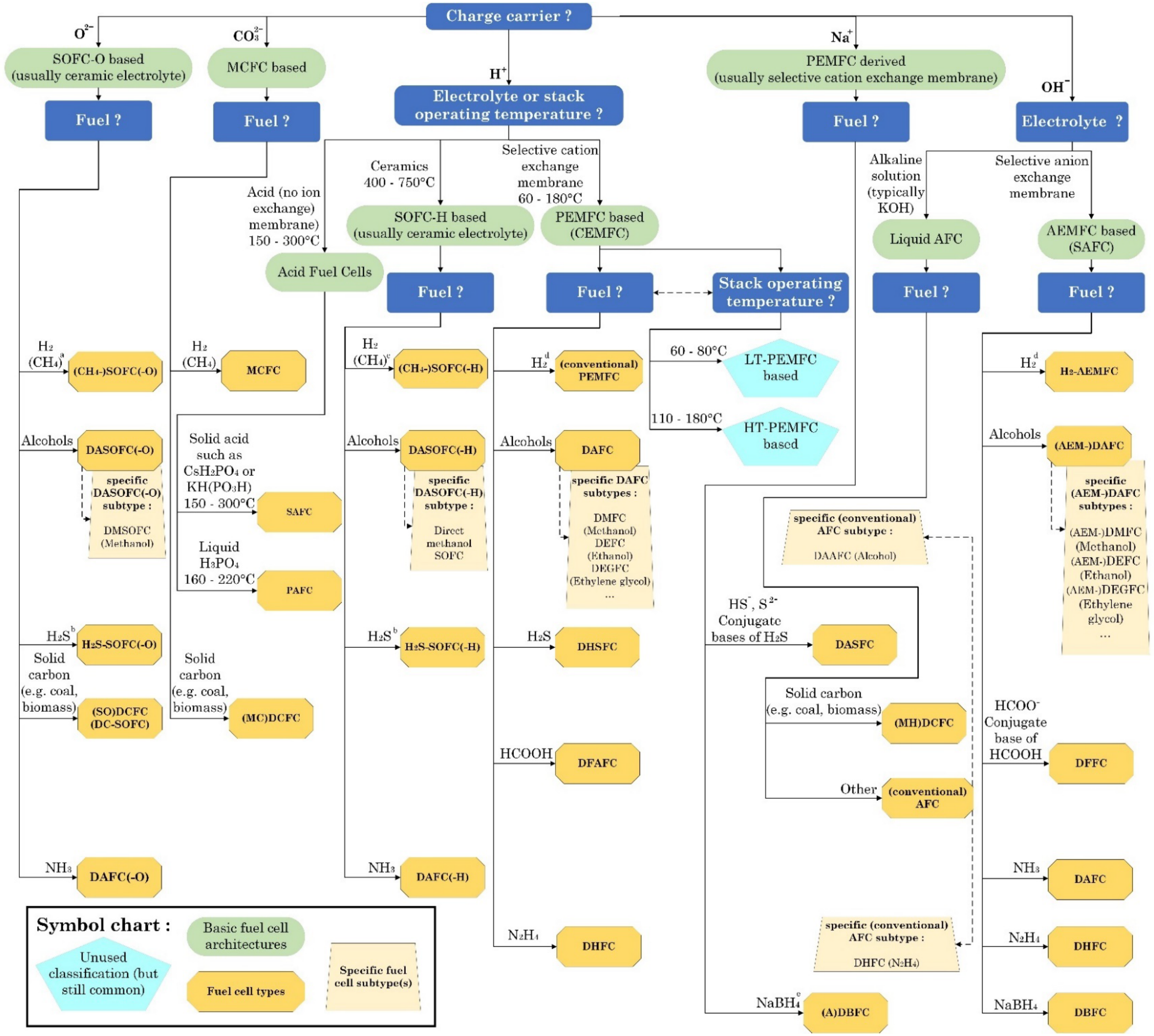


Operation modes of ammonia-fed solid oxide fuel cells [6]

[5] 10.1016/B978-0-444-53563-4.10013-6

[6] 10.1016/j.ijhydene.2021.08.092

Background – Part 3 – Fuel cells



Paper 3 :

Comprehensive assessment of Fuel Cell types: A novel Fuel Cell Classification System, *Journal of Power Sources*, Under Review, 2024

A plethoric amount of DU and DIR fuel cell type exists and it is difficult to sort them all out. They are usually classified according to their **electrolyte** or **fuel**.

However, considerably different fuel cell technologies can have the same kind of electrolyte, as it is the case for H-SOFCs and O-SOFCs or for PEMFCs and ADBFCs, for example.

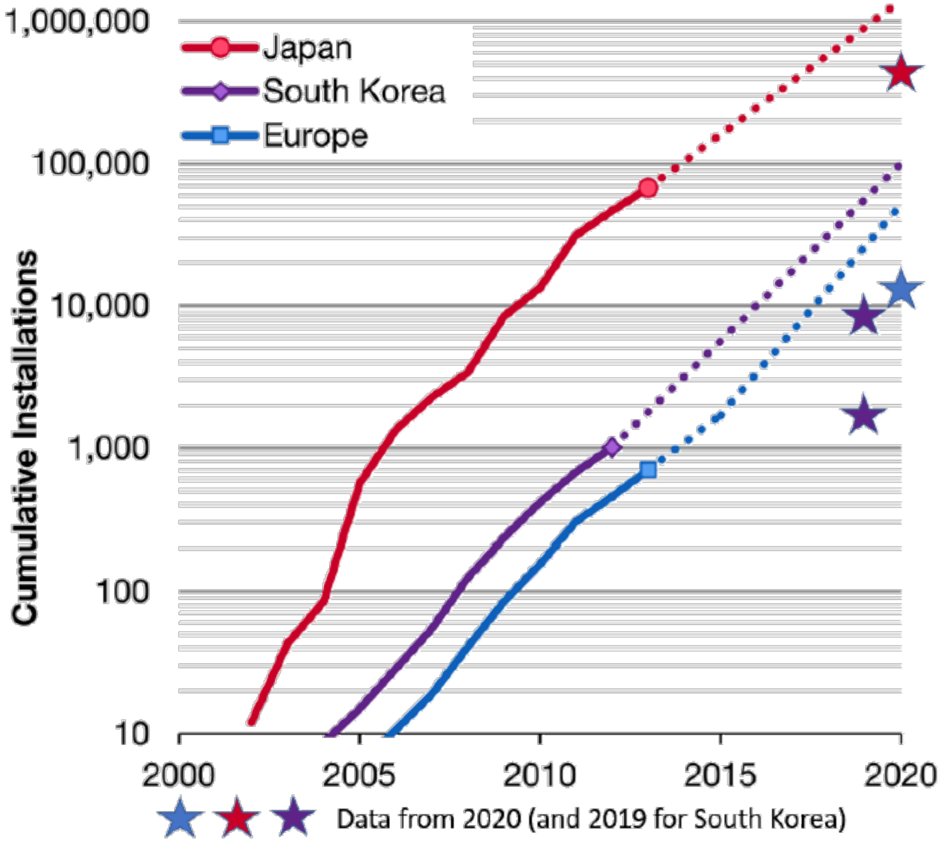
And this is even more the case regarding the fuel as, for example, alcohol fuel cells exist as O-SOFCs, H-SOFCs, AEMFCs, conventional AFCs, PEMFCs, and possibly even more if external or indirect reforming configurations are considered.

I offered a new classification system initially based on the **charge carrier,** leading to **8 basic architectures.**

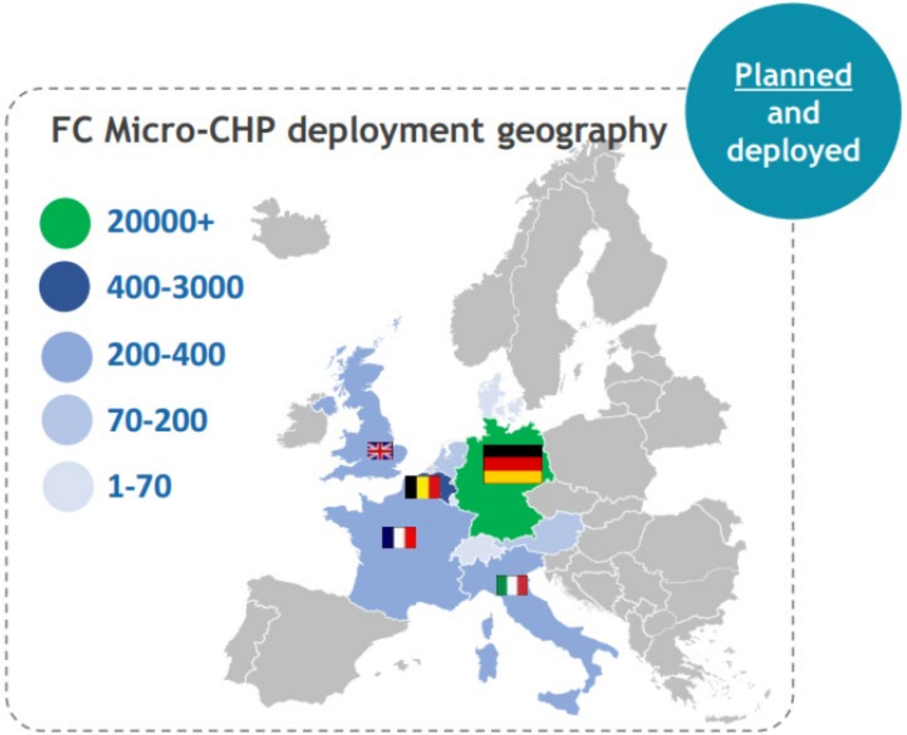
Background – Part 3 – (Residential) Fuel Cells

All systems primarily fed with natural gas

Markets are only growing thanks to public subsidies (except for Japan where the PEMFC technology is now considered competitive – 6,3-8,5 k€/kW – 7-8 years ROI) [9,10]



Cumulative number of residential micro-CHP systems installed (solid lines) and near-term projections (dotted lines) reported in 2015. Reproduced and adapted from reference [7] with 2020 data for Japan and Europe [8] and 2019 data for Korea (Intralink, 2021 & Park, 2020).



Reproduced slide from the Final Conference of the PACE (Pathway to a Competitive European Fuel Cell micro-CHP Market) European Union project (2023).

[7] 10.1016/J.JPOWSOUR.2015.05.050
[8] 10.3390/en14164963

[9] 10.1016/j.apenergy.2018.11.023
[10] 10.1016/j.apenergy.2021.117641

Background – Part 3 – (Residential) Fuel Cells

All systems primarily fed with natural gas

PACE

Pathway to a competitive European Fuel Cell micro-CHP Market

PACE has delivered exciting new products from a group of manufacturers with two Fuel Cell technologies trialled

	Buderus Logapower FC10.2	Buderus System Logaplus	BlueGEN	BlueGEN BG15	Dachs 0.8	eLecta	Vitovalor 300-P,PA2	Sunfire-Home 750
Number of units installed (through PACE) →	100	200	750		200	300	>750	500
	SOFC	SOFC	SOFC	SOFC	PEM	PEM	PEM	SOFC
Nominal electrical power output →	0.7kW	1.5kW	1.5kW	1.5kW	0.75kW	0.75kW	0.75kW	0.75kW
	Buderus	Buderus	SOLID POWER	SOLID POWER	BDR THERMEA GROUP SENERTEC	BDR THERMEA GROUP remeha	VIESSMANN	sunfire
	1-2 family homes (up to end 2018)	1-2 family homes, residential buildings and SMEs with high electricity demand	SMEs, apartment buildings and multifamily homes		1-2 family houses (for new and existing buildings)		Domestic and small commercial	Residential building (with LPG supply)
	No longer commercialized	Same fuel cell as the tested SOFC		New generation (greater connectivity and user experience)	Not available in Belgium (mainly for the German market)			Not available in Belgium (mainly for the German market)

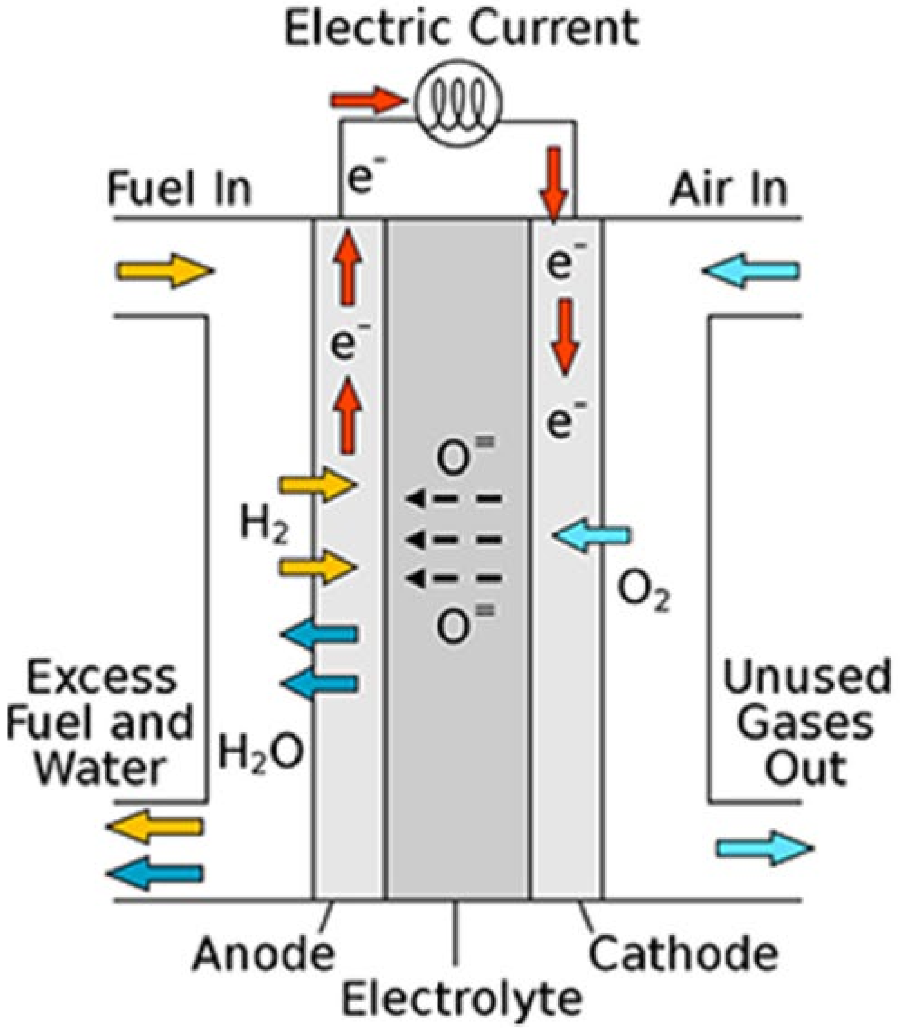
Systems tested during this thesis

NB : Other manufacturers exist, not involve in the PACE program.

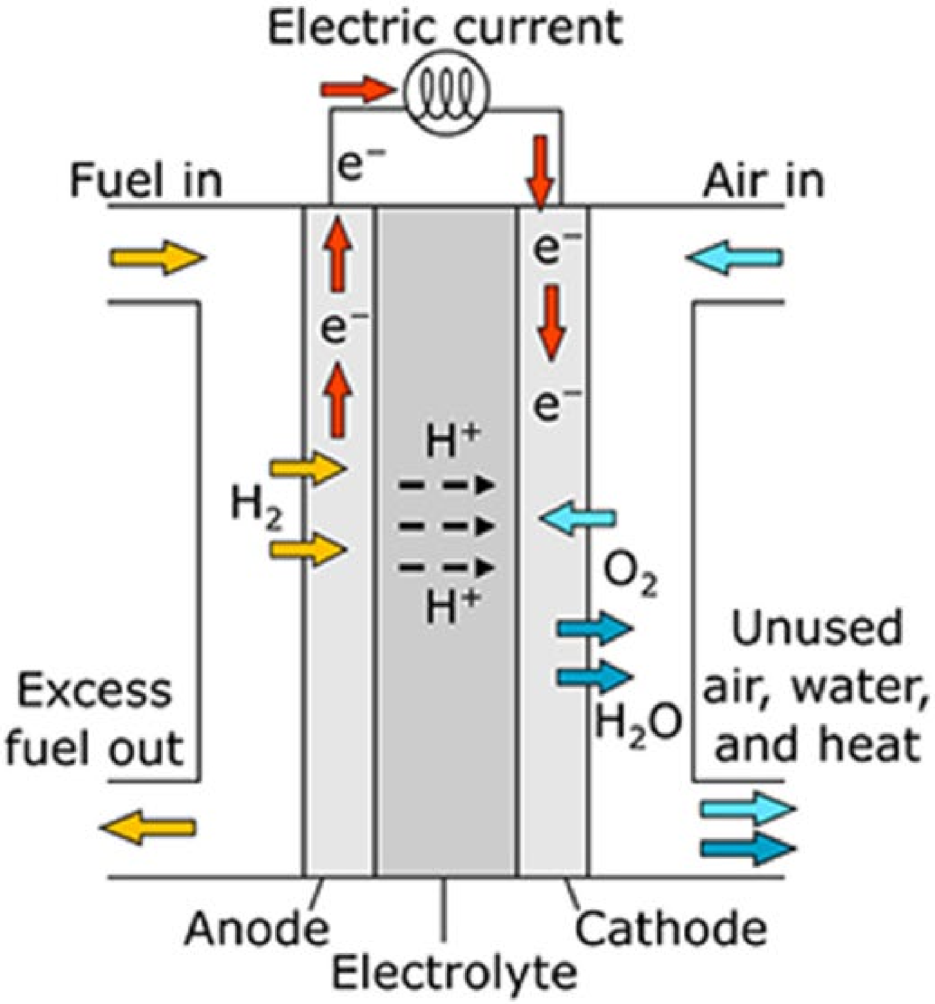
Only LT-PEMFC and SOFC-O micro-CHP systems exist on the market !

Reproduced slide from the Final Conference of the PACE (Pathway to a Competitive European Fuel Cell micro-CHP Market) European Union project (2023).

Background – Part 3 – (Residential) Fuel Cells



SOFC-O [11]



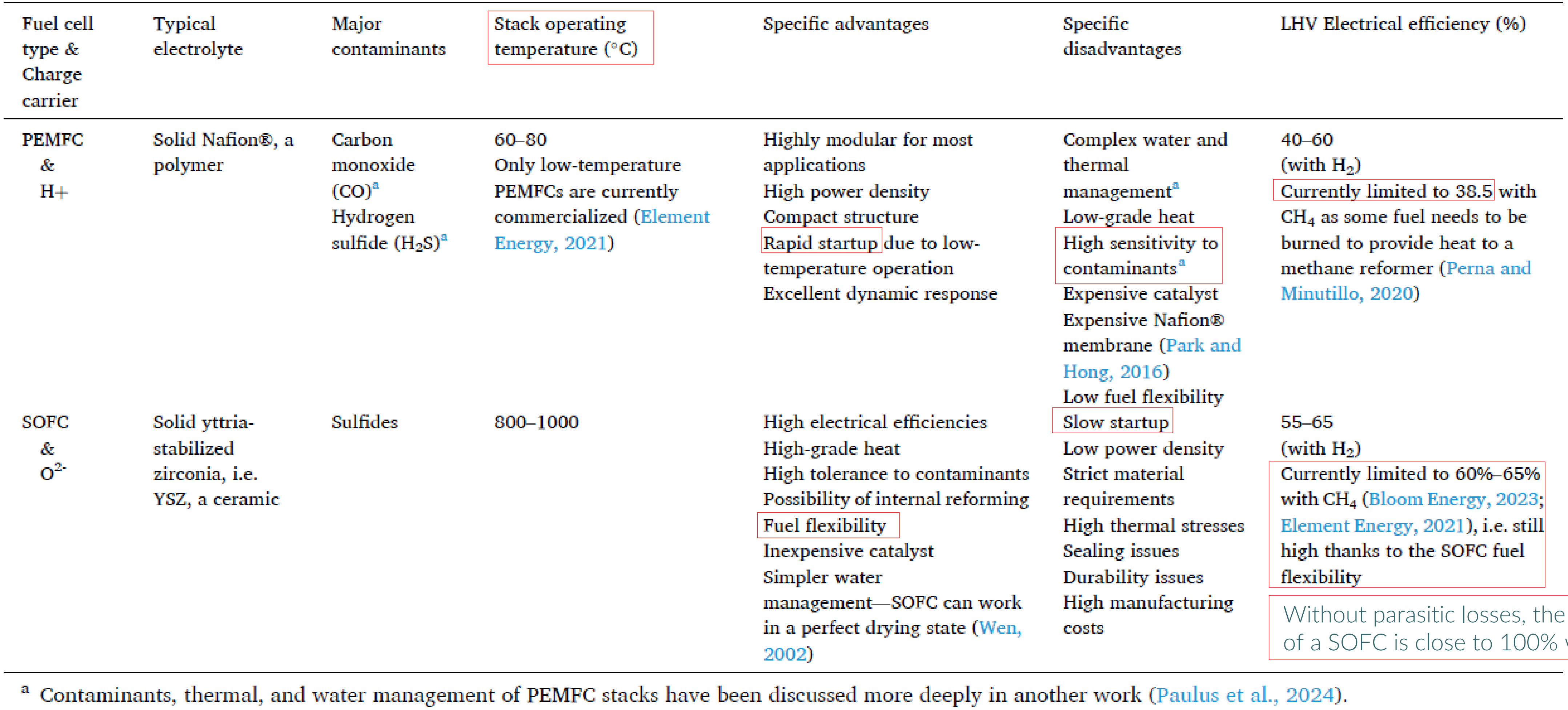
LT-PEMFC [11]

[11] 10.1016/j.jenvman.2024.121017

Background – Part 3 – (Residential) Fuel Cells

SOFC-O and LT-PEMFC can be identified by their electrolyte, respectively ceramic or polymer

Other main differences : working temperatures, fuel flexibility (& sensitivity to contaminants), startup time, electrical efficiency



Fuel cell type & Charge carrier	Typical electrolyte	Major contaminants	Stack operating temperature (°C)	Specific advantages	Specific disadvantages	LHV Electrical efficiency (%)
PEMFC & H+	Solid Nafion®, a polymer	Carbon monoxide (CO)[a] Hydrogen sulfide (H_2S)[a]	60–80 Only low-temperature PEMFCs are currently commercialized (Element Energy, 2021)	Highly modular for most applications High power density Compact structure Rapid startup due to low-temperature operation Excellent dynamic response	Complex water and thermal management[a] Low-grade heat High sensitivity to contaminants[a] Expensive catalyst Expensive Nafion® membrane (Park and Hong, 2016) Low fuel flexibility	40–60 (with H_2) Currently limited to 38.5 with CH_4 as some fuel needs to be burned to provide heat to a methane reformer (Perna and Minutillo, 2020)
SOFC & O^{2-}	Solid yttria-stabilized zirconia, i.e. YSZ, a ceramic	Sulfides	800–1000	High electrical efficiencies High-grade heat High tolerance to contaminants Possibility of internal reforming Fuel flexibility Inexpensive catalyst Simpler water management—SOFC can work in a perfect drying state (Wen, 2002)	Slow startup Low power density Strict material requirements High thermal stresses Sealing issues Durability issues High manufacturing costs	55–65 (with H_2) Currently limited to 60%–65% with CH_4 (Bloom Energy, 2023; Element Energy, 2021), i.e. still high thanks to the SOFC fuel flexibility

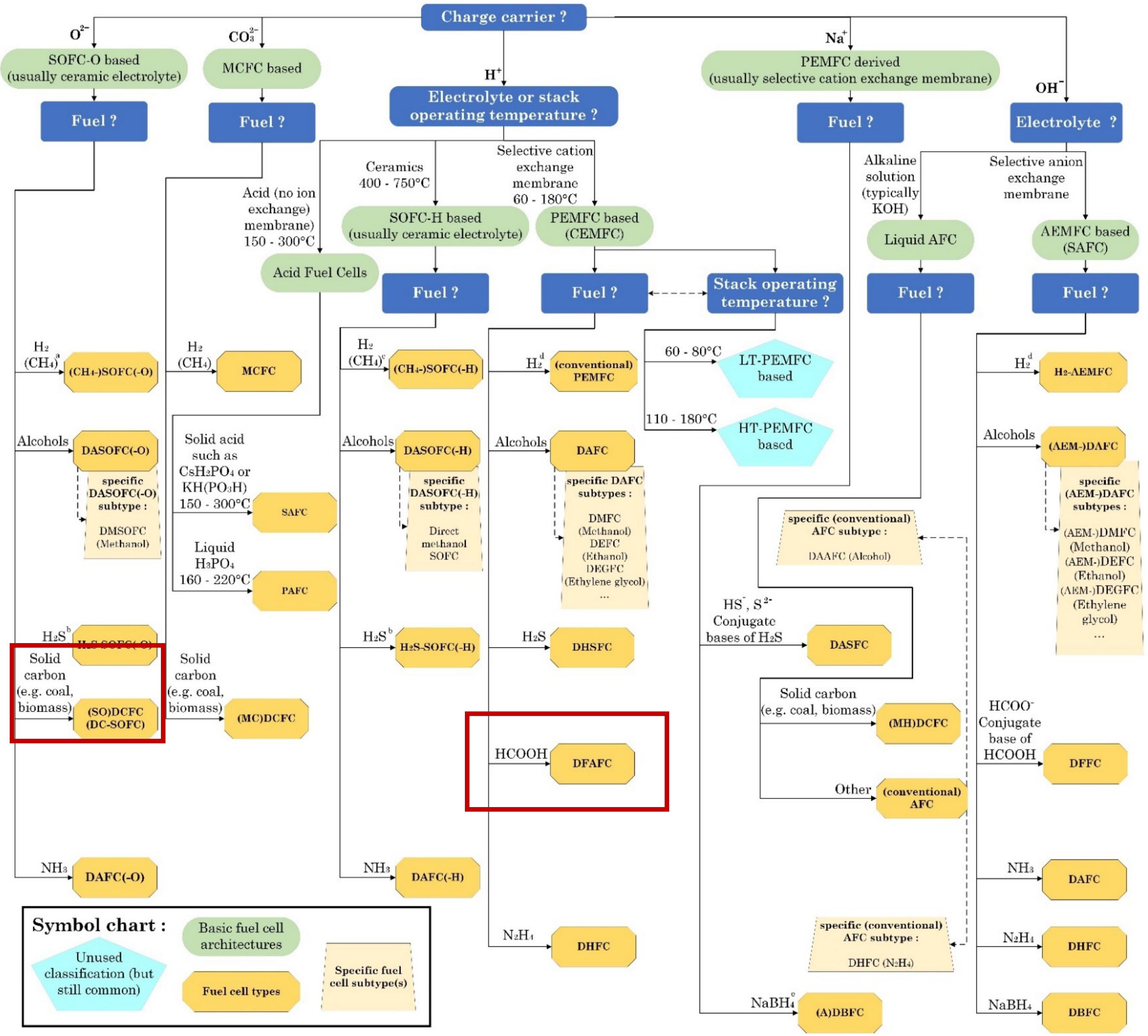
[a] Contaminants, thermal, and water management of PEMFC stacks have been discussed more deeply in another work (Paulus et al., 2024).

Without parasitic losses, the theoretical efficiency of a SOFC is close to 100% with dry methane [12]

Ref: 10.1016/j.jenvman.2024.121017

[12] 10.1038/s41929-019-0310-y

Background – Part 3 – Fuel cells



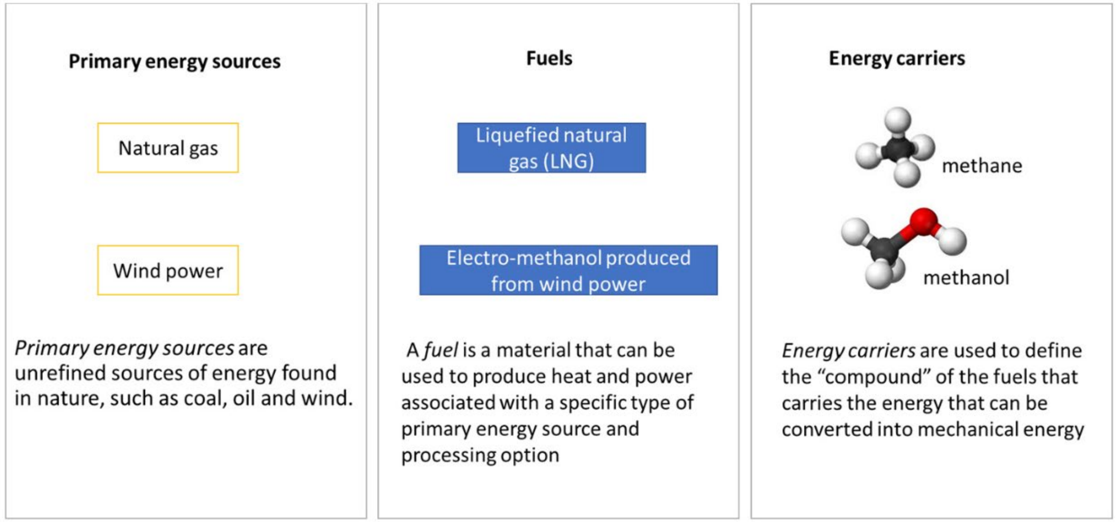
Back to fuel cell types :

The fuel consumed in a fuel cell can be dissociated to the primary (fossil) fuel.

It can be seen as an “energy carrier”.

→ Natural gas vs. e-methane or biogas

Other ex : formic acid (HCOOH), e-ammonia, other electro-fuel (Power-to-X technologies)



Primary energy sources

Primary energy sources are unrefined sources of energy found in nature, such as coal, oil and wind.

Fuels

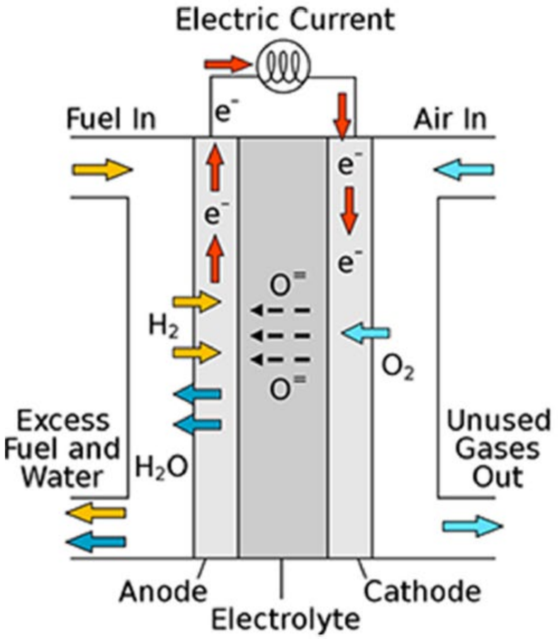
A *fuel* is a material that can be used to produce heat and power associated with a specific type of primary energy source and processing option

Energy carriers

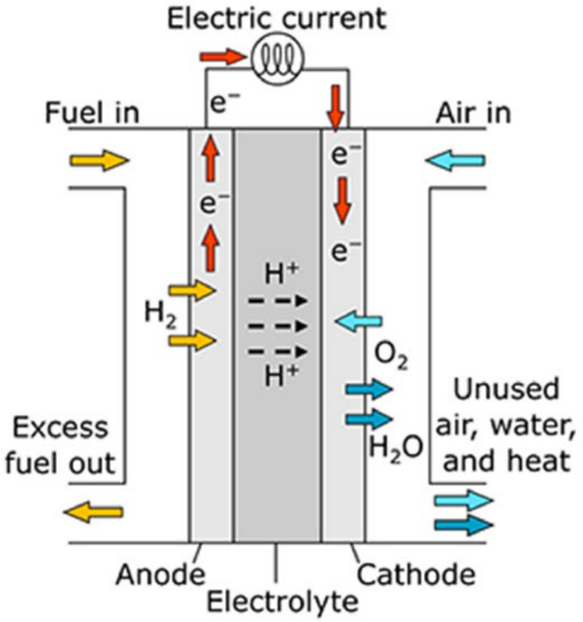
Energy carriers are used to define the “compound” of the fuels that carries the energy that can be converted into mechanical energy

Ref: 10.1016/B978-0-12-824471-5.00017-7

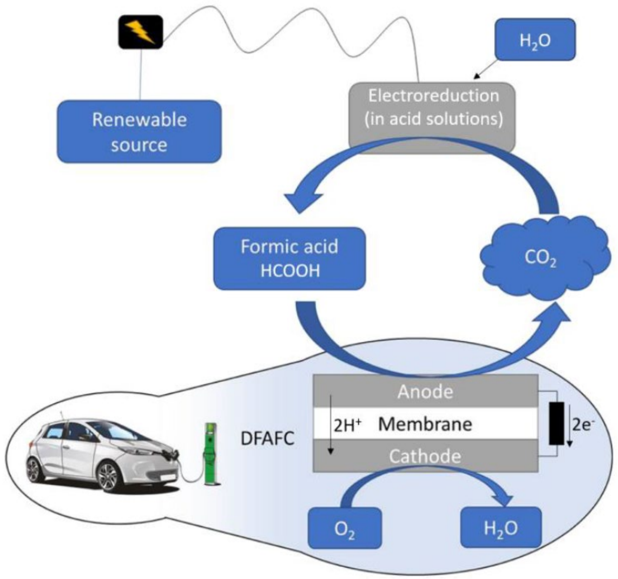
Background – Part 3 – (Residential) Fuel Cells



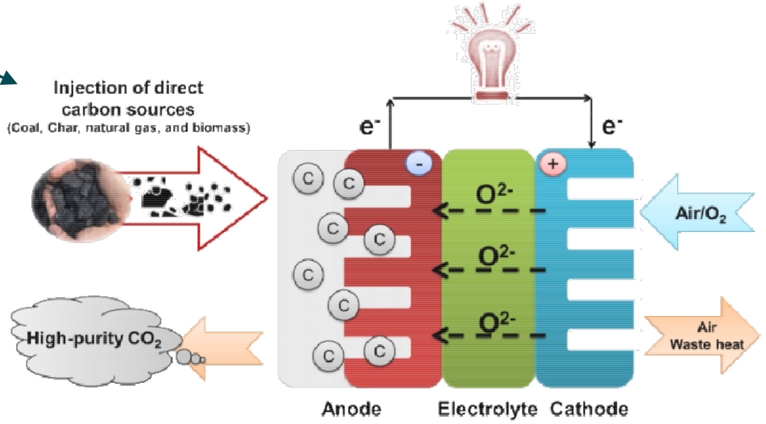
SOFC-O [11]



LT-PEMFC [11]



DFAFC (Direct Formic Acid Fuel Cell)
Ref : 10.1021/acs.iecr.0c04711



DC-SOFC-O (Direct Carbon Solid Oxide Fuel Cell with Oxygen-ion conduction)
Ref : 10.1149/05049.0071ecst

(Almost) pure CO_2 streams at the anode, enabling easy carbon capture !
→ Fuel cell types with ***negative emissions*** *capabilities*

[11] 10.1016/j.jenvman.2024.121017

Tested systems

All systems primarily fed with natural gas

PACE

Pathway to a competitive European Fuel Cell micro-CHP Market

PACE has delivered exciting new products from a group of manufacturers with two Fuel Cell technologies trialled

	Buderus Logapower FC10.2	Buderus System Logaplus	BlueGEN	BlueGEN BG15	Dachs 0.8	eLecta	Vitovalor 300-P,PA2	Sunfire-Home 750
Number of units installed (through PACE) →	100	200	750		200	300	>750	500
	SOFC	SOFC	SOFC-O	SOFC	PEM	PEM	LT-PEM	SOFC
Nominal electrical power output →	0.7kW	1.5kW	1.5kW	1.5kW	0.75kW	0.75kW	0.75kW	0.75kW
	Buderus	Buderus	SOLID POWER	SOLID POWER	BDR THERMEA GROUP SenerTec	BDR THERMEA GROUP remeha	VIESSMANN	sunfire
	1-2 family homes (up to end 2018)	1-2 family homes, residential buildings and SMEs with high electricity demand	SMEs, apartment buildings and multifamily homes		1-2 family houses (for new and existing buildings)		Domestic and small commercial	Residential building (with LPG supply)
	No longer commercialized	Same fuel cell as the tested SOFC		New generation (greater connectivity and user experience)	Not available in Belgium (mainly for the German market)			Not available in Belgium (mainly for the German market)

Systems tested during this thesis

NB : Other manufacturers exist, not involve in the PACE program.

Reproduced slide from the Final Conference of the PACE (Pathway to a Competitive European Fuel Cell micro-CHP Market) European Union project (2023).

Tested systems

Main scientific activities [a] :

- Reverse engineering to understand the fuel cell operations (probable internal schemes and working principle)
- Laboratory test campaigns [b]
- In-situ (field-test) monitoring
  - Real-world efficiencies
  - Economical and environmental (CO_2) analyses through comparison with systems of reference (electrical grid, gas condensing boiler)
- Black-box performance modelling of the systems
- Correlation between laboratory and in-situ measurements (direct or through the black-box models)
- Non-CO_2 pollutants measurements (NO_x, SO_2, CO)

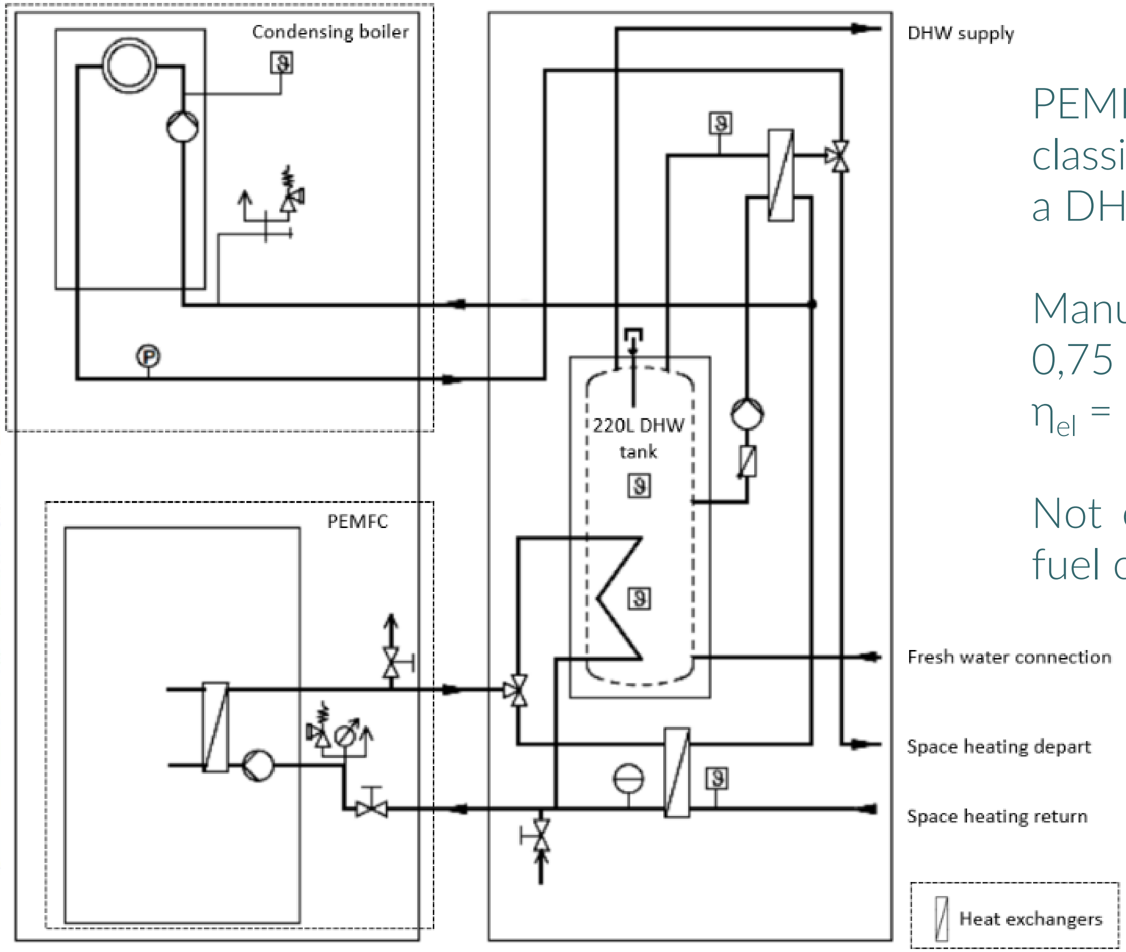
Many scientific publications – all referenced in the thesis manuscript

Specific acknowledgments :

[a] Conducted with the partial financial support of Gas.be, our industrial partner, that also provided the tested systems and combustion analyzer

[b] Mainly conducted by a former colleague of the thermodynamics laboratory, Camila Dávila

Tested LT-PEMFC system

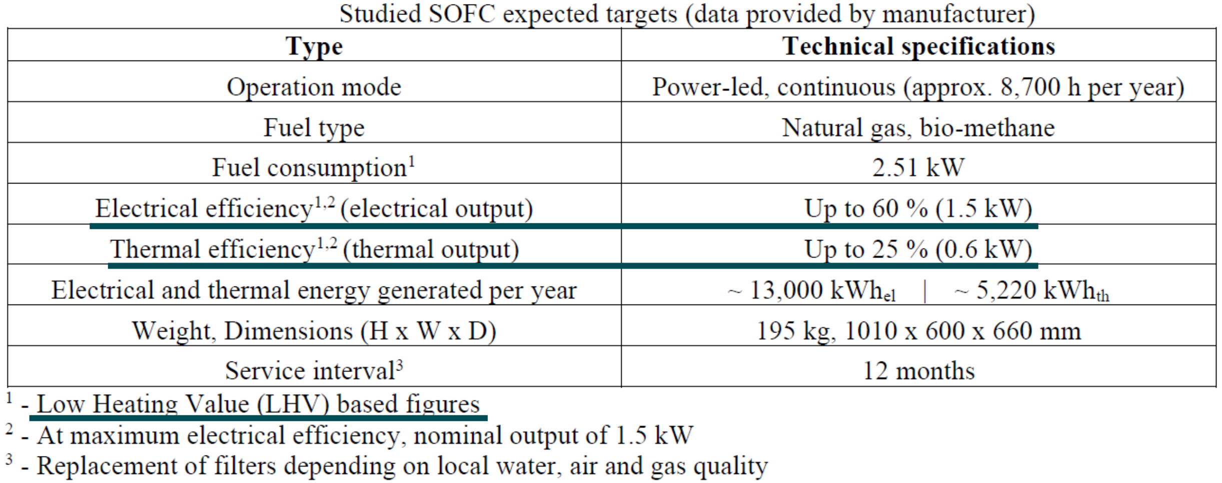


PEMFC stack hybridized to a classical gas condensing boiler and a DHW tank

Manufacturer's data :
0,75 kW_{el} and up to 1,1 kW_{th}
η_{el} = 0,37 & up to η_{th} = 0,55 (LHV)
} FC

Not electrically-driven (continuous fuel cell operations)

Tested SOFC system



Studied SOFC expected targets (data provided by manufacturer)

Type	Technical specifications
Operation mode	Power-led, continuous (approx. 8,700 h per year)
Fuel type	Natural gas, bio-methane
Fuel consumption[1]	2.51 kW
Electrical efficiency[1,2] (electrical output)	Up to 60 % (1.5 kW)
Thermal efficiency[1,2] (thermal output)	Up to 25 % (0.6 kW)
Electrical and thermal energy generated per year	~ 13,000 kWh_{el} | ~ 5,220 kWh_{th}
Weight, Dimensions (H x W x D)	195 kg, 1010 x 600 x 660 mm
Service interval[3]	12 months

[1] - Low Heating Value (LHV) based figures

[2] - At maximum electrical efficiency, nominal output of 1.5 kW

[3] - Replacement of filters depending on local water, air and gas quality

Most efficient micro-CHP on the market (electrically)

Heat recovery system is optional (you must add a circulator and connect the SOFC to your space heating or DHW systems)

Flexible electrically-driven system : 0.5-1.5 kW_{el} range (possibility of remote control)

30 hours startup time

Key outcomes of the field-test study !! case dependent figures !!

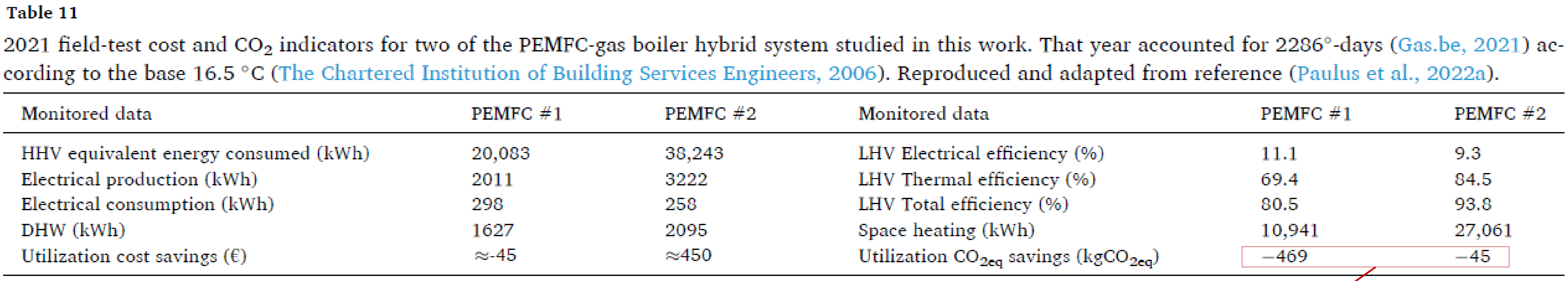


Table 11

2021 field-test cost and CO_2 indicators for two of the PEMFC-gas boiler hybrid system studied in this work. That year accounted for 2286°-days (Gas.be, 2021) according to the base 16.5 °C (The Chartered Institution of Building Services Engineers, 2006). Reproduced and adapted from reference (Paulus et al., 2022a).

Monitored data	PEMFC #1	PEMFC #2	Monitored data	PEMFC #1	PEMFC #2
HHV equivalent energy consumed (kWh)	20,083	38,243	LHV Electrical efficiency (%)	11.1	9.3
Electrical production (kWh)	2011	3222	LHV Thermal efficiency (%)	69.4	84.5
Electrical consumption (kWh)	298	258	LHV Total efficiency (%)	80.5	93.8
DHW (kWh)	1627	2095	Space heating (kWh)	10,941	27,061
Utilization cost savings (€)	≈-45	≈450	Utilization CO_{2eq} savings ($kgCO_{2eq}$)	−469	−45

With natural gas, cannot compete with average grid electricity in Belgium (or anywhere the electrical grid is greener).

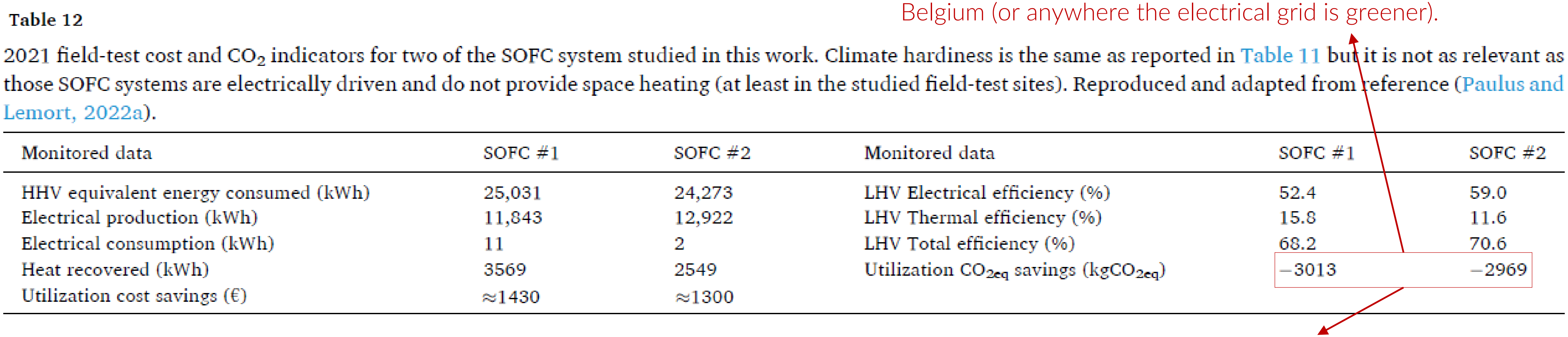


Table 12

2021 field-test cost and CO_2 indicators for two of the SOFC system studied in this work. Climate hardiness is the same as reported in Table 11 but it is not as relevant as those SOFC systems are electrically driven and do not provide space heating (at least in the studied field-test sites). Reproduced and adapted from reference (Paulus and Lemort, 2022a).

Monitored data	SOFC #1	SOFC #2	Monitored data	SOFC #1	SOFC #2
HHV equivalent energy consumed (kWh)	25,031	24,273	LHV Electrical efficiency (%)	52.4	59.0
Electrical production (kWh)	11,843	12,922	LHV Thermal efficiency (%)	15.8	11.6
Electrical consumption (kWh)	11	2	LHV Total efficiency (%)	68.2	70.6
Heat recovered (kWh)	3569	2549	Utilization CO_{2eq} savings ($kgCO_{2eq}$)	−3013	−2969
Utilization cost savings (€)	≈1430	≈1300			

Ref : 10.1016/j.jenvman.2024.121017

However, in 2020 and 2021 (no info available for subsequent years), at least one CCGT (Combined-Cycle Gas Turbine) was always turned on in Belgium, justifying the direct comparison with CCGTs (for **flexible** systems), through the Marginal Emission Factor (MEF) approach.

Decarbonization potentials of micro-CHP fuel cell technologies

Data	Best "current SOFC", 60% LHV electrical efficiency, 25% LHV thermal efficiency (1)
Fuel cell electrical production (kWh_{el}/year)	3500
Gas consumption related to the fuel cell electrical production (kWh/year)	5833
Fuel cell heat production (kWh_{th}/year)	1458
Remaining heat demand, supposably provided by a 90% LHV efficient gas boiler (kWh_{th}/year)	13842
Total (fossil fuel) gas consumption, fuel cell and gas boiler (kWh/year)	21213
Carbon footprint related to the gas consumption - Dataset "A" (tCO_{2eq}/year) - marginal emissions	5,32
Carbon footprint related to the gas consumption - Dataset "E1" (tCO_{2eq}/year)	5,39
Negative carbon footprint from CO_2 capture at the anode exhaust [a]	N/A
Carbon footprint savings - Dataset "A" (tCO_{2eq}/year) - marginal emissions	0,54
Carbon footprint savings - Dataset "E1" (tCO_{2eq}/year)	-0,49

[a] With the assumption of 403 gCO_2/kWh_{fuel} (tCO_2/year or tCO_{2eq}/year in this case). This emission factor has been calculated for dry pinewood biochar (HHV = LHV = 24.49 MJ/kg, 59,86% of carbon content, DC-SOFC with 80% of electrical efficiency [153]). *(see paper for the references)*

Paper 4 :

Decarbonization potentials of fuel cell technologies in micro-cogeneration applications, *Progress in Energy*, Under Review, 2024

Average Belgian dwelling

Systems of reference
(heat with a gas condensing boiler)

Dataset	Gas consumption emission factor (gCO_{2eq}/kWh)	Electricity consumption emission factor (gCO_{2eq}/kWh_{el})	Average gas consumption of the dwelling (kWh/year)	Average electricity consumption of the dwelling (kWh_{el}/year)	Carbon footprint (tCO_{2eq}/year)
Dataset "A" CWaPE	251	456 CCGT = MEF (in 2021)	17000	3500	5,86
Dataset "E1"	254	167	17000	3500	4,90

electricymap.org (from IPCC 2014)

2021 average grid electricity (Belgium)

The flexible existing (tested) SOFC micro-CHP exhibits CO_2 savings compared to CCGTs of 55% LHV efficiency (state-of-the-art) operating without heat recovery (e.g. association with heat district network).

(additional benefits will even come from avoiding transportation and distribution losses thanks to decentralized electrical production, which are estimated to about 6-7% in the EU [20])

PEMFCs efficiency is lower or not expected to ever be significantly higher than CCGTs → not further investigated

[12] 10.1016/j.energy.2009.10.016

Decarbonization potentials of micro-CHP fuel cell technologies

Data	Best "current SOFC", 60% LHV electrical efficiency, 25% LHV thermal efficiency (1)	Best "future SOFC", 75% LHV electrical efficiency, 20% LHV thermal efficiency (2)	Best "future SOFC", 75% LHV electrical efficiency, 20% LHV thermal efficiency, 100% biogas (3)	Best "future DC-SOFC", 80% LHV electrical efficiency, 15% LHV thermal efficiency, 100% biochar with CO_2 capture (4)
Fuel cell electrical production (kWh_{el}/year)	3500	3500	3500	3500
Gas consumption related to the fuel cell electrical production (kWh/year)	5833	4667	4667	0
Fuel cell heat production (kWh_{th}/year)	1458	933	933	656
Remaining heat demand, supposably provided by a 90% LHV efficient gas boiler (kWh_{th}/year)	13842	14367	14367	14644
Total (fossil fuel) gas consumption, fuel cell and gas boiler (kWh/year)	21213	20630	0	0
Carbon footprint related to the gas consumption - Dataset "A" (tCO_{2eq}/year) - marginal emissions	5,32	5,18	0,00	0,00
Carbon footprint related to the gas consumption - Dataset "E1" (tCO_{2eq}/year)	5,39	5,24	0,00	0,00
Negative carbon footprint from CO_2 capture at the anode exhaust [a]	N/A	N/A	N/A	1,76
Carbon footprint savings - Dataset "A" (tCO_{2eq}/year) - marginal emissions	0,54	0,68	5,86	7,63
Carbon footprint savings - Dataset "E1" (tCO_{2eq}/year)	-0,49	-0,34	4,90	6,67

MEF approach

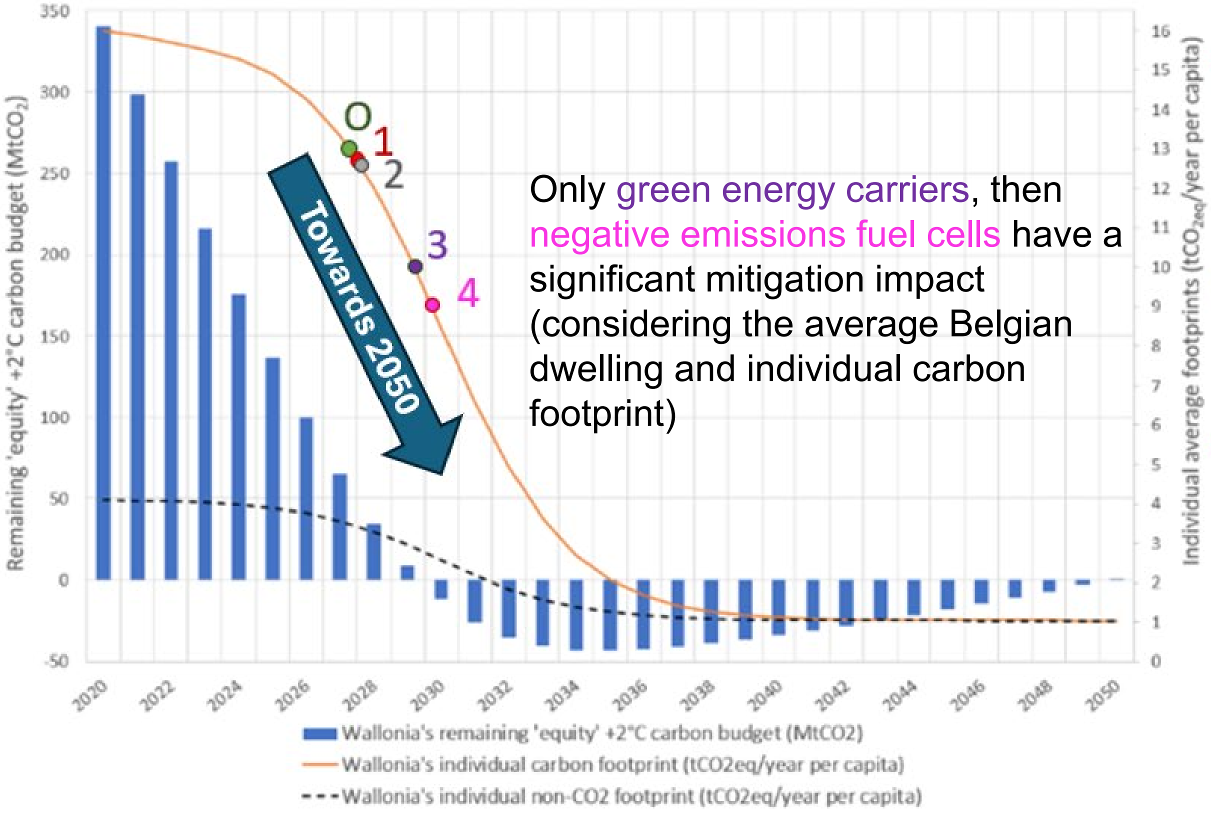
[a] With the assumption of 403 gCO_2/kWh_{fuel} (tCO_2/year or tCO_{2eq}/year in this case). This emission factor has been calculated for dry pinewood biochar (HHV = LHV = 24.49 MJ/kg, 59,86% of carbon content, DC-SOFC with 80% of electrical efficiency [153]). *(see paper for the references)*

What about the future ?

- Increased efficiency of the technology ? (2)
- "Green" energy carrier 100% biogas or e-methane ? (3)
- Fuel cells exhibiting negative emissions ? (4)

Decarbonization potentials of micro-CHP fuel cell technologies

What about the future ?



Only green energy carriers, then negative emissions fuel cells have a significant mitigation impact (considering the average Belgian dwelling and individual carbon footprint)

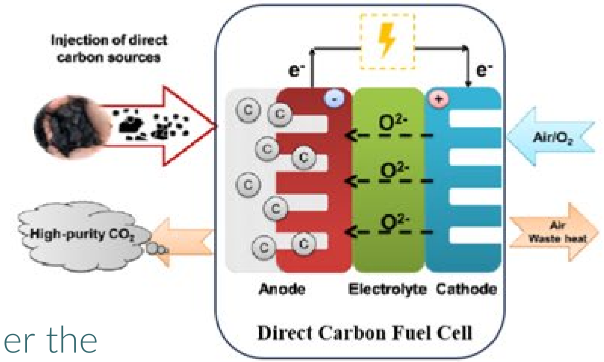
O - My current annual carbon footprint (considering the average Belgian household)

1 - Best "current SOFC", 60% LHV electrical efficiency, 25% LHV thermal efficiency.

2 - Best "future SOFC", 75% LHV electrical efficiency, 20% LHV thermal efficiency.

3 - Best "future SOFC", 75% LHV electrical efficiency, 20% LHV thermal efficiency, 100% biogas.

4 - Best "future DC-SOFC", 80% LHV electrical efficiency, 15% LHV thermal efficiency, 100% biochar with CO_2 capture, electrical vehicle not yet accounted for.



Considering the dwelling alone, even ideal (negative emissions) fuel cells will not be enough.

This approach must be criticized as it indicates that the higher the dwelling's electrical consumption, the higher the negative emission potential of its associated DC-SOFC

→ What about energy sobriety ? Biomass availability ? Life-Cycle Analysis of the fuel cells ? Other planet boundaries ?

Thank you for listening

The role of residential micro-cogeneration fuel cells in the energy transition

- A case study in Belgium -

Nicolas Paulus

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